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ABSTRACT

Title of dissertation: DEVELOPMENT OF A PERFORMANCE BASED, INTEGRATED DESIGN/SELECTION MIXTURE METHODOLOGY FOR FIBER REINFORCED CONCRETE AIRFIELD PAVEMENTS

Stewart David Bennie, Doctor of Philosophy, 2004

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Recent advances in polymer technology have given rise to new research regarding conventional building materials like concrete and the rheological material properties of polymer fiber-concrete composites. Polymers such as polypropylene fiber are now the industry standard for manufacture of geosynthetics which are used as the structural element in earth walls, stabilized slopes, and to improve soft soil bearing capacity. Both industry and researchers now recognize the benefits of polypropylene fiber reinforced concrete in reducing temperature and shrinkage cracking and crack widths, which is important distress criteria in airfield pavements. However, little attention has been given to the use of high tensile strength polypropylene as a structural component of concrete pavements. As important as the research, is the methodology used to obtain the results. There is a need to consider concrete mixture design and selection in conjunction with pavement design since specific mixture properties' behavior and performance

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characteristics are set by pavement design requirements. Such approach will permit the development of an "integrated mixture selection- pavement design methodology". This study quantified the beneficial strength properties of small volume (less than 0.5%) polypropylene fiber reinforced concrete (FRC) as an airfield pavement to meet both military and civilian aviation needs. Polypropylene fiber reinforcement in small volumes displays none of the historical problems of poor workability, or excessive pavement deflections associated with fiber-concrete composites in larger volumes. Through laboratory testing of material properties such as fatigue, toughness and flexural strength and computer modeling this composite showed a consistent improvement in those strength properties that would increase the life of the pavement structure under repetitive aircraft traffic. Perhaps, the most unique property of this composite is its ability to continue to absorb energy after first crack, ductile properties not typically associated with a brittle material like concrete. This increase in toughness is significant to the military in mitigating heaved pavement around bomb damaged runway craters during rapid runway repair. Analogues to safety glass, FRC will mitigate radial fracturing of airfield pavement located around the crater impact area reducing time to repair heaved pavement, an important criteria to air base survivability. This dissertation serves as a blueprint to comprehensively evaluate both design and performance of any fiber concrete composite.

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DEVELOPMENT OF A PERFORMANCE BASED, INTEGRATED DESIGN/SELECTION MIXTURE METHODOLOGY FOR FIBER REINFORCED CONCRETE AIRFIELD PAVEMENTS

by

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Dissertation submitted to the Faculty of the Graduate School of the
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PREFACE

As a retired United States Air Force Civil Engineer, I spent much time with a team of other engineers replacing asphalt airfields in Europe and Turkey with concrete pavements. This was due to high sortie damage from military aircraft, causing subgrade rutting and surface raveling on asphalt surfaces. As a military engineer on the Headquarters staff, I also worked extensively with new technologies to expedite Rapid Runway Repair under battle damage scenarios. Time to repair and pavement toughness being important criterion to the Air Force; repair time dominated by the need to remove heaved concrete runway pavement around bomb damage craters due to fracturing. At the University of Maryland, I enjoyed working on polypropylene fiber research as it pertains to rigid pavements, as I have recognized its potential to solve problems in increasing a pavement's life. Improvements, both in terms of strength (fatigue and flexural), shrinkage (cracking) and toughness due to fiber's unique ability to retard fracturing and absorb energy. Important material properties not only unique to military rigid pavements, but beneficial for general aviation use.

Beginning June 2001, extensive laboratory testing was conducted over a 13-month period at the University of Maryland quantifying the properties of polypropylene fiber reinforced concrete (FRC) as a pavement structure. The success of this testing is in large part due to the efforts of my laboratory partner, Haejin Kim, who has recently immigrated to America with his wife, Seonmi and their daughter, Monica. Haejin and his family epitomize the immigrant spirit of America, welcoming the best and brightest people who become a vital part of the continuous building of this great nation.

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LIST OF ABBREVIATIONS

1. AASHTO American Association of State Highway and Transportation Officials
2. ACI American Concrete Institute
3. AFM Air Force Manuel
4. ANFO Ammonia-Nitrite/Fuel Oil
5. ASTM American Society of Testing Materials
6. C.Y. Cubic Yard
7. E. Modulus of Elasticity
8. FEM Finite Element Method
9. FOD Foreign Object Debris
10. F.R.C. Fiber Reinforced Concrete
11. fmax maximum fatigue strength
12. FPP Fibrillated polypropylene
13. fv maximum fiber fatigue strength
14. g gravity
15. HPC High-Performance concrete
16. HPFRC High Performance Fiber Reinforced Concrete
17. HRWR High Range Water Reducer
18. I Toughness Indices
19. ksi Kips per square inch
20. L/d_f Length/ Fiber diameter(aspect ratio)
21. LEDFAA Layered Elastic Design; Federal Aviation Administration

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22. LVDT Linear Variable Differential Transformers
23. MD Maryland
24. MDOT Maryland Department of Transportation
25. M.O.R. Modulus of Rupture
26. MTS Material Test System
27. Nf Loads to Failure
28. PCA Portland Cement Association
29. R Residual strength values
30. RD Diameter of Ruptured Pavement
31. RRR Rapid Runway Repair
32. S-N Stress to Loads to failure
33. T.M. Technical Manual
34. U.S./U.S.A. United States of America
35. Vc stress wave velocity
36. V_f Volume of Fiber
37. w/c water/cement ratio
38. W.W.M. welded wire mesh

CHAPTER 1. INTRODUCTION

INTRODUCTION

Although concrete is one of man's most common building materials, relatively little is known about damage accumulation to concrete structures subjected to large numbers of load applications during their design life. Concrete deteriorates both in strength and stiffness under repeated load applications especially if it is stressed well beyond half it's rupture modulus in tension (stress ratio > 0.5). Referenced research in Chapter 2 on plain and polypropylene fiber reinforced concrete (FRC) suggests that at fiber contents less than 0.5% and at stress levels below 0.75, Miner's Rule is applicable. Miner's Rule presumes a linear accumulation of damage of materials like concrete until failure (cracking). Beyond stress ratios of 0.75 and fiber contents greater than 0.5%, damage accumulates in concrete in a pronounced, non-linear fashion and energy absorption capacity decreases almost exponentially[1].

If Miner's Rule of linear damage accumulation is applicable for plain and polypropylene fiber reinforced concrete (FRC) at stress ratio's below 0.75, it is reasonable to assume that a relationship exists between aircraft passes to failure (N) and stress level. In order to determine a airfield thickness for a no failure condition due to loading, the following input parameters should be considered, aircraft gear geometry, applied aircraft's tire contact pressure and Modulus of Rupture (MOR) of varying volumes of low fiber content (<0.5%) concrete. The no failure condition being the minimum pavement thickness, in which the stress ratio is low enough that the pavement

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will not fail in fatigue typically defined as the endurance limit. Such a relationships could be expressed mathematically in the form of a design thickness to stress level equation to establish minimum criteria for rigid airfield pavements subjected to a specific repetitive aircraft loading for a stated design life. For example, the Portland Cement Association (PCA) has established similar equations in predicting vehicle loads to pavement failure (Nf) under a stated design wheel load for a given highway pavement's static flexural strength[2].

Minimal volumes of polypropylene fiber (less than 0.5%) in concrete can provide important benefits to the performance of rigid airfield pavements. Current research studies document increased flexural, toughness and fatigue resistance properties as well as an ability to minimize crack propagation and reduce crack widths. Polypropylene fibers increase the flexural and fatigue strength of concrete, which is an important property in reducing the design thickness and increasing the serviceability (design life) of concrete airfields. Polypropylene fiber's ability to absorb energy (toughness) is an important property to the military in reducing heaved pavement from explosive cratering. Minimizing crack propagation and reducing crack widths also reduces Foreign Object Debris (FOD) damage to high performance jet aircraft intakes and loss of subgrade fines through slab pumping by heavy lift aircraft. However, these very elastic properties of polypropylene fiber that are beneficial at small volumes begin to cause concerns with rigid pavement deflections, lower compressive strengths, higher creep strains and poor workability at higher fiber volumes. Considerable research has already been done on polypropylene fiber concrete and is discussed in the literature review chapter of this

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dissertation. Current literature research and preliminary finite element method (FEM) modeling on polypropylene fiber reinforced concrete highway pavements optimizes fiber content at 0.20 % for crack control and 0.25% for serviceability (fatigue resistance) when considering a 20 year design life. Therefore, the focus of this research was to quantify FRC material strength (static flexural, fatigue, energy absorption) and shrinkage (cracking) properties in the laboratory and use that data with established computer models, such as KenSlabs, in order to yield performance models predicting load, thermal stresses and rigid airfield pavement life as a function of thickness. Laboratory testing in this research was undertaken on fiber contents of 0%, 0.1%, 0.2%, 0.3% and 0.4% by volume of a concrete using Mix Design (MD) # 7 for highway pavements as the control mix with number 57 aggregate as defined by the Maryland Department of Transportation (MDOT) [3]. Tests for static flexural strength, fatigue resistance (endurance limit), compressive strength, toughness, shrinkage (plastic and unrestrained), and workability were conducted in an attempt to optimize fibrillated polypropylene fiber content to airfield performance properties.

Regarding airfield rigid pavement design methodology, a systems engineering approach is proposed to comprehensively evaluate all facets of this FRC composite to ensure optimization of its material properties in line with the unique survivability requirements of the military. This dissertation proposes a comprehensive, systematic methodology to quantify the benefits of using low volume (less than 0.5%) polypropylene fiber reinforced concrete (FRC) in an airfield pavement to meet both military and civilian aviation needs. There is a real need for a comprehensive, long-term,

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iterative approach to pavement research, design and performance management and a need to establish judgement criteria for selecting this methodology. Current pavement research generally does not systematically test and evaluate the wide spectrum of properties of a new material so as to determine the synergetic effect of loads, environment, survivability and constructabilty. Current pavement design is typically based on a single criterion of thickness determination under aircraft loading, derived from empirical data. The variables in designing a pavement structure are complex, making them difficult to evaluate without the use of systems engineering. The main effort of this dissertation was to develop an "integrated mix selection / design " methodology for airfield concrete considering specific aircraft, laboratory data on mixture properties and airfield pavement analysis and design requirements. From the Military's perspective, this methodology must be generic enough for worldwide austere location application based on limited material testing data, such as the modulus of rupture (MOR) of a local concrete mix and minimal aircraft loading data, such as tire pressure for a given aircraft to be useful.

BACKGROUND

Fiber-reinforced concrete (FRC) in the context of this research is conventionally mixed concrete containing discontinuous fibers that initially are randomly orientated in three dimensions in the mixture[4]. Although there has been continued interest and research in the use of fiber-reinforced concrete (FRC), there have been few major innovations in proportioning or production of high performance fiber reinforced concrete (HPFRC) since the last state-of-the-art Report [5]. In addition, while past research in FRC has

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examined the influence of modifications of existing steel fibers, fibers with larger aspect ratios and higher fiber volumes, there is now a growing interest in non-metallic fibers such as polypropylene.

Regarding airfield rigid pavement design, most of this experience centered on the use of steel fibers in the late 1980's by the U.S. Army Corps of Engineers[6] at relatively larger fiber contents of 0.5 to 2.0 percent by volume. Because of fibrous concrete's increased flexural strength and the bridging of fibers across cracks that develop in the fibrous concrete, the thickness of airfield pavements could be significantly reduced. The military saw the advantage in steel fiber concrete, particularly in potential war zones where they construct only unrienforced concrete airfields for rapid bomb damage repair of runway craters. Fibers' ability to absorb energy dynamically loaded is a valuable property in terms of the amount of heaved pavement that needs to be removed from a bomb-damaged airfield, damaged pavement which is twice the apparent diameter of the crater. The U.S. Army Corps of Engineers discovered that the addition of 0.5 % or greater volume of fibers to concrete resulted in a composite with increased ductility and impact resistance[7]. However, this composite with large volumes of fiber also resulted in a thinner, more flexible runway structure which caused an increase in vertical deflections and densification or shear failures in the foundation, as well as, pumping of the subgrade material and joint deterioration. To protect against these undesirable factors, the military added limiting vertical deflection criteria to steel fiber FRC airfield design as illustrated in the following table (Table1.1). Additionally, the United States Air Force was concerned regarding potential damage to high performance fighter aircraft from the

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ingestion of steel fibers into engine intakes, so research of steel fiber airfields was abandoned. The failure of this concrete composite research study had as much to do with the "single criteria" approach to material evaluation as with the composite itself.

Current advances in polymer technology makes fibrous (non-metallic) concrete composites a relatively new but viable material for airfield pavement application. However, polymer based composites lack a long-term performance history and their is little empirical data or studies on FRC response under vehicle or aircraft loading. An example would be the lack of fatigue coefficients for FRC, similar to those used by the Portland Cement Association (PCA) to model thickness design of plain concrete.

Table 1.1:Allowable Fibrous Concrete Airfield Deflection (inches).
(Source; Figure 4-19/Figure 4-20 TM 5-825-3/AFM 88-6).

Aircraft/Airfield Type	1,000 Aircraft Passes	10,000 Aircraft Passes	100,000 Aircraft Passes	1,000,000 Aircraft Passes
F-15 Fighter	0.12	0.07	0.06	0.05
C-141 Cargo	0.10	0.06	0.05	0.05
B-52 Bomber	0.08	0.06	0.05	0.05
B-1 Bomber	0.10	0.06	0.05	0.05
C-130 Cargo	0.11	0.07	0.05	0.05
Class I Airfield	0.13	0.08	0.05	0.05
Class II Airfield	0.11	0.07	0.05	0.05
Class III Airfield	0.11	0.07	0.05	0.05

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The U.S. Army Corps of Engineers first used synthetic (non-metallic) fibers in 1965 in blast resistant vertical structures. In their analysis it was discovered that the addition of even small quantities (0.5 percent by volume) of synthetic fibers to concrete resulted in a composite with increased ductility and impact resistance. However, during testing concerns surfaced regarding fiber balling during mixing which hindered uniform fiber distribution, mix workability and abrasion resistance of the concrete surface. Glass fibers were also studied and discarded because they quickly became brittle from the alkalinity of the concrete. In contrast, during these tests, polypropylene fibers showed improvements in flexural and tensile strength, significantly reduced bleeding and reduced cracking[8]. Despite these early findings, to date relatively few studies have examined the use of small volume (<0.5% fiber) concentrations of fiber and their effect on mix workability, ductility, strength, impact resistance and abrasion as it pertains to airfields.

These synthetic fibers are man-made fibers resulting from relatively current research and development in the petrochemical and textile industries. Polypropylene fibers are extruded from olefin resin and today are being used extensively throughout the U.S.A. and Canada in all types of concrete construction. They have proven to be an effective method to better distribute cracking and reduce crack size[7]. Testing has also showed superior fatigue strength, endurance limits (loads to failure) and toughness properties associated with even small amounts of polypropylene fibers. Toughness is an indication of the load carrying capabilities of the fibers within the concrete matrix after first crack. Flexural strengths, toughness and endurance limits (fatigue) are important

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design parameters, particularly in a airfield's pavement longevity (design life), because these structures are subjected to repeated fatigue loading by aircraft.

RESEARCH OBJECTIVES

The major objectives of this research were to construct a step by step methodology for comprehensively evaluating all facets of fiber-reinforced concrete's (FRC) material's behavior as it applies to improving the performance of the airfield pavement as a system. Evaluate the benefits of using fiber reinforced concrete in terms of pavement design thickness reduction, energy absorption and potential reduction in pavement crater damage. To achieve these objectives the following steps were undertaken.

Step 1. Conduct a literature review on the design behavior of fiber reinforced concrete. The objective of this search is to determine those material properties that enhance the performance of concrete as an airfield pavement. Once determined, the criteria for "High-Performance Airfield Concrete (HPAC)"can be developed.

Step 2. Conduct laboratory testing for evaluating the behavior and performance of fiber reinforced concrete as a HPAC. The results from the laboratory testing were used in pavement analysis and design through finite element computer programs to develop pavement thickness reduction equations.

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Step 3. Through analytical modeling, establish relationships between fiber concrete properties, specific aircraft gear geometry and wheel contact pressures to develop predictive airfield design life equations.

Step 4. Develop equations to quantify the heaved pavement reduction potential of fiber-concrete airfields due to explosive cratering.

Step 5. Propose an integrated concrete design selection methodology that includes field testing for validating the assumptions and analysis of airfield pavement design based on aircraft type and load configuration, environment, and fracture energy with actual conditions in an iterative model improvement process.

In order to achieve the objectives of this research a variety of laboratory testing tasks and mechanistic modeling were undertaken. In some cases, data was obtained from past studies as well. These tasks were as follows:

(1) Examine the mix design and workability characteristics of low volume (<0.5 %) polypropylene fiber reinforced concrete. The objective of this testing was to evaluate workability of polypropylene fiber concrete at 0.1%, 0.2 %, 0.3%, 0.4% volumes as compared to plain (0%) concrete. Slump was evaluated with ASTM C 995 by monitoring the time of flow through the inverted cone test**.** The inverted cone test was specifically developed to measure FRC workability and can be used to compare FRC to conventional mixtures with similar slump values. For workability, the advantage of the inverted slump cone test is that it takes into account the mobility and viscosity

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characteristics of concrete, which comes about due to vibration. Plain concrete slump was measured with the slump cone as outlined in ASTM C143. The standard ASTM air content test equipment and procedures were used (ASTM C 138). Unit weight and 28-day compressive strength values were evaluated for each specimen and mixture.

(2) Evaluate the strength characteristics of polypropylene fiber reinforced concrete. The objective of this testing was to evaluate the static flexural strength and fatigue resistance of polypropylene fiber concrete at 0.1%, 0.2 %, 0.3%, 0.4% fiber volumes as compared to plain (0%) concrete. The endurance limits (fatigue strength) in dynamic flexural loading were determined as well. In this testing the third-point loading was used as outlined in ASTM C 78.

(3) Examine the energy absorption capability of fiber reinforced concrete. ASTM C 1018 was used in toughness evaluation. ASTM C 39 Compressive Strength of Cylindrical Concrete Specimens was used to study FRC ductility. Quantify, the energy absorption capability of plain (0%), 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete from laboratory toughness testing analysis, compressive strength testing for ductility and impact resistance literature research for polypropylene fiber concrete.

(4) Examine the shrinkage characteristics of low volume (<0.5%) polypropylene fiber reinforced concrete with ASTM C 157 and the Steel Ring Test.

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(5) Through Finite Element Modeling (FEM), establish pavement design requirements for the concrete and relationships estimating pavement design thickness based on specific aircraft wheel pressures and geometry. The fatigue models anticipate rigid pavement design life for loading repetitions considering limiting pavement deflections, and the material properties of concrete. Based on the above analysis, establish pavement reduction values for FRC.

(6) Based on laboratory testing values of concrete specimens containing varying amounts of polypropylene fiber up to 0.4%, create heaved pavement reduction equations for airfield bomb damage crater analysis. These predictive equations were used to quantify heaved pavement reduction based on material properties.

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ORGANIZATION OF THE REPORT

The first chapter provides an overview of the need of an FRC composite for airfield pavements, a brief historical review on the development of fiber-concrete composites, the research objectives and a description of the organization of this dissertation. Chapter two presents an extensive literature review of past research on polypropylene fiber reinforced concrete, FRC material testing protocols and Finite Element Method-Rigid Pavement programs. Chapter three presents the integrated mix design methodology. The fourth chapter summarizes the extensive laboratory testing quantifying the properties of polypropylene fiber reinforced concrete (FRC) as a pavement material. Chapter five details the analytical evaluation and modeling used to build the performance models quantifying the beneficial effects of FRC and includes the fracture reduction model for explosive cratering so as to determine the reduction in heaved pavement. Chapter six presents an example of the use of methodology for quantifying the beneficial material properties of the polypropylene fiber reinforced concrete composite for the C-17 aircraft using a concrete Design Mix #7. Finally, Chapter seven presents the summary, conclusions and future recommendations.

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CHAPTER 2. LITERATURE REVIEW

INTRODUCTION

The objective of this literature search was to review current research on polypropylene fiber concrete and determine its material properties that will eventually enhance the performance of concrete as an airfield pavement. These properties would be used to develop the criteria for "high-performance airfield concrete (HPAC)". According to the Federal Highway Administration (FHWA), High Performance Concrete is defined as concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using only conventional materials and normal mixing, placing, and curing practices[5]. In short, any concrete that satisfies certain criteria proposed to overcome limitations of conventional concretes may be called high-performance concrete (HPC). The requirements may involve enhancements of characteristics such as placement and compaction without segregation, long-term mechanical properties, early-age strength, toughness, volume stability, or service life in severe environments. In the case of airfields, performance characteristics that enhance concrete's ability to withstand higher stresses imposed by aircraft tire pressures, but less loading repetitions as compared to highways. Performance characteristics that retard surface deterioration (cracking) and improve impact resistance of runways due to the unique operating environment of military aircraft.

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MATERIAL BEHAVIOR CHARACTERISTICS

Polypropylene fiber is hydrophobic, meaning it does not absorb water and is alkaline resistant. Polypropylene fibers do not bond chemically in the concrete mix, but bonding has been shown to occur by mechanical interaction. Mechanical bonding properties of the polypropylene fiber were found to be greater for twisted collated fibrillated polypropylene fibers or for fibers with buttons (enlargements) added to the fiber ends. Improved mechanical bonding is a direct result of the cement matrix penetrating the fibrillated fiber network that anchors the fiber in the matrix. This anchoring feature is called pegging[7]. Recommended fiber length in the concrete matrix is usually a function of mix aggregate size (Table 2.1). Additionally, concrete workability and abrasion resistance is satisfactorily maintained with admixtures and minimum mix proportion adjustments[5].

Table 2.1: Recommended Fiber Lengths (ref. Ozyildirim, Moen 1996).

Aggregate Top Size	Fiber Length
1/4 inch(6 mm)	3/4 inch(19 mm)
1/2 inch(13 mm)	1 1/2 inch(38 mm)
3/4 inch(19 mm)	2 1/4 inch(54 mm)
1 inch(25 mm)	2 1/2 inch(60 mm)

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Fatigue Strength of Polypropylene Fiber Reinforced Concrete

According to the ACI 544.1 R-96 " Fiber Reinforced Concrete" American Concrete Institute Report[7], flexural fatigue strengths and endurance limit are important design parameters, particularly in pavements, because these structures are subjected to fatigue load cycles. ACI defines failure (fatigue) strength as the maximum flexural fatigue stress at which a beam can withstand two million cycles of non-reversed fatigue loading. The endurance limit of concrete is defined as the flexural fatigue stress at which the beam could withstand two million cycles of non-reversed fatigue loading, expressed as a percentage of the modulus of rupture of plain concrete. According to ACI, in slab-on-grade applications with collated fibrillated polypropylene fiber contents up to 0.3 percent by volume, the fatigue strength was increased dramatically. The addition of polypropylene fibers, even in small amounts, had increased the flexural fatigue strength. Using the same mixture proportions, the flexural fatigue strength was determined for 0.1, 0.2, 0.3 percent fiber volumes and it was shown that the endurance limit was increased by 15 to 18 percent as compared to plain concrete. In another test, as polypropylene fiber content increased 0.1%, 0.5%, 1.0% by volume at two million cycles the flexural fatigue strength increased by 16%, 18%, and 38% respectively in comparison to plain concrete. As stated by the ACI, there is a trend of increasing fatigue strength as polypropylene fiber content is increased.

In a study by Nagabhushanam, Ramakrishnan, and Vondran[9], fatigue strength increased when fibrillated polypropylene fibers were added to the concretes. Fatigue strength for plain concrete was 395 psi. Fatigue strength of 386 psi, 500 psi and 521 psi

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were observed for 0.1%, 0.5% and 1% fiber concrete mixes respectively. These values show a decrease of 2% for the 0.1% fiber concrete mix and an increase of 27% and 32% for the 0.5% and 1% fiber concrete mixes. The endurance limit for the mixes with 0% (plain), 0.1%, 0.5%, and 1% fiber contents were 50%, 58%, 59%, and 69% respectively when expressed as a percentage of their own MOR by fiber case and not just as the percentage of the modulus of rupture for plain concrete. Endurance improved with fiber content, thus showing an improvement in the fatigue performance of FRC. Figure 2.1 shows fatigue strength values of 2.72 Mpa for plain concrete, 2.6 Mpa for 0.1% fiber, and 3.45 Mpa for 0.5% fiber and 3.56 Mpa for 1.0% fiber content**.** When the endurance limit is expressed as the percentage of the modulus of rupture for plain concrete, the endurance limit for 0.1%, 0.5% and 1.0% fiber contents were 116%, 118% and 138% respectively. Thus fibrillated polypropylene (FPP) fiber reinforcement improves concrete's fatigue strength properties and endurance limits, which translate to added years of pavement longevity.

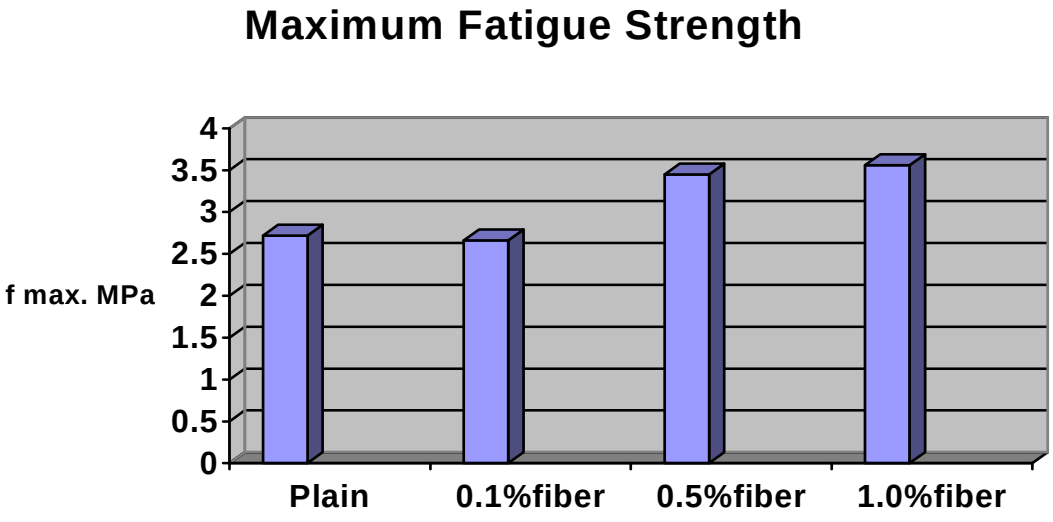

Figure 2.1: Maximum Fatigue Strength (ref. Nagabhushanam 1989).

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Flexural fatigue strength of fibrillated polypropylene fiber-reinforced concrete was also investigated by Nagabhushanam in 1989 [9]. Nagabhushanam's paper presents the results of an experimental investigation to determine the flexural fatigue strength of concrete reinforced with three different concentrations of fibrillated polypropylene fibers. The properties and performance of fresh and hardened concrete with and without fibers are compared. The test program included the evaluation of 1) flexural fatigue strength and endurance limit 2) hardened concrete properties, such as compressive strength, static modulus, pulse velocity, modulus of rupture, and toughness indexes and 3) fresh concrete properties, including slump, vebe time, inverted cone time, air content, and concrete temperature. The test results indicated an appreciable increase in post-crack energy absorption capacity and ductility due to the addition of fibers. When compared with plain concrete, the flexural fatigue strength and the endurance limit at two million cycles significantly increased. The static flexural strength of the specimens also increased after being subjected to repetitive loading at a stress level below fatigue strength.

In the paper by Vondran, G.L., Nagabhushanam, M., Ramakrishnam, V. " Fatigue Strength of Polypropylene Fiber Reinforced Concretes" [31] of flexural fatigue strength of concrete reinforced with three different concentrations of fibrillated polypropylene fibers are presented. In this study it was observed that there was an appreciable increase in post-crack energy absorption capacity and ductility due to the addition of fibers. When compared to plain concrete, there was a significant increase in flexural fatigue strength and the endurance limit for two million cycles. The main thrust of the investigation was to determine the endurance limit in fatigue loading. The two million cycles were chosen

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to approximate the life span of a structure that may typically be subjected to fatigue loading, such as a bridge deck or highway pavement.

Interestingly, two million cycle fatigue loading testing at stress levels below the endurance limit did not lead to a decrease in static flexural strength when the specimens were later re-tested. In most cases, the flexural strength increased slightly, especially when the stress to which the specimen was subjected earlier was lower than the fatigue stress at the endurance limit. This may or may not be attributed to specimen aging. According to these researchers, a significant advantage of polypropylene under dynamic loads is its relatively low elastic modulus at slow rates of loading, which increases because the effect of time-dependent visco-elastic behavior is eliminated. ACI 544.1R-49 reports similar results, that polypropylene fiber reinforced concrete subjected to fatigue stress loading below the endurance limit show increased static flexural strength. The implications of increased modulus of rupture values over time, under vehicle or aircraft loading conditions below the endurance limit would be significant.

Yin, W. S. and Hsu, T. C [10] studied fatigue behavior of fiber reinforced concrete under uni-axial and bi-axial loading. The stress ratio (S) to load cycles to failure (N) curves and the cyclic deformations of fiber concrete were compared to those of plain concrete. It was found that the S-N curve of fiber concrete is a straight line from one to one million cycles, rather than a curve. The addition of fibers to concrete increases the fatigue life, while the failure mode remains the same.

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Ramakrishnan, V. and Lokvik, B. J. [11] presented the results of an analytical investigation to determine the flexural fatigue strength of fiber reinforced concretes (FRC). Four different types of fibers were used: straight steel, corrugated steel, hooked end steel, and polypropylene fibers. These fiber concretes were investigated for two different fiber quantities (0.5% and 1.0% by volume), whereas the same basic mix proportions had been used for all the concretes. More than 300 beams were subjected to fatigue testing with third point loading at a frequency of 20 load cycles per second, in a range of one to four million cycles and were then analyzed. For a better accuracy in generating the S-N curves, statistical and probabilistic concepts are introduced to predict the flexural fatigue model and the fatigue life expectancy of the composite. In this study, it was also found that fiber reinforced concrete at it's endurance limit, fatigue strength increased with fiber volume.

A study by Grzybowski and Meyer[1] investigated damage accumulation in concrete with and without fiber reinforcement. The study's goal was the development of a damage model that permits the prediction of remaining life of a material subjected to a load history of known characteristics. The study underscores the important role of micro cracking especially at stress levels (S) in excess of 75% of ultimate strength where crack growth accelerates toward failure. In fiber reinforced concrete, well-dispersed and distributed fibers retard the growth of micro-cracks. Furthermore, in FRC the development of a large number of small cracks instead of a small number of large cracks is observed, large cracks would normally cause failure.

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In this same study, S-N curves for concrete with varying quantity content of polypropylene and steel fibers were developed. A fiber content of 0.25% optimized fatigue behavior. As an example, for a stress ratio of 0.8, the number of cycles to failure for plain concrete was 1,000. If 0.25% of polypropylene fibers are added, the number of cycles to failure is increased to over 10,000. The implication of increased fatigue resistance for concrete highway or airfield pavements, subjected to high traffic volume, is improved pavement longevity and lower maintenance and repair costs.

In the study by Grzybowski and Meyer[1] energy dissipation as a measure of damage accumulation in concrete was observed. One cycle per second (cps) fatigue test results are shown in Figure 2.2**.** This test shows the number of cycles to failure as a function of stress ratio and fiber volume. Fiber reinforcement has a clear beneficial effect on the fatigue behavior of concrete as long as the fiber count is not much larger than 0.25 percent. At 0.25%, the beneficial effect of polypropylene on the total energy-absorption capacity of concrete seems to peak, irrespective of the stress level. Beyond 0.5% percent fiber volume, the effect is insignificant. Additionally, at higher stress ratios (S > 0.75) polypropylene fiber's energy absorption capacity decreases almost exponentially. The experimental results confirmed the dual effect of fiber reinforcement on the cyclic behavior of concrete. By bridging microcracks, fibers tend to retard their growth, thereby causing a strength increase. Fibers also increase the pore and initial microcrack density, thereby causing a strength decrease. The combination of these two effects is a net increase in cyclic strength with increasing fiber volume up to 0.25%.

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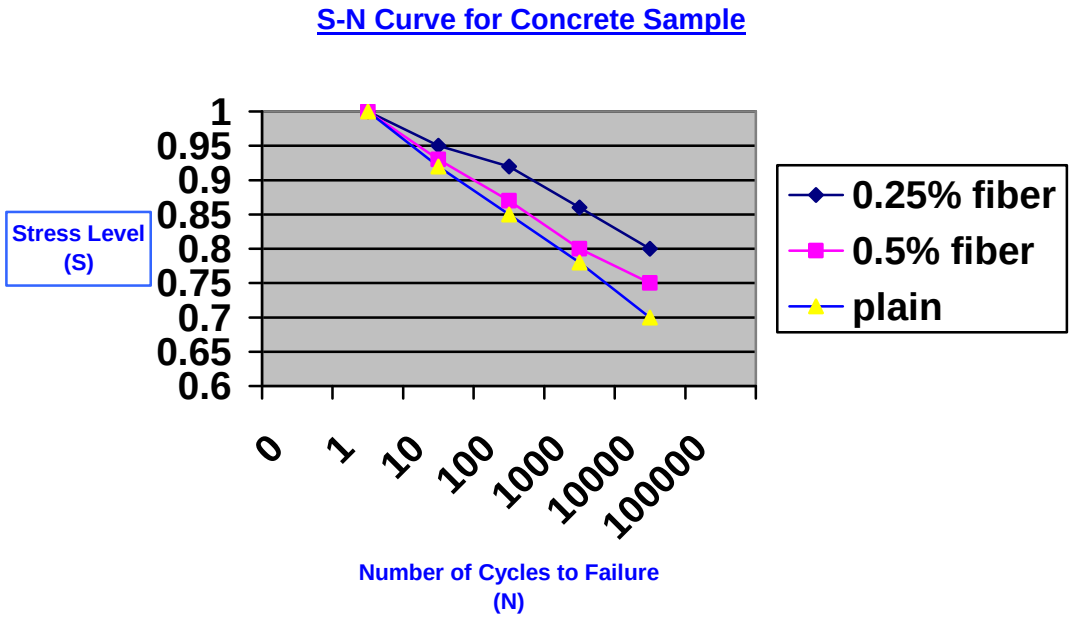

Figure 2.2: Fatigue Strength (ref. Grzybowski, Meyer 1993).

Static Flexural Strength of Polypropylene Fiber Reinforced Concrete

There is no consensus in the published literature about the effect of adding polypropylene fibers on flexural strength (modulus of rupture). Studies conducted have reported that the modulus of rupture determined at 7 and 28 days was slightly greater for fibrillated polypropylene FRC at fiber contents of 0.1 to 0.3% percent by volume. When using the same basic mix proportion, decreases in compressive strength at higher fiber contents (0.1% to 2%) suggests the direct flexural test may be misleading regarding FRC comparisons. Figure 2.3 illustrates the effect of adding varying quantities of fibrillated polypropylene fiber to a concrete mix for plain concrete. When normalized for the compressive strength ($\sqrt{fc}$) for each fiber case, flexural strength results are more pronounced at 0.1% to 0.5 % volumes. This suggests a need to adjust mix designs to ensure similar compressive strengths for fiber flexural strength comparisions[7].

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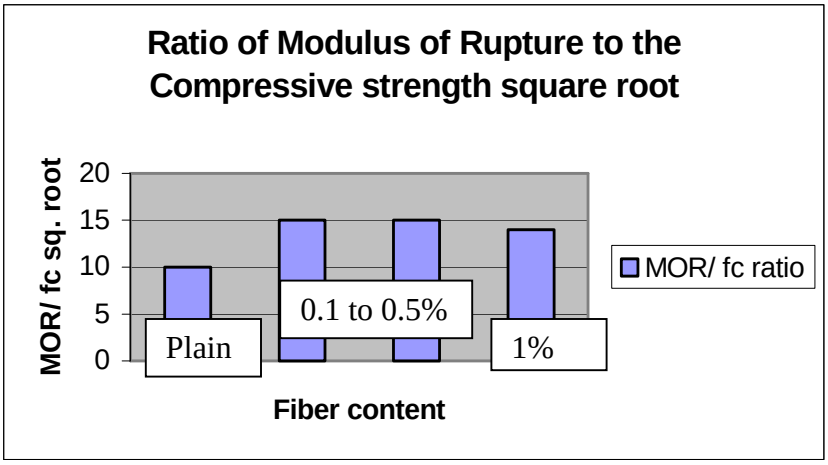

Figure 2.3: ACI-FRC Flexural Stress Comparisons (ref. ACI 544.1R96 1997).

Alwahab and Sororushian reported significant improvements in polypropylene fiber concrete's flexural strength in a Bayasi and Zeng study. Specifically at 0.3 % percent fiber volumes, a strength of 900 psi was obtained as compared to a plain concrete value of 700 psi and a 0.1% fiber strength value similar to plain. This was attributed to the application of fibrillated polypropylene fiber, which could maintain a significant portion of its flexural resistance at large deformations beyond peak load[10].

According to the Bayasi and Zeng study[10], there are a number of factors that influence the behavior and strength of FRC in flexure. These include: type of fiber, fiber length (L), aspect ratio (L/d_f) where df is the diameter of the fiber, the volume fraction of the fiber (V_f), fiber orientation, fiber shape, and fiber bond characteristics (fiber deformation). Although increasing aspect ratio (L/d_f) has long been recognized as a positive influence on FRC performance, because of the improved resistance to pullout of the fibers from the matrix, the effect of the aspect ratio was quite small compared with

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that of the fiber content. Fiber content seems to be the parameter that is of primary importance in determining the first-crack and ultimate strengths under static flexure loading.

In a flexural test study by Tawfiq , Armaghani and Ruiz, collocated fibrillated polypropylene fibers(FiberMesh) were subjected to static flexural testing (ASTM C 78) and demonstrated a 10% average increase in strength as compared to the plain concrete samples. In the plain concrete beams the strain measurements were 70 percent less than the strain values from the fiber reinforced concrete beams at an applied stress of 500 psi. This test result quantified the delay period in strain and crack development in fiber reinforced concrete. Testing indicates that fiber reinforcement delays crack initiation by about 18 percent, correcting an inherent weakness of concrete in tension due to the mechanical bonding behavior of fibers in the concrete matrix[11].

A significant flexural strength characteristic of fiber reinforced concrete is the pseudo-strain hardening phenomena associated with dynamic fatigue loading of specimens below their endurance limit. There is an increase in flexural strength for FRC and some plain concrete beams after they were tested for fatigue. An increase in flexural strength that is higher than can be attributed to the increase in age alone and appears to be a function of the fatigue stress at which the specimens were originally loaded. The Ramakrishnan study concluded that the increase in flexural strength of a beam after fatigue loading was inversely proportional to the applied fatigue stress. When fiber concrete is subjected to a fatigue stress below its endurance limit, there is an increase in

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the flexural strength by as much as 35% for 0.50% fiber volumes. If a beam is subjected to an applied stress lower than its fatigue stress, it may never fail in repetitive loading at that stress level[9]. This has important implications for both highway and airfield pavements, which are typically designed in this regard. This unique material characteristic of FRC contributes to the improvement of fatigue strength over time.

Tensile Strength of Polypropylene Fiber Reinforced Concrete

According to Shah [12] analysis of tensile tests results done on concrete with glass, polypropylene and steel fibers indicate that with such large volume (ranging up to 15 percent) of aligned fibers in concrete, there is substantial enhancement of the tensile load carrying capacity of the matrix. In Splitting Tensile tests**,** the failure in tension of cement-based matrices is rather brittle and the associated strains are relatively small in magnitude. The addition of fibers to such matrices, whether in continuous or discontinuous form, leads to a substantial improvement in the tensile properties of the FRC in comparison with the properties of the un-reinforced matrix.

In his investigation of FRC for use in transportation structures, Celik Ozyildirim[13] tabulated the results of varying volumes of fibrillated polypropylene fiber on spilt tensile and compressive strength properties (Table 2.2). As fiber volume increased, there was an increase in tensile strength.

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Table 2.2: Fiber Tensile Strength Values (ref. Ozyildirim, Moen 1996).

Fiber Content	Compressive Strength Mpa (psi)	Split Tensile Strength Mpa (psi)
0%(plain concrete)	41.7 (6,050)	4.26 (620)
0.2%	46.6 (6,760)	4.44 (645)
0.3%	42.0 (6,100)	4.56 (660)
0.5%	45.5 (6,600)	4.80 (695)
0.7%	39.7 (5,760)	4.70 (680)

Toughness Behavior of Polypropylene Fiber Reinforced Concrete

According to ASTM C 1018, there are three stages of the load-deflection response of FRC mixtures tested; first crack, peak strength in flexure and toughness (Figure 2.4). A relatively linear response up to point A is observed initially. The strengthening mechanism in this portion of the behavior involves a transfer of stress from the concrete matrix to the fibers by interfacial shear. The imposed stress is shared between the matrix and fibers until the matrix cracks at what is termed as “first cracking strength”. Next there is a transition nonlinear portion between point A and the maximum load capacity at point B. After cracking, the stress in the matrix is progressively transferred to the fibers. With increasing load, the fibers tend to gradually pull out from the matrix leading to a nonlinear load–deflection response until the ultimate flexural load capacity at point B is reached. This point is termed as “peak” strength. Finally, a post peak descending portion, following the peak strength until complete failure of the composite. The load–deflection response in this portion of behavior and the degree at which loss in strength is

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encountered with increasing deformation is an important indication of the ability of the fiber composite to absorb large amounts of energy after failure and is a characteristic that distinguishes fiber-reinforced concrete from plain concrete. This characteristic is referred to as toughness.

In terms of flexural toughness, the toughness index is an indication of the load carrying capabilities of the fibers within the concrete matrix after the first crack. The toughness index (I) is a measure of the capacity of fracture energy absorption and ductility of the specimen. The toughness index is defined as the area under the load-deflection curve up to a specific deflection divided by the area under curve up to the point where concrete first cracks. Plain concrete fails immediately upon cracking, without further load carrying capacity so I is always equal to 1.0 for plain concrete. However, concrete beams reinforced with fiber continue to deflect in a ductile fashion. Regarding the toughness index, the beams with higher fiber contents exhibited higher energy absorption and improved ductility properties (Figure 2.5). According to ASTM C 1018, there are three measured deflection points for toughness; I-5 (3 times the deflection at 1^{st} Crack), I-10 (5.5 times the deflection at 1^{st} Crack), and I-30 (10.5 times the deflection at 1^{st} Crack). Residual strength factors $R_{5\text{-}10}$ and $R_{10\text{-}20}$ represent the average level of strength retained after first crack as a percentage of the first crack strength for the deflection intervals[14]. Values of 100 correspond to perfectly plastic behavior and plain concrete has a residual strength value of zero.

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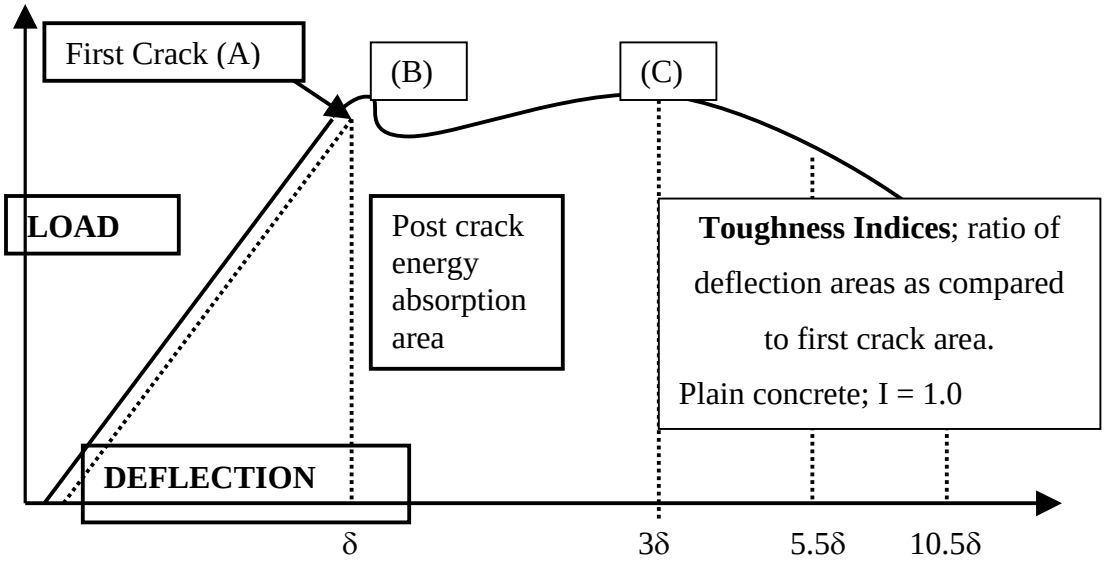

Figure 2.4: ASTM C 1018; Load-Deflection Curve (ASTM Standards 2001).

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According to ACI 544.1R-49, strength at first crack and at complete failure increased significantly with the addition of polypropylene fiber compared to plain concrete. Additionally, post crack reduction in load generally decreased as fiber content increased. Fiber reinforced concrete's ability to absorb elastic and plastic strain energy and to transfer tensile stresses across cracks is an important performance factor for serviceability.

A comparative evaluation of the static flexural strength for concretes with and without four different types of fibers: hooked-end steel, straight steel, corrugated steel, and polypropylene fibers was conducted by Ramakrishnan [15].The fibers were tested at 0.5, 1.0, 1.5 and 2.0% by volume. It was reported that maximum quantity of hooked-end fibers that could be added without causing balling was limited to 1.0 percent by volume

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and the same basic mix proportions were used for all concretes. Compared to plain concrete, the addition of fibers increased the first cracking strength 15 to 90 percent and static flexural strength 15 to 129 percent. Compared on equal basis of 1.0 percent by volume, the hooked-end steel fiber contributed to the highest increase, and the polypropylene fibers provided the least appreciable increase in the above mentioned properties.

Johnston and Zemp[5] investigated the flexural performance under static loads for nine mixtures. The results of Johnston's work indicated that increasing the fiber content from 0.50 to 1.50% had a significant beneficial effect on the first crack and ultimate strengths despite the negative influence of increasing water/cement ratio (w/c). The increase in first crack strength was 31%, unadjusted for the differences in w/c. With the adjustment in w/c, the increase is 63% over the value for 0.5% of the same fibers.

Bayasi and Celik[16] studied the flexural strength of synthetic fiber-reinforced concrete. Two fiber types were used, fibrillated polypropylene fibers and polyethylene-terphalate polyester fibers. Fiber volume fractions ranged from 0 to 0.60% and fiber length were 12 mm (0.5 in.). Silica fume was used as partial replacement of Portland cement on an equal mass basis at 0, 5, 10 and 25%. The results indicate that polyester fiber and polypropylene fibers have an inconsistent effect on the flexural strength but significantly increase the flexural toughness and the post-peak resistance of concrete.

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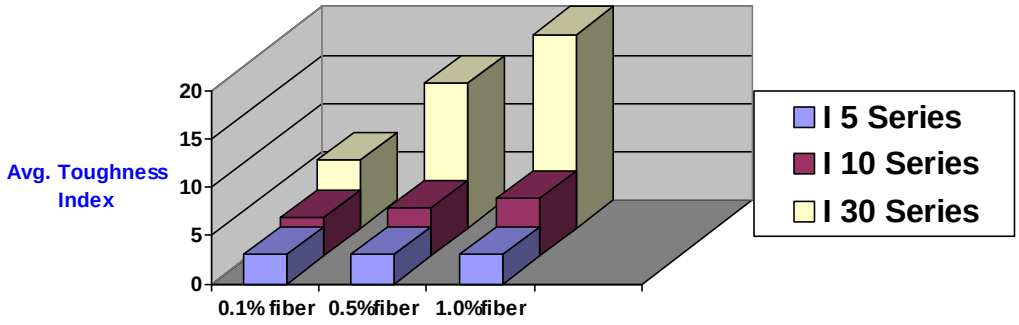

Figure 2.5: Toughness Indices (ref. Bayasi, Celik 1993).

In a study by Celik Ozyildirim and Christopher Moen[17] the strength properties of polypropylene fiber at different volume contents were evaluated. First crack strength and toughness values were determined in accordance with ASTM C-1018 and the results of the laboratory investigation are tabulated in Table 2.3. The toughness of concrete improved with increasing fiber content, and first crack strength reached a peak at a fiber content of 0.20%.

Table 2.3: Polypropylene Fiber Concrete Properties (ref. Ozyildirim, Moen 1996).

Fiber Content	First Crack Mpa (psi)	Toughness Indices I-5	I-10	I-20	Residual Factors R-5,10	R-10,20
0 %	4.95 (720)	1	1	1	0	0
0.2 %	5.40 (785)	1.7	2.4	3.9	14.9	14.8
0.3%	4.25 (615)	2.4	4.1	7.3	33.8	31.7
0.5%	5.05 (730)	2.8	5.0	9.2	44.3	42.5
0.7%	5.15 (745)	3.8	6.9	13	61	61

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Compressive Strength of Polypropylene Fiber Reinforced Concrete

Compressive Strength of concrete is evaluated according to ASTM C 39 using 6 inch x 12 inch concrete cylinders. According to ACI 544.1 R-96 " Fiber Reinforced Concrete" [7] polypropylene fibers at different quantities have no effect on compressive strength. However the fibers had a significant effect on the mode and mechanism of failure of concrete cylinders in a compression test. The fiber cylinders failed in a more ductile mode, particularly true for higher strength concrete where the cylinders endure large deformations without shattering.

The "Damage Accumulation in Concrete with and without Fiber Reinforcement" study by Grzybowski and Myer investigated damage accumulation in concrete with varying volumes of fiber reinforcement[1]. Regarding the results of compressive tests, the mean strength of plain concrete was very close to the target strength of 7000-psi (48.3 kN). The results further indicated that polypropylene fiber reinforcement has no noticeable effect on the compressive strength of concrete. If anything, a slight reduction due to the fiber's low elastic modulus as compared to the concrete modulus. Other researchers, Nakagawa[5] conducted compressive strength tests of concrete with short discrete fibers. The results indicated that compressive strength tends to decrease when the fiber volume was increased. The effect of large volume of entrained air, due to the increase of fiber volume, had a significant influence on this reduction of strength.

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Three 10 ft x 10 ft x 0.5 ft concrete slabs were cast at the Wiss, Janney, Elstner Associates laboratories. One slab plain, one slab with 0.10% polypropylene fiber (FIBERMESH) and one slab with one layer of 6x6-W1.4 x W1.4 welded wire mesh (W.W.M.). A standard 4,000 psi, one cubic yard concrete mix for all slabs; Type I Portland cement, non air entrained, #6 gravel, #2 sand and use of a water reducing retarder. The plain, welded wire mesh and FIBERMESH slabs failed at 16,000 lb, the flexural capacity of FIBERMESH was 2% higher and in compression, 8% higher than plain concrete. Compressive and flexural strength tests are summarized in Table 2.4. FIBERMESH is considered a suitable substitute for W.W.M. The following engineering values were provided from their report (Table 2.5).

Table 2.4: 0.10% Fiber Strength Values (ref. Wiss, Janney, Elstner Associates).

CONCRETE SLAB(28 days)	Compressive Strength	Flexural Strength
Plain	5,930 psi (41.51 N/mm(mm))	750psi (5.25 N/mm(mm))
FIBERMESH(0.10 %) fiber	6,260 psi (43.82 N/mm(mm))	755 psi (5.28 N/mm(mm))
W.W.M.	Not given	Not given

Table 2.5: 0.15% Fiber Strength Values (ref. Wiss, Janney, Elstner Associates).

CONCRETE SLAB (28 days)	Compressive	Flexural	Splitting Tensile
Plain	3,905psi (27.33 N/mm(mm))	385psi (2.51 N/mm(mm))	275psi (1.93 N/mm(mm))
FIBERMESH(0.075 %) fiber	4,240 psi (29.68 N/mm(mm))	390psi (2.73 N/mm(mm))	290psi (2.03 N/mm(mm))
FIBERMESH (0.15%)	4,345psi (30.42 N/mm(mm))		

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Impact Resistance of Polypropylene Fiber Reinforced Concrete

Impact resistance in the Nagabhushanam, Ramakrishnan, and Vondran study[9] reported blows to failure for plain concrete specimens were very low; for specimens reinforced with polypropylene fibers the blows to failure increased tremendously. For all fiber concretes (0.1%, 0.5%, 1%) the number of blows to first crack and final failure was higher than that of plain concrete. Blows to first crack using the drop-weight test were 10, 30, 20 and 50 and full failure at 20, 50, 75 and 100 for plain, 0.1%, 0.5%, and 1% fiber volumes. Fiber concrete has excellent impact resistance, which increases with an increase in fiber content.

According to the ACI committee Report 544.2R[4], impact strength at first crack and complete failure increased significantly with the addition of polypropylene fiber at 0.1% to 2% by volume with improvements in fracture energy between 33% and 1,000 %. At 0.5% fiber volumes, impact fracture energy was twofold for 6,000 psi concrete and tenfold for 12,000 psi concrete. In Ramakrishnan, Wu and Hosalli's paper[18], a comparative evaluation of concrete properties with and without four types of fibers (hooked-end steel, straight steel, corrugated steel, and polypropylene) at two different quantities (0.5 and 1.0% by volume), using the same basic mixture proportions are presented. The impact strength was increased substantially as compared to plain concrete. by the addition of all four types of fibers. The ¾" polypropylene fiber composites showed an improvement in the drop-weight test of blows to failure of 200, 250, and 225 for 0.1%, 0.5% and 1% fiber contents.

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In the “Investigation of Fiber-Reinforced Concrete for Use in Transportation Structures”[17]the results for impact resistance indicated the number of blows to first crack and ultimate failure increases with increasing fiber volume and length as tabulated in Table 2.6.

Table 2.6: Impact Data ;ACI 544.2R (ref. Ozyildirim, Moen 1996).

Fiber Content	Blows to First Crack	Blows to Failure
Plain Concrete (0%)	65	68
0.2%	60	69
0.3%	56	69
0.5%	79	94
0.7%	111	131

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Creep Behavior of Fiber-Reinforced Concrete

ASTM C 512; Creep of Concrete in Compression measures creep of molded 6 inch x 12-inch concrete cylinders subjected to a sustained longitudinal load by a spring–loaded creep frame[14]. Balaguru and Ramakrishnan conducted creep tests in accordance with ASTM C 512 on fiber reinforced concrete[19]. The 0.6% fiber content specimens (V_f = 0.6%) with a length to fiber diameter ratio (L/d_f = 100) were subjected to a sustained load between 19% and 25% of their compression strength (stress to strength ratio; 0.19 to 0.25). Tests showed that the creep strains were consistently higher for FRC as compared to plain concrete. Creep tests conducted by Houde[5] on polypropylene and steel fibers also showed that the addition of fibers increases the creep strains of the fiber composite by about 20% to 30% in comparison with the un-reinforced matrix. Mangat and Azari reported reductions in the creep strains with FRC in comparison with plain concrete at greater fiber volumes[5]. For instance, at 3% by volume of fibers and at stress to strength ratio of 0.30, a reduction of about 25 % in creep strain compared to plain concrete. However, it was observed that the fibers were less effective in restraining creep at high stress to strength ratios of 0.55. The low effectiveness of fibers in decreasing the creep strains at large stress to strength ratio was attributed to the reduced interfacial bond characteristics of the fibers under creep. A large stress to strength ratio increases the lateral strains and hence decreases the interfacial pressure between the fibers and the surrounding concrete. This in effect reduces the restraint to sliding action between the fibers and the concrete matrix and results in larger creep strains.

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Shrinkage Cracking of Polypropylene Fiber-Reinforced Concrete Slabs

Any potential shrinkage may lead to complications, externally because of structural interaction with other components or internally when the concrete is reinforced. There may even be distress if either the cement paste or the aggregate changes dimension, with tensile stresses set up in one component and compressive stresses in another. Cracks may be produced when the relatively low tensile strength of the concrete or its constituent materials is exceeded. Cracking not only impairs the ability of a structure to carry its design load but may also affect its durability and damages its appearance.

In airfield pavements, crack propagation is a potential source of Foreign Object Debris (FOD) with dislodged aggregates damaging high performance fighter aircraft as they are sucked into jet engine intakes. Pumping occurs under slabs subjected to repeated passes of heavy lift transport aircraft like the C-141/C-5 aircraft. During pumping, these cracks transport fine-grained subsurface soils onto the pavement surface, leaving large subgrade voids under the slab.

ACI 544.1 R-96 cited that several reports have shown that low denier fiber and high fiber counts reduced the effects of restrained shrinkage cracking. The addition of fiber also reduced the average crack width significantly as compared to plain concrete. Plastic shrinkage reductions of 12 to 25% have been reported for 0.1% to 0.3% fiber

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volumes. ACI also reported reductions in drying shrinkage (volume changes) using polypropylene fibers at 0.1% by volume in unrestrained concrete specimens. Using accelerated drying conditions, under variable conditions, early age specimen measurements showed a 18%, 59%, and 10% reduction in shrinkage for 0.1%, 0.2%, and 0.3% fiber volumes as compared to plain concrete.

Soroushian, Mirza, and Alhozaimy investigated the effects of polypropylene fibers during construction operations on the plastic shrinkage cracking of concrete slabs[20]. Polypropylene fibers, at relatively low fiber volume fractions, were observed to reduce substantially the total area and maximum crack width of slab surfaces subjected to restrained plastic shrinkage movements. The rate of screeding (finishing) of the fresh concrete surface was also a critical factor, particularly in plain concrete. Slower screeding rates led to reduced plastic shrinkage cracking.

Plastic shrinkage cracking occurs in fresh concrete within a few hours after placement. The principal cause of this type of cracking is an excessively rapid evaporation of water from the concrete surface[21]. In a study by Johnston[22], results obtained by forced air testing over a polypropylene fiber reinforced slab at fiber contents of 0.05, 0.1 and 0.2 % by volume and fiber lengths of 13, 19 and 51 mm indicate that plastic shrinkage cracking can be reduced from 20 to 90%. The best results were obtained at a fiber content of 0.2%, fiber lengths of 19 mm and 51 mm, water-cement ratio of 0.48, 40 % relative humidity and at 35 °C.

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In a paper by Balaguru[23], results indicate that both steel and synthetic fibers make a definite contribution to shrinkage crack reduction during the initial and final setting periods. According to Shah and Grzybowski[24], the effect of fibers in restraining the free drying shrinkage strains was found to be insignificant. The primary advantage of fibers in relation to shrinkage is their effect in reducing the width of shrinkage cracks.

The American Society of Testing Materials standard test for shrinkage is for free shrinkage (ASTM C 157) which describes the method for measuring the length change (using a comparator dial) of hardened concrete at any age due to causes other than externally applied forces and temperature changes[25]. Another important test to evaluate the performance of fiber reinforced concrete as compared to plain would be the steel ring test (Figure 2.6) to evaluate restrained shrinkage. Restrained shrinkage has been monitored using the steel ring to measure crack width, and crack development[7].

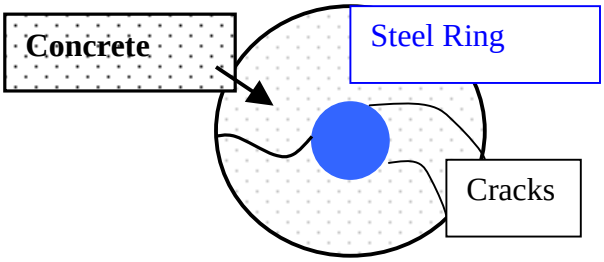

Figure 2.6: Steel Ring Test (ref. ACI 544.1R96 1997).

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In a study by Miroslaw Grzybowski and Surendra P. Shah[24]the steel ring test was used to measure restrained shrinkage cracking of concrete with collated, fibrillated polypropylene fiber contents of 0.1 to 1% by volume. The results of the test showed that small amounts of fibers (0.25%) could substantially reduce crack width. The average crack width of the specimen reinforced with 0.25% polypropylene fiber was 0.5mm (0.016 inches), or about one-half the value of plain (0% fiber) concrete after six weeks (Table 2.7). However, at 0.1% fiber content, polypropylene fiber did not influence observed crack width as compared to plain concrete.

The ACI [7] has not declared a standard test for restrained plastic shrinkage evaluation of FRC, however the test being studied involves fan-forced air over the surface of a new concrete slab to induce plastic shrinkage and then a count is made of crack width and lengths over a specified area. Recent FRC results, using this test indicate a 20%-90% reduction in shrinkage cracking as compared to a plain matrix (Figure 2.7).

Table 2.7: Concrete Restrained Shrinkage Cracking (ref. Grzybowski, Shah 1990).

Fiber Content	0%	0.1%	0.25%	0.5%	1%
Number of Cracks	1	1	1	1	2
Crack Width (mm)	0.900	0.875	0.480	0.230	0.150

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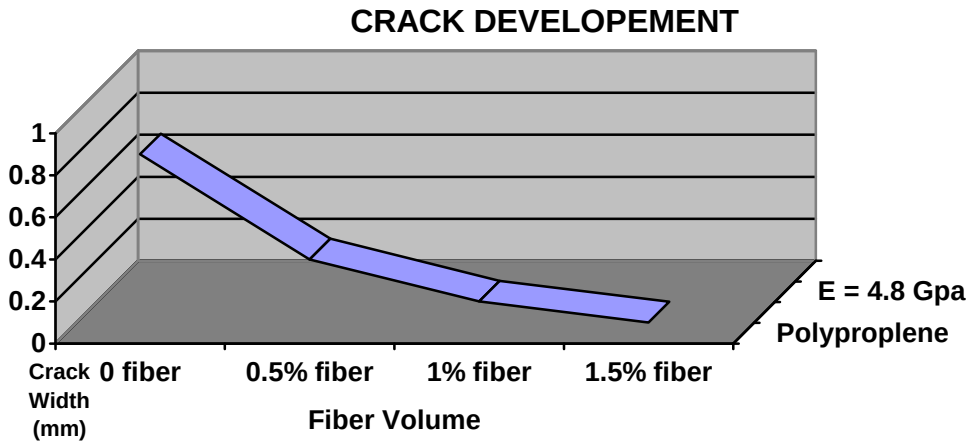

Figure 2.7: Restrained Shrinkage Cracking (ref. ACI 544.1R96 1997).

Freeze-Thaw and Surface Deterioration Resistance of Polypropylene Fiber Reinforced Concrete

As pointed out by ACI Committee 544[5], the addition of fibers themselves has no significant effect on the freezing and thawing resistance of concrete. That is, concretes that are not resistant to freezing and thawing will not have their resistance improved by the addition of fibers. The well known practices for achieving durable concrete and the same air entrainment criteria for plain concrete should be used also for fiber reinforced concrete. The test standard for scaling resistance of concrete pavements is ASTM C 672; Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals. After 250 freeze-thaw cycles, the sample is observed visually and subjectively rated as follows (Table 2.8).

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Table 2.8: Surface Scaling Rating (ref. ASTM Standards).

Rating	Surface Condition
0	No scaling
1	Slight scaling(1/8 inch); no visible aggregate
2	Slight to Moderate Scaling
3	Moderate scaling(some coarse aggregate visible)
4	Moderate to Severe Scaling
5	Severe Scaling(surface coarse aggregate visible)

In a study by Nanni and Johari[26], the results indicated some beneficial effects of fibers on scaling prevention of existing pavements. Most studies point to low water/cement (w/c) ratios as the significant factor in resistance to deicing[27]. In another study by Langan and Ward[28], the salt scaling of non air-entrained concrete at different w/c was tested according to ASTM 672. No scaling was found in the concrete and concrete showed that w/c was the most important factor in evaluating scaling resistance of these concrete's at the w/c of 0.24 and 0.27.

The addition of polypropylene fiber to a concrete mix with adequate curing enhances the deterioration resistance of concrete surfaces subjected to cyclic wet/dry seawater exposure as reported by Al-Tayyib and Al-Zahrani[29]. Tests were carried out on 30 concrete slab specimens made with and without polypropylene fibers. Some specimens were cured under laboratory-controlled conditions and were subjected to the wet/dry cycles for 85 weeks, while others were cured under field conditions and were subjected to the same cycles for 50 weeks. The results indicate that addition of polypropylene fibers effectively retard the deterioration process of the surface skin of the concrete specimens cured in hot weather environment.

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Abrasion tests by Nanni[26] in accordance with ASTM C 799, procedure C on field–cut and laboratory–made specimens showed no significant difference between the abrasion resistance of plain concrete and steel or synthetic fiber-reinforced concrete. Klieger and Lamond studies[4] reported consistently higher abrasion losses of fiber reinforced concrete as determined by ASTM C1138 testing over a wide range of water-cement ratios and compressive strengths. Losses generally due to less coarse aggregate per unit volume of concrete as compared to plain concrete.

Permeability of Polypropylene Fiber Reinforced Concrete

Permeability refers to the amount of water migration through concrete when the water is under pressure, and also to the ability of concrete to resist penetration of any substance, be it liquid, gas, or chloride ion. AASHTO T 277 and ASTM C 1202-91 Rapid Chloride Permeability Test were developed because of a need to rapidly measure permeability of concrete to chloride ions. The testing procedure includes factors such as temperature, AC impedance, initial DC current, charge passed, and chloride ion profiles during polarization of concretes. Al-Tayyib and Al-Zahrani's research results of electrical resistively, water absorption, and permeability tests do not show any significant improvement due to the inclusion of polypropylene fibers[30]. Using the Von water migration test method for 6"X 6" X12" concrete cylinders, the specimens containing polypropylene fiber (Durafiber) showed a definite reduction in permeability when compared to the control specimens (Table 2.9).

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Table 2.9: Von Water Migration Test Method (ref. AASHTO Durafiber Study).

Water Migration (Mls)	2 Days	7 Days	21 Days	28 Days	Total	Migration (%)
Control(0% fiber) Concrete	0	1.0	1.7	2.6	5.3	100
Durafiber	0	0	0.4	1.6	2.0	38

Workability of Polypropylene Fiber Reinforced Concrete

According to ACI 544.1 R-96 [7] satisfactory workability has been maintained even with a relatively high fiber content (2.0 percent by volume) with the addition of an appropriate amount of high range water reducer to maintain equal strength and water-cement ratio. In a study by Vondran, Nagabhushanam, Ramakrishnam[31]satisfactory workability was maintained even with a relatively high fiber content and there was no balling or tangling of fibers during mixing and placing. This was achieved by adjusting the amount of superplasticizer or water-cement ratios to maintain the same strength.

Elastic Modulus, Poisson's Ratio and Coefficient of Thermal Expansion of FRC

According to ACI 544.1 R-96[7], the addition of fibrillated polypropylene fibers to concrete had no effect on the static modulus of elasticity. The properties of polypropylene fibers used in this study are shown in Table 2.10. According to FHWA-RD-97-030 State-of-Art Report[5] by Zia, Shuaib, Ahmad, and Leming, the authors are not aware of any investigation dealing with the thermal expansion or poisson's ratio of fiber-reinforced concrete.

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Table 2.10: Polypropylene Fiber Properties (ref. ACI 544.1R96 1997).

Fiber Type	Specific Gravity	Tensile Strength (ksi)	Elastic modulus (ksi)	Ultimate elongation (percent)	Ignition temp. (degrees F)	Melt Temp. (deg. F)	Water Absorption
Poly-propylene	0.9-0.91	20-100	500-700	15	100	330	Nil.

ANALYTICAL MODELS

For the analytical evaluation of this research, two finite element method (F.E.M.) programs were selected. These programs were used to predict airfield pavement performance over a 20-year design life as specified by the Federal Aviation Administration (FAA) or military standards. The laboratory testing data for flexural and fatigue strength of plain and fiber reinforced concrete in Chapter four was used to calculate pavement thickness for a specified aircraft and design mixture. Comparisons between FRC and plain concrete were made to determine pavement reduction values.

Yang H. Huang, Professor of Civil Engineering, developed the Finite Element Program KenSlabs at the University of Kentucky. KenSlabs is based on a finite element program in which a concrete pavement slab is divided into rectangular finite elements with a large number of nodes. Both wheel loads and subgrade values are applied to the slab as vertical concentrated forces at certain nodes. Each slab can have a maximum of 15 nodes in both the x and y direction. Foundation assumptions are based on Westergaards' theory (liquid layer/winkler spring), the solid foundation theory (Boussinesq) or the layer theory (Burmister). For Damage Analysis, the program is capable of dividing the year

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into 24 periods (seasons) and can evaluate up to 24 vehicle load groups. Seasonal variations are accounted for by a factor applied to the modulus of subgrade reaction (K) so as to vary foundation conditions. Damage is based on fatigue cracking only, which is the significant failure characteristic of fiber reinforced concrete. Specifically, through the following fatigue model in this program which is mathematically expressed as:

$$\text{Log } N = f\,\hat{\imath} - f\,(\sigma / S\acute{c}) \qquad (2.1)$$

Where N is the allowable number of vehicle loads to failure, σ is the tensile stress of the slab and Sć the concrete modulus of rupture. The f values are PCA fatigue coefficients, which define a chosen fatigue strength failure probability line for plain concrete based on empirical data from past studies. As example, default coefficients of 17.61 define the 50% probability of fatigue failure line between stress ratio and loads to failure (N) from a number of different concrete specimen fatigue tests presented by Haung[2].

KenSlabs is an excellent tool for evaluating fiber's unique material properties and could be used in support of laboratory testing on high performance airfield concrete (HPAC). The program places no constraints on material values such as modulus of rupture or modulus of elasticity. No constraints on aircraft geometry, tire pressures, loads to failure, pavement deflections or minimum thickness as other programs do.
As example, KenSlabs is capable of evaluating repetitive loading of airfield pavements with high tire pressure aircraft. Test programs were successfully run using Boeing 747 and 777 aircraft with 204 psi and 182 psi tire pressures values on dual and tridem gear configurations and at load repetitions of 4,000 and 10,000 passes per year. Figure 2.8

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illustrates the KenSlabs computer analysis footprint, showing the location of the Boeing 777 and 747 aircraft on a 20-foot by 20-foot concrete slab and the location of the nodes used for the analysis. KenSlabs' versatility for input data is adaptable in analyzing the military's minimum standards for fiber concrete airfield design in accordance with the joint use U.S. Army Technical Manual ™ 5-825-3/ Air Force Manual (AFM) 88-6; Rigid Pavements for Airfields. As example, minimum military standards for fibrous concrete pavement thickness design are established at four inches, maximum allowable deflections at 0.06 inches (shoulder design), and maximum flexural strength for plain concrete (0% fiber) of 900 psi. Values that are less stringent than the design standards of other agencies like FAA and input parameters of other FEM programs like LEDFAA.

LEDFAA v 1.2. FAA's (Layered Elastic Design-Federal Aviation Administration, version 1.2) program, was originally developed by the Corps of Engineers, and is the only approved FEM program for pavement thickness design for the Boeing 777 aircraft[32]. This computer program was developed and calibrated specifically to analyze a mixture of up to 20 different aircraft. Design information is entered by means of two graphical screens, one for the pavement structure and one for traffic. The core of the program is JULEA, a layered elastic computational program implemented as a WINDOWS™ FORTRAN application. Dr. Jacob Uzan, Technion at Haifa, Israel developed JULEA. Pavement design from the user's perspective is that the "design aircraft" concept has been replaced by the pavement design failure concept expressed in terms of a "cumulative damage factor" (CDF) using Miner's rule. When the cumulative damage factor sums to a value of 1.0, the design conditions of fatigue failure has been reached. The design process considers one mode of failure for rigid pavement, cracking

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of the concrete slab. Limiting horizontal stress at the bottom surface of the concrete guards against failure by cracking of the surface layer. Thickness, elastic modulus and poisson's ratio are the major pavement material properties inputted in the program for analysis .

One of the limitations of the program is that the maximum allowable flexural strength input value for concrete is 800 psi, a value much less than exhibited by polypropylene fiber reinforced concrete. However, the program provides excellent modeling for multi-aircraft traffic and its impact on rigid pavement airfield thickness design for plain (0% fiber) concrete in accordance with current FAA standards. LEDFAA provides the conventional airfield design thickness value based on a given mix of aircraft, loading conditions and design life, as well as pavement, base course and sub-base material properties. The LEDFAA design thickness for airfield pavement is then reduced by FRC pavement design thickness reduction values. Design thickness reduction values are derived from KenSlabs, considering the differences in pavement thickness due to FRC's enhanced flexural and fatigue characteristics as compared to plain concrete. KenSlabs places no limitations on material input values, such as exhibited by FRC so it is used to derive the pavement reduction values (PRV) from the laboratory tests. LEDFAA incorporates all the FAA standards governing civilian airfields, so it is the design standard for aircraft rigid pavement thickness in this regard.

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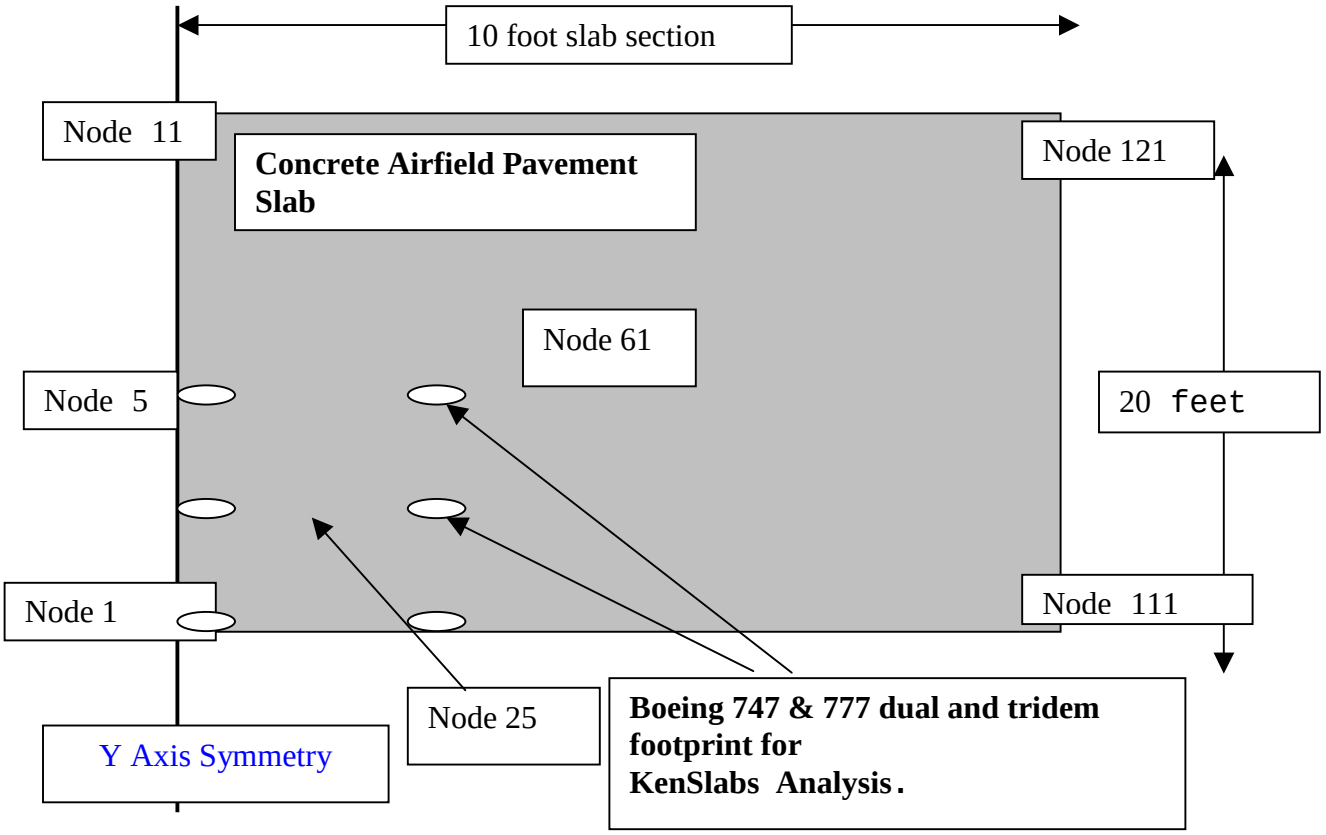

Figure 2.8; KenSlabs Schematic.

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CONCLUSIONS

Literature research validated polypropylene FRC as a viable composite for HPAC. Tests showed superior flexural, fatigue strength, endurance limits and toughness and ductility properties associated with even small amounts of polypropylene fibers. The material behavior of polypropylene reinforced concrete pavement in terms of strength could be examined in terms of its performance before and after “first crack”. In terms of static flexural, fatigue and tensile strength, fiber content had an influence on increasing strength and the tensile load carrying capacity of the matrix. Polypropylene fiber concrete shows an increase in flexural and tensile strength with increasing fiber content. Flexural fatigue strength and endurance limits are important design parameters, particularly in pavements, because these structures are subjected to fatigue load cycles. Research studies reinforce the above conclusion. In the study by Nagabhushanam, Ramakarishnan, and Vondran[9] a fatigue strength increase of 27 % for 0.5 % polypropylene fiber content as compared to plain concrete. Most studies conclude that any improvement in fatigue strength in polypropylene FRC occurs in small volumes. Above 0.5% fiber content, there is no improvement in strength. The damage accumulation in concrete study by Grzybowski and Myer[1] showed the number of cycles to failure as a function of stress ratio and fiber volume. In this study, fiber reinforcement had a clear beneficial effect on the fatigue behavior of concrete as long as the fiber content is about 0.25 percent. At 0.25%, the beneficial effect of polypropylene on the total energy-absorption capacity of concrete seems to peak, irrespective of the stress level. Beyond 0.5% percent fiber volume, the effect is insignificant and at higher stress

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ratios (S > 0.75) polypropylene fiber's energy absorption capacity decreases almost exponentially. The endurance limit was also increased with the addition of fibrillated polypropylene fibers due to FRC's increased fatigue strength[9] (Figure 2.9). Such an effect would substantially extend pavement design life.

Regarding toughness, the load carrying capability of fibers within concrete after "first crack", increasing fiber content significantly increased toughness. In the Ozyildirim and Moen study [17], they evaluated the strength properties of polypropylene fiber at different volumes. The toughness of concrete improves with increases in fiber volume and first crack strength peaked at a fiber content around 0.2%. Regarding ductility, fibers had a significant effect on the mode and mechanism of failure of concrete cylinders in the compression test. The fibers failed in a more ductile mode, particularly true for higher strength concrete where the cylinders endure large deformations without shattering.

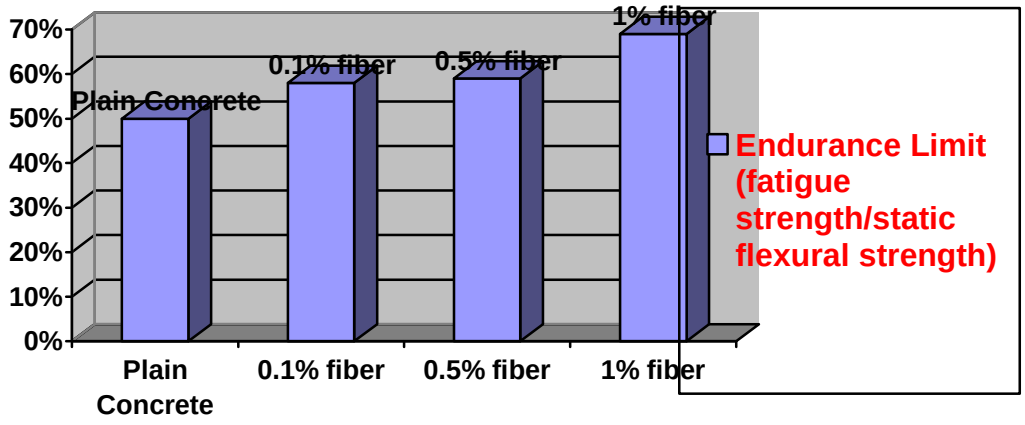

Figure 2.9: Endurance Limits (ref. Nagabhushanam, Ramakrishnam 1989).

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Regarding impact resistance, in the Nagabhushanam, Ramakrishnan, and Vondran study[9] fiber concrete has excellent impact resistance, which increases with an increase in fiber content. The results for impact resistance indicated the number of blows to first crack and ultimate failure increases with increasing fiber volume and length[17].

The report prepared by the ACI Committee 544, May 1997 states that cast in place concrete will accommodate up to 0.4 percent by volume of polypropylene fibers with minimal mix proportion adjustments[7]. Good workability can be maintained in polypropylene fiber reinforced concrete (FRC) by adding an appropriate amount of admixtures.

The addition of low volumes of fiber reduced the effects of shrinkage cracking by 12 to 25% and also reduced the average crack width significantly as compared to plain concrete. According to Johnston, the best results were obtained at a fiber content of 0.2% and fiber lengths of 19 mm and 51 mm[22]. Steel Ring results reported by Grzybowski and Shah[24] showed that small amounts of fiber could substantially reduce cracks. The average crack width of the specimen reinforced with 0.25% polypropylene fiber was 0.5 mm (0.016 inches) or one half the value of plain concrete after six weeks.

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CHAPTER 3. DEVELOPMENT OF AN INTEGRATED CONCRETE DESIGN/SELECTION METHODOLOGY FOR FIBER REINFORCED CONCRETE.

INTRODUCTION

There is a need for a systematic approach to couple material selection with rigid airfield pavement design, so as to improve mix design and pavement performance and consider all possible variables affecting them. Using a Systems Engineering approach essentially examines all aspects of a system, not just individual components, to synthesize solutions to a stated problem. The system's analysis considers alternative strategies, establishes ordered set of choices and develops a methodology of optimizing alternate strategies. Systems Engineering also includes design implementation and follow up on the performance evaluation as part of the problem solution, or evaluation of the chosen strategy to meet an objective in a continuos improvement process.[34] Such a system will improve both the quality of analysis, information, and decision making when faced with such a complex set of variables. The intention is to construct a rational framework for comprehensively evaluating and integrating all facets of the material's behavior and airfield pavement design as it applies to improving the performance of the airfield pavement as a system. The United States Air Force and the United States Army Corps of Engineers historically, have amassed a considerable database of information on aircraft-airfield pavement interface, material strength properties of soils, concrete and asphalt as they pertain to airfield performance worldwide. Pavement performance data under a wide

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variety of aircraft loading and environmental conditions. The data is considerable, but not necessarily scientific in its approach to pavement design and material properties as it is a compilation of information developed primarily from engineering experience and field observations. With the advent of high-speed computers, creation of numerous finite element rigid pavement programs, and programmable material testing machines for repetitive load testing, it is possible to conduct iterative calculations and dynamic load testing to better predict airfield pavement performance. Much of the Military's current rigid pavement design methodology focuses on structural thickness determination, a single criteria approach to pavement design. A Systems Engineering approach aids in optimizing a fiber-concrete mix selection by flexural and fatigue strength for a specific aircraft traffic, but also considers other properties like shrinkage potential (cracking), workability, and energy absorption potential. Since the United States Air Force operates worldwide, some FRC composite material criteria may vary regionally. As example, in Europe, durability criteria may dominate versus fatigue strength needed at major air cargo hubs in the United States. Similarly, in the Middle East or Asia, survivability may be the predominant parameter for fiber-concrete material selection. Such criteria will be reflected in the development of regional contract specifications, drawings and construction standards from tabular data in technical manuals. Tabular data based on fiber response from laboratory or analytical testing methodology detailed in this dissertation. This approach couples material selection and mix design with pavement design criteria to improve airfield pavement performance based on mission needs and regional climatic conditions.

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LIMITATIONS OF THE CURRENT DESIGN METHODS

Great strides forward have been made by the United States Military in evolving the rigid pavement design criteria from empirical "design curves" towards a mechanistic, computer based, flexural strength thickness model. Historically, the design charts had served the Military well by establishing a way to design airfields based on past pavement performance. However, these charts were mainly based on field observations and actual aircraft-airfield interface, encompassing an array of different loading and environmental variables to construct a "one size fits all" approach to design. As example, material properties such as the Modulus of Elasticity (E) were assumed in all cases to be 4,000,000 psi and Poisson's ratio of 0.15. Calculation of new airfield slab design on existing rigid pavements required adaptation of concrete overlay formulas to approximate a principal of thickness reduction.[35] Design “rules of thumb” such as an assumed 25 % reduction in edge stress due to doweling are used. Determining joint depths based on slab thickness, different joint spacing criteria per agency (Air Force or Army), and designing dowel diameter, spacing and length based on pavement thickness alone. To date, unchanging design details, in spite of different aircraft weight and gear geometry, differing environmental temperature or moisture conditions for a particular airfield location[35] . Consideration needs to be given to a more systematic approach to airfield thickness design considering specific material properties and related thermal stresses, durability and shrinkage as a function of actual site environmental conditions. Tests that replicate extreme environmental conditions, such as temperature- restrained shrinkage also lack standards. ASTM has yet to standardize testing protocols for concrete restrained

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shrinkage testing. Some tests and analytical methods do exist, such as ASTM C-157; Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete[14] and joint spacing calculations based on temperature differential through a slab as offered by Huang. Scientific approaches, moving away from the "rule of thumb" approach of PCC joint design[2] or material behavior.

There are many challenges and unknown variables that complicate incorporation of a new material into design. As example, fiber-concrete composites for airfield pavements lack a long-term performance history, which form the basis of much of the empirical design methodologies used in Civil Engineering. In a larger sense, new material analysis should include repetitive loading for fatigue testing of concrete specimens to better approximate actual dynamic aircraft loading when evaluating airfield concrete strength properties. However, material laboratory testing, such as dynamic fatigue tests that replicate moving aircraft loads on concrete pavements are as yet to be standardized by ASTM. Additionally, laboratory-testing results on the behavior of a new material provides at best an incomplete picture of its properties, particularly when evaluating fiber volumes in small amounts. Technology itself further complicates this process by rapidly fielding heavier aircraft with different gear geometry that increase pavement stress, as well as, creation of new fiber-concrete materials with greater potential strengths. This dissertation is about developing a systems engineering based methodology integrating mixture design with pavement design criteria for defining a performance based methodology for evaluating fiber-concrete composite materials. In this case

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polypropylene fiber, however such a methodology can eventually be expanded to other concrete materials.

A BETTER DESIGN METHODOLOGY

Despite the long tradition within the Department of Defense to support ongoing research and development of weapon systems, no standing research methodology has been established for airfield pavement systems to analysis emerging fiber-concrete materials to improve this weapon system platform. As such, one has been presented in this document as a blueprint. The objective of this system engineering methodology is to establish a rational set of procedures (steps) in developing a FRC mix design approach based on pavement performance criteria for military and FAA airfields. As aircraft traffic, loading and gear geometry continue to impose greater stresses on airfields and technology produces superior composite materials with unknown performance characteristics, a systematic approach to evaluating mix designs is needed. Concrete mix design is often based on a balance of several parameters such as stiffness and strength to prevent excessive deflection, flexibility for fatigue and fracture resistance (cracking) under increasingly higher stresses and harsh environmental conditions. Mix designs should be evaluated based on output performance and pavement design criteria, and validated by both field and laboratory testing. In this case, the polypropylene fiber concrete composite needs to improve the fatigue strength and fracture resistance of rigid pavement airfields. Initial studies on polypropylene fiber reinforcement in small volume displays several advantages in fatigue, toughness, and flexural strength. Analysis showed

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an increase in those strength properties that would increase the life of the pavement structure under repetitive aircraft traffic. Stated differently, this improvement in strength could reduce required pavement design thickness by ¼ inch to ½ inch for a fixed aircraft traffic loading and design life. In terms of economics, if you consider constructing an entire airfield the implications are significant. Perhaps, one of the most unique characteristics of this composite is its ability to continue to absorb energy after first crack, ductile properties not typically associated with a brittle material like concrete. This fourfold increase in toughness associated with this composite as compared to conventional concrete not only increases pavement life, but is significant to the military in mitigating heaved pavement around bomb damaged runway craters during rapid runway repair. Time to repair heaved pavement is the single most important criteria to air base survivability.

A Systems Engineering methodology is needed to provide a rational framework for organizing and integrating both existing and new fiber concrete research into airfield design to improve pavement performance[4]. The models presented here and related to pavement thickness design, heaved pavement reduction were intentionally structured to be generic in nature so as to generalize a research-design- test methodology to be used for any concrete composites.

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Defining the System Methodology

Establishing the need and value of any new civil engineering system within the Department of Defense, such as a new composite material evaluation methodology for airfield pavements, requires that the research address vulnerability or threat reduction. Getting the approval authority to "buy into" an innovative concrete mixture and pavement design approach requires assurances that the system will quantifiably show a reduction in threat or vulnerability to a weapons system platform such as an airfield in terms of performance. Equally important is reliability, in that the methodology can consistently measure the performance of FRC composites. Also, is the research methodology flexible, adaptable to other studies of new and better emerging technology, such as introduction of a superior fiber concrete composite. Research and Development is an integral part of the Defense institution and invested research costs. This is particularly true for new airfield material research and design approaches, which are considered low cost studies and expenditures in comparison to the aircraft they support.

The judgment criterion for adopting a new FRC airfield materials research and design methodology is performance, reliability, and flexibility in that order. In terms of a stochastic system, weighted values for performance, reliability, and flexibility may be 45%, 30% and 25% respectively. In regards to performance, can mechanistic models and field-testing quantifiably measure differences in performance, such as fatigue strength improvements (design thickness reduction) of varying fiber content in an FRC composite under actual repetitive aircraft loading? Is energy absorption (reduction of heaved

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pavement) of FRC composites quantifiable under actual explosive testing using both ANFO (ammonia-nitrite/fuel oil) ground shot blasting and ground penetration munitions testing due to differences in explosive weight and velocity of the blast? Does the methodology include field testing to quantifiably measure surface cracking under actual environmental conditions? In regards to reliability, can the design-engineering model optimize fiber content in concrete as it pertains to fatigue strength, energy absorption, cracking and constructability of a military and civilian airfield? How well does a mechanistic predictive model compare to actual field-testing under actual aircraft loading? Can the analytically derived models be modified by feedback from field testing to better predict performance? In flexibility, is the pavement design models flexible enough to be adapted to consider other mixtures or fiber types in airfield concrete as a composite material? It is recognized that FRC research testing is an ongoing, iterative process requiring years of evaluation. It is also recognized that the pace of material composite technology is the fastest growing catalyst to change in civil engineering building systems. It is expected, that continued advances in polymer technology would continue to yield fibers that enhance the desired material characteristics for airfield pavements far beyond polypropylene. The system developed in this study is shown in figures 3.7 and figure 3.8 and the steps of the methodology are described in detail next.

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STEP 1. EVALUATE AND SELECT NEW MATERIAL

Polymers such as polypropylene fiber are now the industry standard for numerous engineering applications and are available worldwide through a host of vendors. Polymers of known engineering properties, locally available are important new material selection capability for worldwide airfield construction. As example, both industry and researchers now recognize the benefits of polypropylene fiber reinforced concrete in reducing temperature and shrinkage cracking and crack widths, which is an important distress criteria in airfield pavements. However, little attention has been given to the use of high tensile strength polypropylene as a structural component of concrete in structures like pavements. Development of cost effective optimized composite applications and design parameters for all FRC is an ACI stated research need. Continued technological advances in non-metallic fiber development, particularly in the field of polymers, will continue to present "breakthrough performance" opportunities for traditional building materials such as concrete to enhance targeted properties. In this first step, three actions would be taken. 1) A comprehensive review of existing literature to identify fiber-concrete composite as potential candidates for airfields based on known beneficial material performance. 2) Identify ingredients and mixtures to consider as HPAC. 3) Determine appropriate testing to evaluate the above beneficial properties.

Targeted material properties of a FRC composite that would be characteristic of a high performance airfield concrete (HPAC) mixture would be the ones that:

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- Reduce deflections, stresses and strains reflected through the FRC composite to underling pavement materials produced from aircraft gear geometry, repetitive loading and environmental factors. Furthermore, composites that can reduce design thickness.
- Material properties that reduce pavement surface deterioration and foreign object debris (FOD) through reduction of concrete shrinkage, cracking and scaling due to construction, maintenance, traffic abrasion or thermal effects.
- Composites that enhance energy absorption characteristics of the airfield concrete such as toughness, ductility, and impact resistance to high-energy stress waves generated by explosive catering and dynamic loading.
- Composites that improve constructability of airfield pavements in terms of placement (workability) of the composite, thus reducing construction time and cost.

STEP 2. LABORATORY PERFORMANCE PREDICTIONS

This research included the following laboratory testing tasks of identified HPAC material properties from Step one and Chapter two. In addition, data from past studies were considered in the analysis to complement laboratory test results.

Mix design and workability characteristics of low volume (<0.5 %) polypropylene fiber reinforced concrete for pavements were examined. The objective of this testing was to evaluate workability of polypropylene fiber concrete at 0.1%, 0.2 %, 0.3%, 0.4% volumes as compared to plain (0%) concrete.

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- Workability. ASTM C143, American Society of Testing Materials' standard laboratory test to determine slump of plain concrete. This test defines the relative ease of placement and finish of a mix design.

- ASTM C995, Slump evaluation through time of flow through inverted cone test**.** The inverted cone test was specifically developed to measure FRC workability and can be used to compare FRC to conventional mixtures with similar slump values.

- Air Content. ASTM C 138, American Society of Testing Materials' standard air content test equipment and procedures for conventional concrete were used. Unit weight and 28-day compressive strength values was also evaluated for each specimen of a specified mix.

The strength characteristics of low volume (<0.5%) polypropylene fiber reinforced concrete mixtures were examined as well. The objective of this testing is to establish the static flexural and fatigue strength values of polypropylene fiber concrete at 0.1%, 0.2 %, 0.3%, 0.4% volumes as compared to plain (0%) concrete.

- ASTM C 78; American Society of Testing Materials' standard laboratory test to determine the peak fiber stress in tension under third point loading. The stress at which the beam breaks is known as the Modulus of Rupture (MOR) and is a critical material property input data value in pavement design calculations.

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- Fatigue strength testing. Non standard test of cyclic loading of a concrete beam under third point loading at a stress level below its MOR. The important data value is the breaking fatigue stress of a beam at 2,000,000 load cycles, which is known as the endurance limit and is a better indicator of the fiber-concrete's strength under repetitive loading.

To examine the energy absorption capability of low volume (<0.5%) polypropylene fiber reinforced concrete, toughness can be measured using ASTM C 1018. The objective of this test is to quantify the energy absorption of plain (0%), 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete from laboratory toughness testing analysis through indices' values. Compressive strength ductility can be examined using ASTM C 39; "Compressive Strength of Cylindrical Concrete Specimens". The objective of this test is to observe the ductility characteristics of FRC in function of fiber design mix.

- ASTM C1018; American Society of Testing Materials' standard laboratory test to determine the energy absorption capability of fiber-concrete composites after first crack as expressed in terms of Toughness Indices.

- ASTM C39; American Society of Testing Materials' standard laboratory test to determine compressive strength of concrete cylinders. Regarding fiber-concrete composites, the ductile mode of failure of the cylinder is obsererved.

-

Toughness, ductility, and fracture resistance are manifestations of the energy absorption capabilities of fiber reinforced concrete. Laboratory testing will generate the following alternative strategies in comparing and quantifying the improvement of FRC composite as a high performance airfield concrete (HPAC) pavement as compared to plain (0% fiber) concrete**.** Increases in I-5, I-10, I-20 Toughness Indices are the desired objective values (Figure 3.1). Increases in fracture and impact resistance are the desired objective values. Qualitatively, observation during laboratory testing of fractured stress and strain controlled loaded specimens failed in compression, flexure, fatigue and toughness tests can be evaluated for remaining structural integrity after first crack. As an example, fiber content (0%, 0.1%, 0.2%, 0.3%, 0.4%) specimens with greater fracture free cross-sections after 1st crack is the value objective. Energy absorption is an important characteristic of polypropylene fiber reinforced concrete in the reduction of heaved pavement around airfield craters created by bomb damage. Fracture resistant concrete reduces the amount of pavement that needs to be removed after an attack. Thus, the following tests were considered:

- Determination of concrete toughness using ASTM C1018 toughness indices and post 1st crack specimen observations for 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete.

- Determination of impact resistance values from past studies for 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete.

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- Determination of concrete's ductility using ASTM C 39 observations for 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete.

- Monitoring of concrete's post 1st crack behavior using ASTM C 78 specimen observations for 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete.

- Monitoring of concrete's post 1st crack behavior using fatigue test specimen observations for 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete.

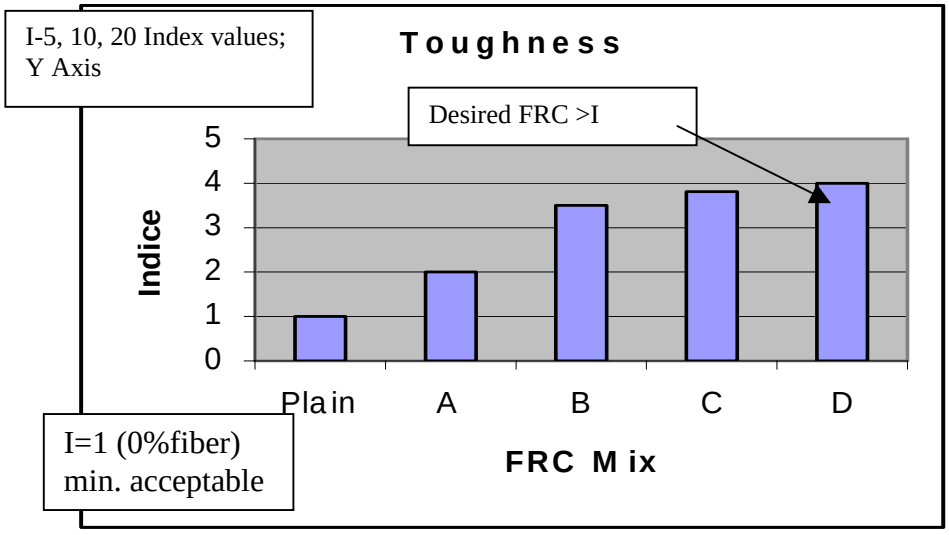

Figure 3.1: Measure of Energy Absorption; Toughness Index (I).

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Shrinkage characteristics of low volume (<0.5%) polypropylene fiber reinforced concrete are a HPAC property to be examined. The objective of this testing is to evaluate cracking and volume change of polypropylene fiber concrete at 0.1%, 0.2 %, 0.3%, 0.4% volumes as compared to plain (0%) concrete. ACI and ASTM have not declared a standard test for restrained plastic shrinkage evaluation of FRC.

- Unrestrained Shrinkage using ASTM C 157, Length Change of Hardened Hydraulic-Cement Mortar and Concrete. The objective of the test is to determine the volumetric change (shrinkage) of concrete as it hydrates and hardens .

- Restrained Shrinkage using the Steel Ring Test. Non standard research test method of measuring the tensile stresses induced in concrete by allowing concrete to harden around a steel ring. Measures the crack resistant capability of fiber-concrete composites.

Past studies indicate that crack widths in plain (0% fiber) concrete containing small volumes of polypropylene fiber (<0.5%) could substantially be reduced. Plain concrete crack widths after six weeks were typically 0.035 inches. As cracking in concrete is a significant source of Foreign Object Debris damage for high performance jet aircraft intakes, the performance standard should be cracking less than plain concrete. The fiber mixture that provides the maximum crack width reduction is the value objective (Figure 3.2).

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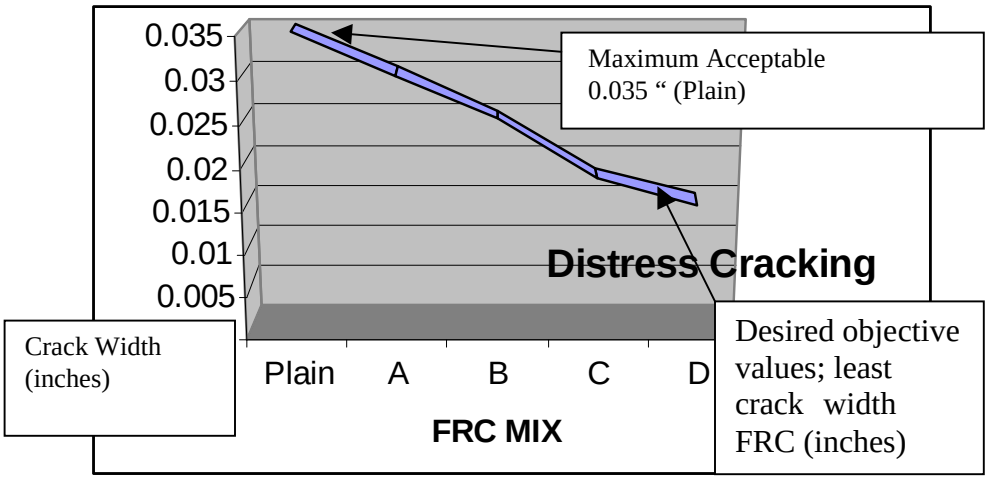

Figure 3.2: Measure of Distress Cracking.

STEP 3. DESIGN THICKNESS ANALYSIS

Two finite element method (F.E.M.) programs were selected for the pavement analysis of the performance of polypropylene fiber concrete. These programs were used to determine airfield pavement design thickness for a 20-year design life as specified by the Federal Aviation Administration (FAA) or the United States Military using single or muti-aircraft traffic, and generating alternative design strategies. Data from the laboratory testing for flexural and fatigue strength of plain concrete and mixes containing 0.1%, 0.2 %, 0.3%, 0.4% of polypropylene fiber reinforcement were inputted to calculate pavement thickness for the specified aircraft(s). The operational characteristics of these computer programs are contained in Chapter two. These programs are:

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1. KenSlabs is a finite element method rigid pavement computer program. KenSlabs calculates the tensile stress at the base of concrete pavements subjected to various loads, traffic, and tire contact pressures. The program considers various concrete material parameters like Modulus of Rupture (MOR), Modulus of Elasticity, Poisson's ratio, can limit slab deflections, calculate design thickness and the impact of thermal stresses on slabs due to temperature changes. KenSlabs damage analysis and design life predictions are based on Miners rule for damage accumulation.

2. Layered Elastic Design, Federal Aviation Administration (LEDFAA) is a visual basic, rigid pavement FEM program for multi-aircraft, airfield design thickness analysis. LEDFAA is the only program approved by the FAA for the Boeing 777 aircraft and is used to determine conventional design thickness requirements for civilian airfields.

The objective of the finite element modeling was to establish relationships estimating design pavement thickness based on specific aircraft wheel pressures and geometry and FRC material properties. The flexural and fatigue properties of the mixtures are used in the analysis for calculating rigid pavement design thickness for specified loading repetitions. There are five principal input variables for the mechanistic analysis.

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1. Aircraft Geometry. Essentially the gear and tire footprint of a mix of military and civilian aircraft are used which are considered critical contributors to airfield pavement damage due to their high tire pressure and gear geometry. Selected aircraft: Boeing 777, Boeing 747, Boeing C17, Lockheed Martin C141, and Lockheed Martin F-16 aircraft.

2. Load Variables. The range of applied stress values based on specific aircraft gear geometry requiring an increase in design thickness to maintain an acceptable tensile stress at the base of a given rigid pavement slab. In this analysis, the relationship between stress level (contact area stress/MOR) and pavement thickness for a given composite FRC material is determined.

3. Traffic. A fixed number of aircraft passes are considered, in this case a minimum of 2,000,000 passes to determine pavement thickness of a FRC material at its endurance limit.

4. Material Properties. Essentially the Modulus of Rupture (MOR), Modulus of Elasticity (E) and fatigue strength (fmax) values at each FRC mix endurance limit is used. FRC material properties as determined from laboratory testing of plain, 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber mixtures were used.

5. Environmental factors. Adjustments (% reductions) to a standard set of assumed subgrade strength values are used representing environmental conditions such as spring thaw. KenSlabs also considers the temperature differential between base and top of

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concrete airfield slabs along with the thermal coefficient of concrete for calculating curling stress.

The outputs from the mechanistic analysis are.

1. Through the finite element method modeling, the equations predicting airfield design thickness for FRC pavements at fiber contents of 0%, 0.1%, 0.2%, 0.3% and 0.4% and at stress levels of less than 0.7(0.29,0.39. 0.49,0.59,0.69) for a given aircraft wheel loads are obtained. The design thickness and stress level relationship when graphed, yield a linear equation that will establish coefficients for minimum thickness for airfield design life (L) and limit pavement deflection (D) so as to prevent subgrade failure from pumping. These equations are used to predict a 20 year design life pavement thickness value based on a specific aircraft gear geometry and wheel loads (contact stress), using laboratory derived values for flexural, and fatigue strength at the endurance limit of FRC composites of varying fiber content.

For a design aircraft, two design equations were defined; one for static loading conditions and one for repetitive (dynamic) loading conditions. The FRC with the minimum design thickness, for a given aircraft for 2,000,000 passes is the desired mixture. Airfield pavement thickness prediction using KenSlabs by single aircraft geometry; Boeing 777, Boeing 747, Boeing C17, Lockheed Martin C141, and Lockheed Martin F-16 aircraft were determined. The differences in pavement thickness by fiber case were used to determine pavement reduction values (PRV) as a quantifiable measure

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of the improvement in strength of FRC as compared to plain concrete. PRV were determined by:

- Determination of pavement thickness using KenSlabs and the Modulus of Rupture value for 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete. Determine flexural PRVs.

- Determination of pavement thickness using KenSlabs and maximum fatigue strength (fmax) of 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete. Determine fatigue PRVs.

Determination of pavement reduction values generates two alternative strategies for determining design thickness (Figure 3.3). Single and Multi-Aircraft model comparisons will be made to quantify the improvement of FRC composite strength as a function of pavement thickness reduction as compared to plain (0% fiber) concrete.

- Single Aircraft Model. Using KenSlabs, determination of design thickness by single aircraft using Military standards for plain concrete. Modeling considers the Boeing C-17, Lockheed Martin C-141 and F-16 aircraft and then subtracts the appropriate PRV by fiber case.
- Multi-Aircraft Model. Determination of FRC pavement thickness meeting FAA standards using LEDFAA. Modeling considers a mix of aircraft; Boeing 777, Boeing 747, Boeing C-17, Lockheed Martin C-141 then subtracts the appropriate PRV by fiber case.

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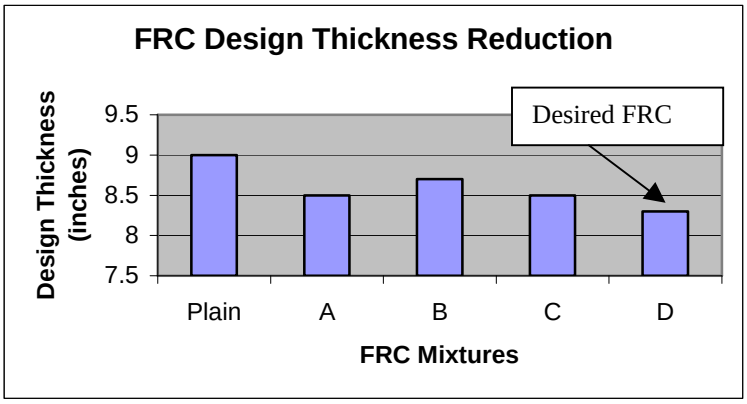

Figure 3.3: Measure of FRC Design Thickness Reduction.

2. Determine the effect of pavement thickness and fiber content on pavement curling stresses and corner deflections. Quantify the reduction in curling stresses under different temperature differentials as a function of FRC mixture pavement thickness and modulus values as compared to plain (0% fiber) concrete (Figure 3.4). Consider any reduction in corner deflection due to pavement thickness reduction under a given aircraft wheel load.

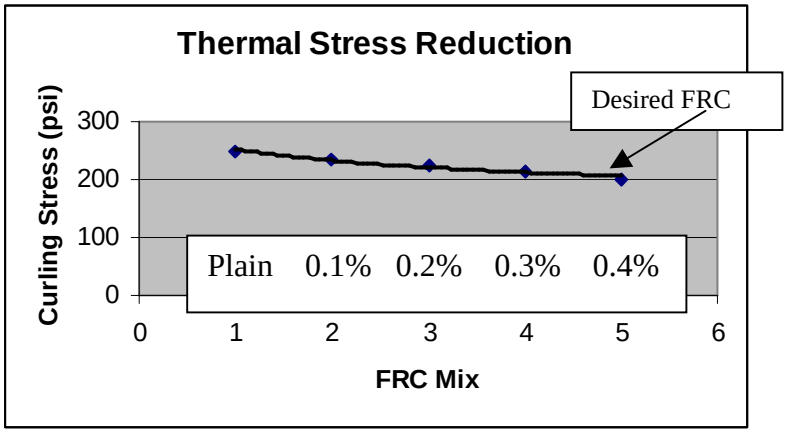

Figure 3.4: Measure of FRC Thermal Stress Reduction.

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3. Construction cost reduction as a function of pavement thickness values for 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete (Figure 3.5). Reduction in pavement thickness due to the FRC characteristic of increased strength results in a reduction in construction time and concrete materials. The value objective is reduction in concrete material costs due to the reduced pavement cross-section. Reduced thickness by fiber case is a quantifiable indicator of reduction of agency costs.

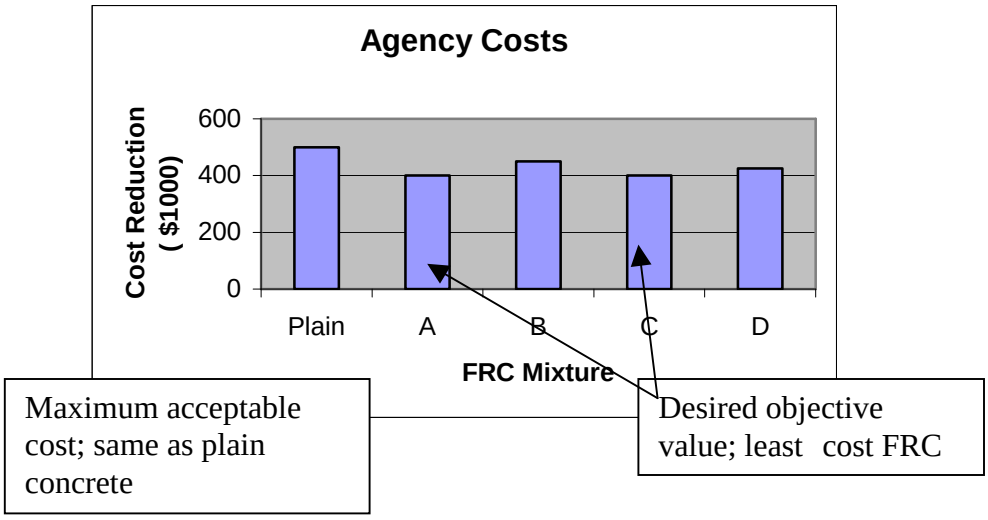

Figure 3.5: Measure of Agency Costs; Construction Time and Materials.

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STEP 4. HEAVED PAVEMENT PREDICTIONS

Energy absorption is an important characteristic of polypropylene fiber reinforced concrete in the reduction of heaved pavement around airfield craters, created by bomb damage. Fracture resistant concrete reduces the amount of pavement that needs to be removed after an attack. Toughness, ductility, and impact resistance are manifestations of the energy absorption capabilities of fiber reinforced concrete that can be quantitatively and qualitatively measured by laboratory testing. Analytically, predicting the mechanism of blast fractures of concrete has to do with kinetic energy and stress wave theory and is discussed in Chapter five. The relationship of detonation velocity to wave propagation velocity through concrete is a function of concrete's material properties, as well as distance from the crater center.

A considerable database of information already exists in the literature on the material properties of plain and polypropylene fiber reinforced concrete. However, information regarding current military munitions capabilities such as explosive weight, detonation velocity and depth are classified and varied between munitions. The United States Air Force Manual; AFMAN 10-219 states that pavement upheaval typically continues up to 25 feet beyond the crater lip of a 50-foot diameter crater[36] and that stress wave velocity (Vc) through a given linear-elastic material is a function of that materials properties such as Modulus of Elasticity and unit weight and mathematically expressed as $Vc = \sqrt{E_{\text{plain concrete}}/\gamma_{\text{plain concrete}}/\text{gravity (g)}}$ where γ / g = the material's density (ρ).[37]

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In general, the diameter of radial fracturing from a bomb-damaged airfield is twice the crater diameter considering the material properties of plain concrete (0.0% fiber). Normalized for fiber reinforcement material properties, and considering wave propagation theory, the relationship of fracture diameter (RD) to crater diameter (D) in feet could be expressed as:

$$RD = \frac{2D}{} \frac{[\sqrt{E \text{ fiber concrete}}/ \gamma \text{ fiber concrete}/(g)]}{[\sqrt{E \text{ plain concrete}}/ \gamma \text{ plain concrete}/(g)]} \quad (3.1)$$

This relationship will be used to quantify the fracture and heaved pavement reduction capability of low volume (<0.5%) polypropylene fiber reinforced concrete pavements. Heaved pavement reduction modeling can be used to quantify the radial fracturing of 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete (Figure 3.6). Literature research of impact resistance, ductility and toughness characteristics can be analyzed and is considered in Step two. Quantitatively, the energy absorption capability of plain (0%), 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete was measured from laboratory toughness testing analysis (Figure 3.3). Qualitatively, compressive strength ductility observations can be made by fiber case.

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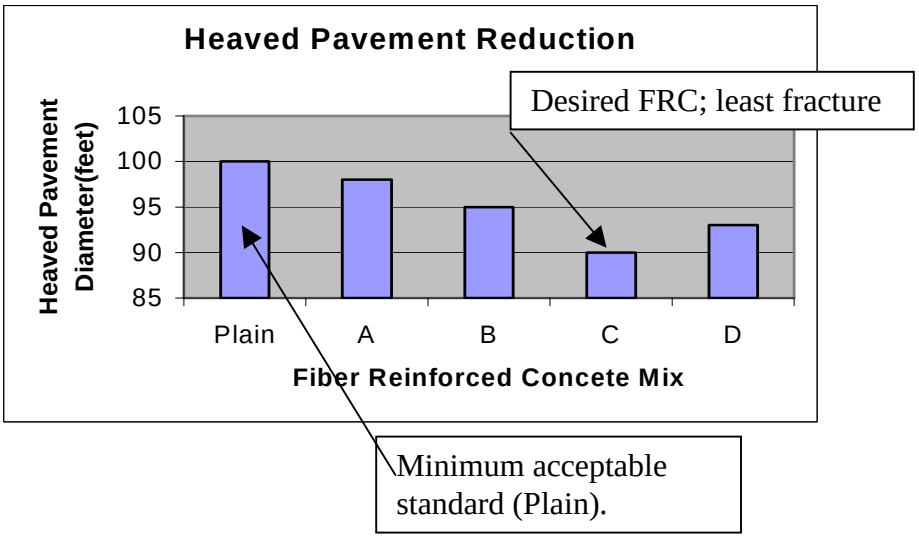

Figure 3.6: Heaved Pavement Reduction.

STEP 5. MIX DESIGN SELECTION AND FIELD TESTING

The idea behind a systematic methodology for mix design of fiber-reinforced concrete for airfield pavements is to improve both the quality of information and decision making when faced with a complex set of variables requiring analysis. A successful system yields quantifiable data enabling decision-makers to select the optimum fiber-concrete composite based on structural, environmental and survivability criteria. After literature review, analytical analysis and laboratory testing as shown in Figure 3.8, performance prediction models are validated under actual aircraft loading and environmental conditions (Figure 3.9). In this step, the models and acceptance criteria

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identified are used to select the concrete mixture in an iterative process until the optimum performance by fiber mix is determined. Such effort is beyond the scope of this dissertation to undertake except as a methodology discussion. Laboratory testing is at best an indirect indicator of performance of actual aircraft loading conditions. For example, static flexural testing of concrete is not indicative of actual static aircraft wheel loading nor is fatigue testing at 20 Hertz repetitive loading of concrete specimens indicative of actual aircraft wheel loading repetitions. Similarly, toughness-testing indices provide a measure of energy absorption properties of concrete and is not a direct measurement of an FRC composite's performance in this regard.

Implementation (test pad construction) of optimized FRC material composite slabs for actual field-testing is the next logical step after analytical and laboratory performance evaluation. Data obtained from field-testing becomes the new input data for an iterative system analysis. The iterative process provides feedback for improving the analysis and better predicts the pavement's life and response based on single and multi-aircraft loads. Feedback (revised inputs) are returned to the system from actual field testing to validate or modify laboratory or computer program simulations of actual loading and environmental conditions and to improve the accuracy and reliability of the performance models as a credible tool for use by decision makers at all levels. Field data acquisition yields improvements in test methods, data collection and interpretation of laboratory results, as well as performance and deterioration modeling.

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- Aircraft Loading. Control (0% fiber) and FRC slabs should be constructed on an airfield for actual load testing by design aircraft. Measures of deflection and strain in function of FRC's material properties should be collected.

- Environmental testing. Control (0%fiber) and FRC slabs should be constructed by the airfield for shrinkage testing. Record cracking (PCI visual method), and conduct pulse velocity testing to determine deterioration. Thermal changes through slab measurements and volumetric changes using the deflectometer should be examined. Install thermocouples, determine FRC's coefficient of thermal expansion (α), then calculate thermal stresses using KenSlabs.

- Explosive testing. Control (0%fiber) and FRC slabs should be constructed for Ammonium Nitrate-Fuel Oil (ANFO) explosive testing. The reduction in radial fractured FRC pavement from the charge should be monitored and the relationship between explosive type/net explosive weight, bore hole diameter and radial distance of heaved pavement from crater center should be examined. Heaved pavement is defined as the pavement with greater than ¼ inch vertical displacement (USAF Repair Quality Criteria; RQC).

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FRC DESIGN AND SELECTION CRITERIA

Figures 3.8 and 3.9 provide a step by step flow chart in achieving the objectives detailed in Chapter one. Each step is detailed in this Chapter. Once an FRC composite has been identified for laboratory and analytical evaluation from the literature, the following protocol for decision making may apply. Regarding values and decision rules, the following priority for ranking selected HPAC performance criteria is as follows. The priority may be changed based on mission requirements, or local environmental conditions and threats (Figure 3.7).

1. Greatest reduction in pavement thickness and thermal stresses.
2. Greatest increase in the energy absorption potential of the FRC material.
3. Greatest reduction in pavement distress (cracking).
4. Greatest reduction in agency costs.

The protocol for decision making within HPAC performance criteria is as follows. Optimization occurs by selection of the fiber mixture possessing the greatest beneficial behavior by fiber content. In the generation and optimization of alternatives the following analysis should be taken for evaluating the impact on pavement performance by:

1. Greatest reduction in pavement thickness by fiber mixture using:

- Single Aircraft Fatigue approach.
- Single Aircraft Flexural approach.
- Multi-aircraft Fatigue approach.

-

2. Greatest increase in energy absorption potential by fiber mixture considering.

- Explosive fracture/ heaved pavement analysis.
- Toughness indices and first crack strength.
- Impact resistance analysis.
- Visual observation of ductility failure in compression, fracture reduction of fatigue and flexural specimens after failure.

3. Greatest reduction in pavement distress; crack width, cracking and thermal stresses by fiber mixture.

- Restrained Shrinkage.
- Free Shrinkage.
- Thermal stress analysis from FEM.

4. Greatest reduction in Agency costs from alternative mixtures.

- Savings from pavement thickness reduction in construction time and materials.
- Costs related to workability (man-hours, construction time).

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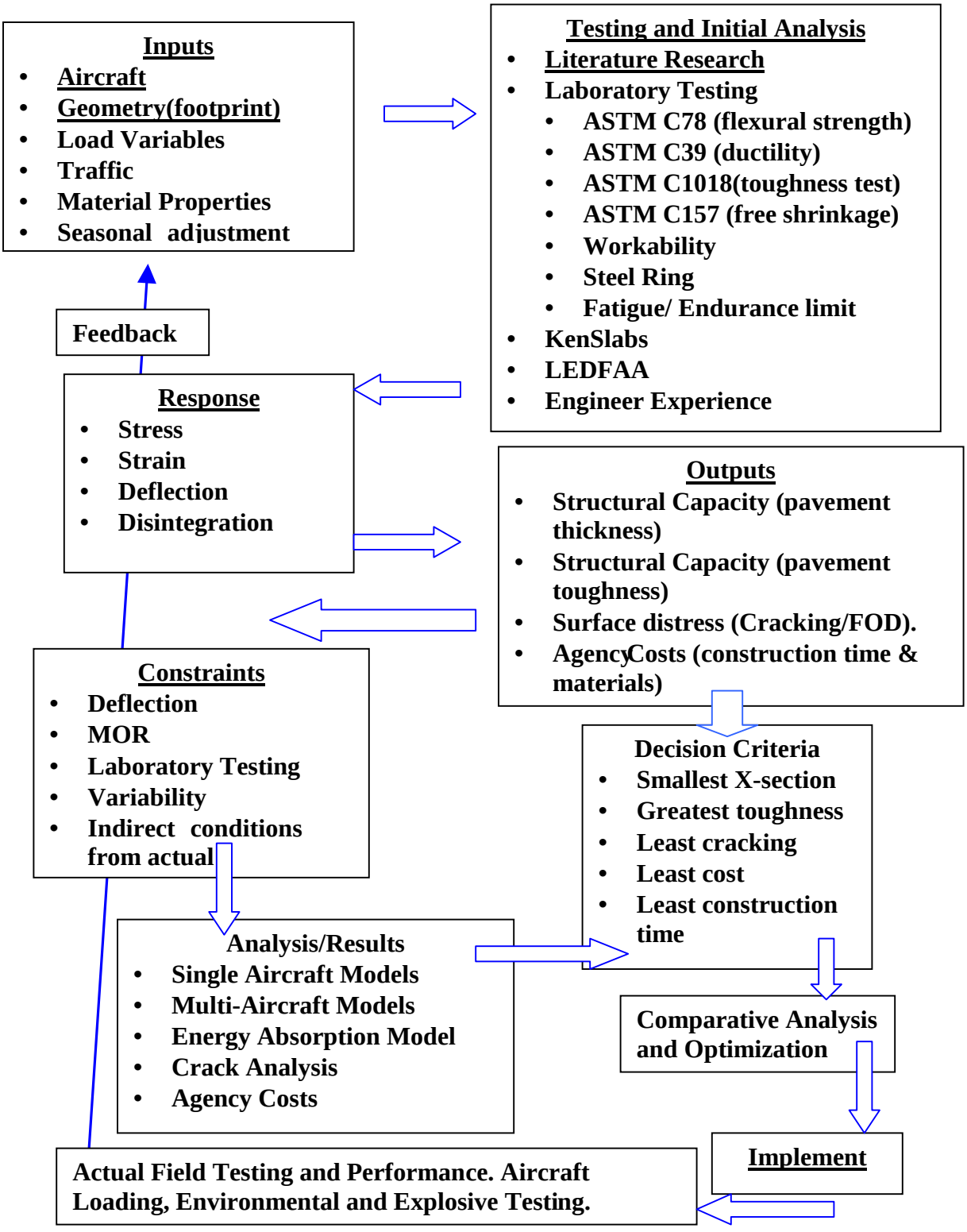

Figure 3.7: System Engineering Phases and Componets.

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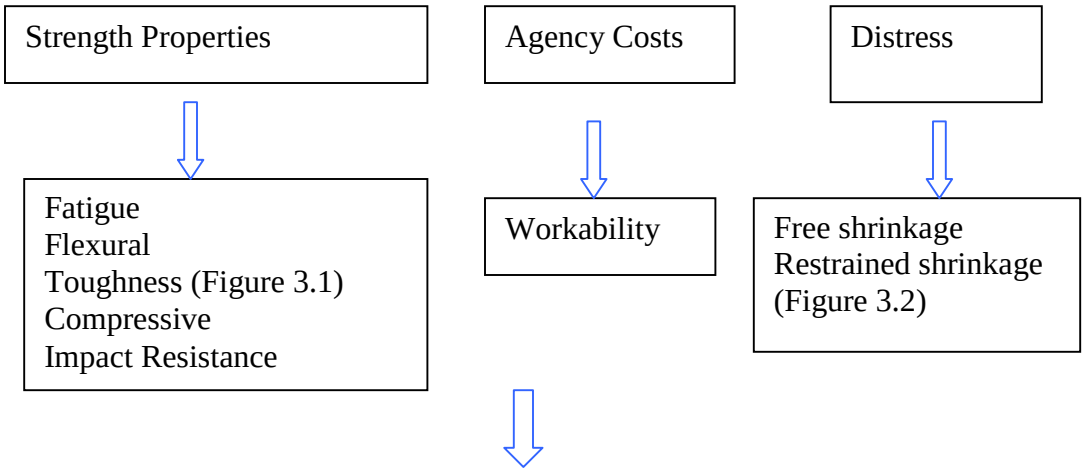
Step 1 . Evaluate and Select New Materials

Conduct literature search on non-metallic, synthetic fiber for fiber reinforced concrete (FRC). Select fiber for High Performance Airfield Concrete and characterize material behavior. Select Pavement FEM programs.

Step 2. Laboratory Performance Prediction



Step 3. Analytical Evaluation; Design Thickness Reduction

Determine Mechanistic Model Inputs, Outputs. Conduct Finite Element Modeling using laboratory values (Figure 3.7). Select FRC with greatest thickness reduction (Figure 3.3), thermal stress reduction (Figure 3.4), reduce Agency costs (Figure 3.5).

Step 4. Analytical Evaluation; Heaved Pavement Reduction

Calculate greatest reduction in heaved pavement based on FRC material properties (Figure 3.6).

Figure 3.8: Performance based Mix Design and Selection Methodology.

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Step 5. Mix Design Selection and Implementation

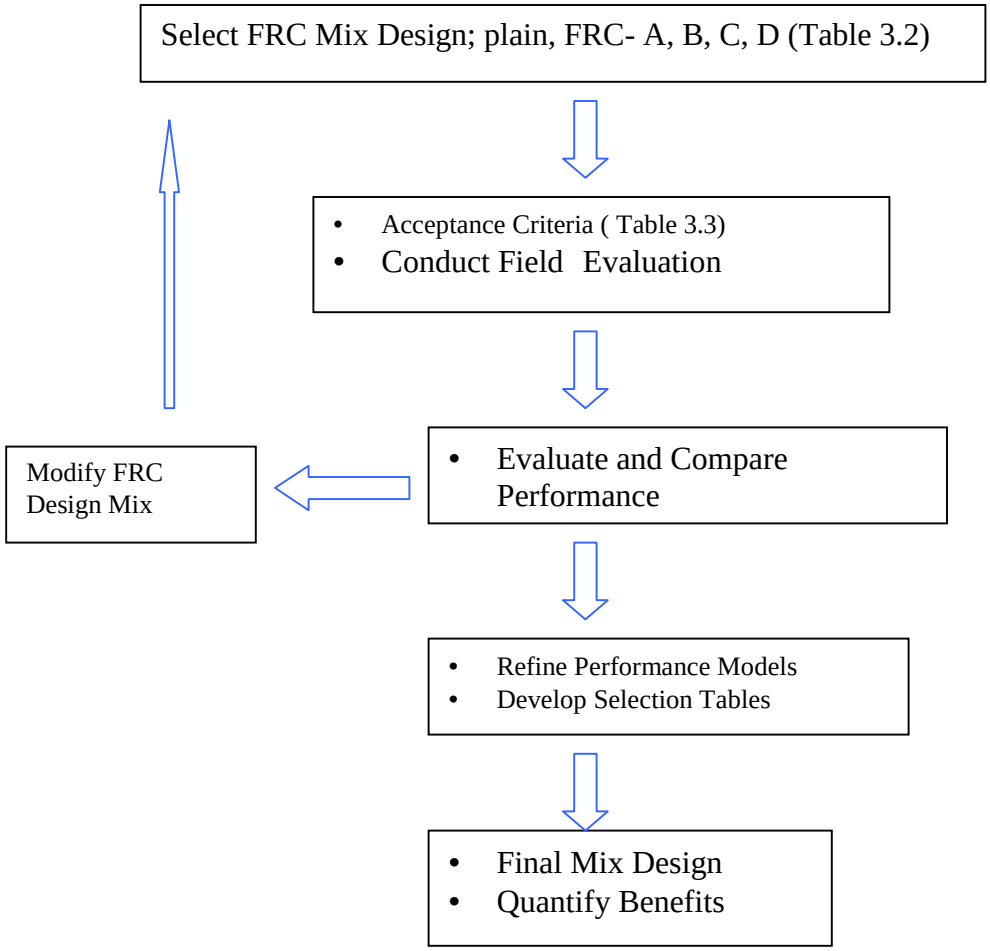

Figure 3.9: Performance based Mix Design and Field Testing Methodology.

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CONCLUSION

There is a real need and opportunity to consider all properties of a new fiber concrete composite and optimize those properties into an integrated, material selection-design approach to improve pavement performance. The information age and the Internet have provided unprecedented opportunities to evaluate new material research in real time to select targeted HPAC composites. Advances in polymers have improved concrete's strength, energy absorption and shrinkage properties, which are important to the survivability of military airfields. Finite Element Modeling continues to advance, providing greater accuracy in predicting pavement design thickness as a function of a specific aircraft and mix design. Refining predictive analytical equations and laboratory values with field testing better couples analytical modeling with actual performance in a more scientific, less empirical pavement design approach. Regarding acceptance criteria, flexibility in prioritizing and selecting desired FRC material properties in airfield design is also needed. Since the United States Air Force operates worldwide, important mix design criteria may vary regionally requiring different fiber concrete designs to enhance specific characteristics required at a location. Considering both the U.S. Military's and commercial aviation's global reach, concrete mixture and rigid pavement design criteria may be regionally specified based on local desired performance requirements due to mission, environment and threat, as well as a consideration of local material properties. Based on local conditions, development of regional contract specifications, drawings and construction standards could be derived from tabular data like Table 3.1. Considering

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laboratory and analytical analyses as in Table 3.2, fiber mix selection would be based on local acceptance criteria. As example, in wet weather Europe, FRC enhanced crack reduction criteria may dominate as compared to airfield fatigue strength improvement needed at major air cargo hubs in the United States. In the Middle East or Asia, survivability (energy absorption) may be the desired airfield fiber-concrete material property.

Table 3.1: FRC Design Thickness Table.

Traffic	Annual Departures	Military Standards Kenslabs Design Thickness	LED-FAA Design Thickness	FRC pavement thickness reduction value (PRV.)
Boeing 777 Boeing 747 C-141	33,000 33,000 33,000		19.44 inches (MOR;800psi)	0.1%/0.3”reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
Boeing 777 Boeing 747 C-141 C-17A	25,000 25,000 25,000 25,000		19.22 inches (MOR;800psi)	0.1%/0.3”reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
Boeing 777	100,000	10.5 inches A/B Traffic Areas 8.3 inches C Traffic Areas		0.1%/0.4”reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
C-141	100,000	10.5 inches A/B Traffic Areas 9.5 inches C Traffic Areas		0.1%/no reduction 0.2%/0.1” reduction 0.3%/0.3” reduction 0.4%/no reduction
C-17A	100,000	10.5 inches A/B Traffic Areas 8.7 inches C Traffic Areas		0.1%/0.4” reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction

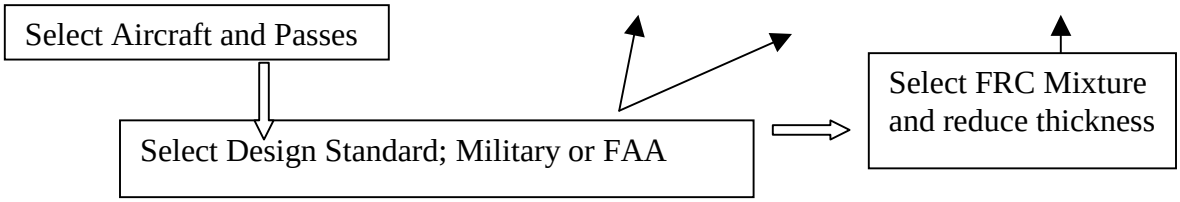

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Table 3.2: FRC Mix Design Acceptance Criteria.

Performance Criteria(Models)	Plain Concrete	0.1% FRC	0.2% FRC	0.3% FRC	0.4% FRC
Fatigue Strength (Design-thickness reduction)		**Optimum**		**Optimum**	
Flexural Strength (thickness reduction)				**Optimum**	
Energy Absorption (heaved-pavement)				**Optimum reduction**	
Curling Stress				**Optimum reduction**	
Crack Reduction			**Optimum**		
Workability	**Optimum**				
User Costs		**Optimum**			

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CHAPTER 4. LABORATORY TESTING AND RESULTS

INTRODUCTION

Extensive laboratory testing was conducted over a 12-month period at the University of Maryland quantifying the properties of polypropylene fiber reinforced concrete (FRC) for pavement structures. Advances in polymer technology are creating new opportunities for traditional building materials like concrete, potentially improving fatigue, energy absorption and shrinkage properties, which are important to improving the serviceability of civilian airfields and survivability of military airfields. However, there are challenges and unknowns that complicate the understanding of this composite. As example, fiber-concrete composites are a new material lacking a long-term performance history as a structural element, which form the basis of much of the empirical design methodologies used in Civil Engineering. Also, recommended FRC tests are a stated research need identified by ACI. Regarding material laboratory testing such as dynamic fatigue tests that replicate moving aircraft loads on concrete pavements, are as yet to be standardized by ASTM. Tests that replicate extreme environmental conditions, such as temperature-restrained shrinkage also lack standardization. ACI 544.2R-89 "Measurement of Properties of Fiber Reinforced Concrete"[4] provides some recommended tests for polymeric fiber reinforced concrete pavements. An objective of this Chapter is to recommend laboratory tests for FRC as a HPAC and obtain data values. Tests recommended for fiber reinforced concrete (FRC) were conducted in the University of Maryland's Materials Testing Laboratory and are summarized in this Chapter.

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MIX DESIGN AND WORKABILITY

Materials and Mixtures

The materials used consisted of ASTM C-150 Type I/II Portland cement, ground blast furnace slag from Sparrows Point Maryland, natural sand as the fine aggregate with a fineness modulus of 2.57 and #57 coarse aggregate with a gradation as shown in Table 4.1. Fibermesh, a homopolymer-fibrillated polypropleyene fiber made from olefin resins, ¾" long was used and applied at four quantities; 0.1%, 0.2%, 0.3% and 0.4%. Daravair, an air –entraining admixture meeting the requirements of ASTM C260 was used to maintain air content. WRDA 35 mid range water-reducer admixture and ADVA superplasticizer were used to maintain plasticity and slump at the designated water cement ratios (w/c) of 0.40 and 0.44. The synergistic effect of these admixtures produced concretes using 0.0%-0.4% reinforced fibers with enhanced finishing characteristics while maintaining proper air-entrainment for freeze-thaw protection and slump with low water-cement ratios. Grace construction products, in Cambridge Maine, manufactures the above mentioned admixtures. Detailed mix design results for all test samples are presented in Table 4.2.

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Table 4.1: Mix Design Matrix .

MIX NO.	MD 7	7 MD	MD 7	MD 7	MD 7
AGGRE-GATE TYPE	#57 ASTM (control)	#57ASTM (Fatigue Resistant)	#57ASTM (Fatigue Resistant)	#57ASTM (Fatigue Resistant)	#57ASTM (Fatigue Resistant))
SIEVE SIZE					
2-1/2 “					
2 “					
1-1/2 “	100	100	100	100	100
1”	95-100	95-100	95-100	95-100	95-100
3/4”					
1/2”	25-60	25-60	25-60	25-60	25-60
3/8”					
No. 4	0-10	0-10	0-10	0-10	0-10
No. 8	0-5	0-5	0-5	0-5	0-5
No. 10					
No. 16					
No. 30					
No. 40					
No. 50					
No. 100					
No. 200					
W/C	0.44	0.44	0.44	0.44	0.44
Min. Cement Type I	580 lb./cy 345 kg./m3	580 lb./cy 345 kg./m3	580 lb./cy 345 kg./m3	580 lb./cy 345 kg./m3	580 lb./cy 345 kg./m3
Air Content	6.5%	6.5%	6.5%	6.5%	6.5%
Slump	1-1/2” to 3”	1-1/2” to 3” 8-30 sec.	1-1/2” to 3” 8-30 sec.	1-1/2” to 3” 8-30 sec.	1-1/2” to 3” 8-30 sec.
Concrete Temp.	70°F	70°F	70°F	70°F	70°F
Fiber Content (1/2 to 1 1/2 inch)	0%	1.5 lb./cy (0.1%)	3.00lb./cy (0.2%)	4.5 lb./cy (0.3%)	6 lb./cy (0.4%)
Air Entrainment	1.7oz/100Lb	1.9oz/100Lb	1.9oz/100Lb	1.9oz/100Lb	1.9oz/100Lb
Water Reducer	5 oz/100Lbs	5 oz/100Lbs	5 oz/100Lbs	5.5oz/100Lb	6 oz/100Lbs

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Mix Batching Proportions and Procedures

Proportionally, each mix contained 377 Lbs./Cy Cement, 203 Lb./Cy. Slag, 1,898 Lb./Cy. Aggregate, 1,176 Lbs./Cy. Sand and 255 Lbs./Cy of tap water. Coarse and fine aggregate were mixed with two-thirds of the required water for 90 seconds to allow for water absorption. Then cement, slag, fibers and the remaining water were added and mixed for three minutes. The mix was allowed to rest for two minutes and additional mixing for three minutes in accordance with ASTM C 192 procedures. An additional minute was added to the final mixing time to enhance fiber dispersion in the matrix. Immediately after mixing, the concrete was transferred to the wheelbarrow and slump, unit weight and air content was measured. Specimens were then molded and allowed to cure for 28 days in water at 73° F prior to testing. Fiber reinforced concrete samples were externally vibrated and plain samples rodded in accordance with ASTM standards. Tests were conducted during the summer, where slump and air content loss was more rapid for both plain and fiber reinforced concrete when the temperature range was above 80° F.

Mix Design and Workability Results

Pavement mix designs are often the compromise of stiffness for strength to prevent excessive deflection and flexibility for fatigue and fracture (cracking) resistance under increasingly higher stresses imposed and harsh environmental conditions. Mix designs should be evaluated based on output performance criteria, unique to the user and validated by both field and laboratory testing. In this case, polypropylene fiber concrete

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needs to improve the fatigue strength and fracture resistance of rigid military airfields. Air content and slump values provide an indication of workability of a concrete mix. Regarding air content, standard ASTM air content test equipment and procedures for conventional concrete was used (ASTM C 138). However, FRC samples were consolidated using internal/external vibration, not rodding. For FRC specimens, Slump (ASTM C 995) Time of flow through Inverted Cone test was used. The inverted cone test was specifically developed to measure FRC workability and can be used to compare FRC to conventional mixtures with similar slump values. The inverted cone time increases with a corresponding decrease in slump. For workability, the advantage of the inverted slump cone test is that it takes into account the mobility of the concrete and viscosity, which comes about due to vibration. Satisfactory workability is achieved if the FRC mix passes through the cone between 8 and 30 seconds. Plain concrete slump was measured with the slump cone in the conventional manner outlined in ASTM C143.

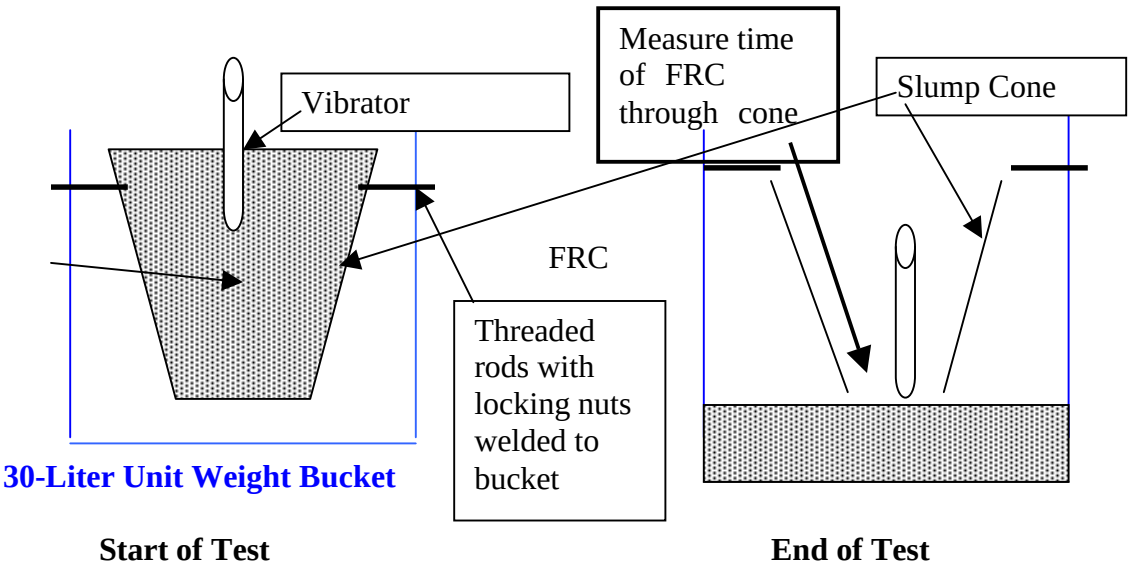

Figure 4.1: Inverted Slump Cone Test for FRC.

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Similar to the results reported by the American Concrete Institute (ACI) Report[7], cast in place concrete will accommodate up to 0.4 percent by volume of polypropylene fibers with minimal mix proportion adjustments. Good workability can be maintained in polypropylene fiber reinforced concrete (FRC) by adding an appropriate amount of admixtures. Slump and air content values provide an indication of workability of a concrete mix. Given a limited slump range (1–1/2 to 3 inches) and fixed air content of 6.5%, adequate mix design was maintained using water reducers and air entraining admixture (Table 4.2). The synergistic effect of these admixtures produces concretes (0.0%-0. 4% fiber reinforced) with enhanced finishing characteristics while maintaining proper slump and air-entrainment for freeze-thaw protection in concretes with low water-cement ratios. However, for a given water–cement ratio, the trend was that as fiber content increased, slump and air content decreased requiring additional admixtures (Table 4.3). Finishing became more difficult as fiber content increased, but still manageable at 0.4 % volumes. Surface finish, quality of the molds and compaction were a function of vibration, superior with external vibration as compared to rodding. However, excessive vibration (> 20 seconds) would cause segregation of the fibers from the concrete matrix resulting in fiber balling or migration of fibers to the base of the specimen (Figure 4.2).

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Table 4.2: Workability Matrix.

Specimen	Slump	Air Content	Unit Weight	Compressive Strength(28 days)
Plain Concrete 1	3.5 inches	6.6%	142.8 lb/cf	5,377 psi
Plain Concrete 2	3.5 inches	6.6%	142.8 lb/cf	4,217 psi
Plain Concrete 3	4.3 inches	6.6%	142.8 lb/cf	5,624 psi
0.1Fiber Concrete	1.9 inch/8.5 sec.	4.6%	147.8 lb/cf	6,296 psi
0.1Fiber Concrete	1.9 inch/8.5 sec.	4.6%	147.8 lb/cf	5,854 psi
0.1Fiber Concrete	1.9 inch/8.5 sec.	4.6%	147.8 lb/cf	6,403 psi
0.2Fiber Concrete	2.3 inch/8.0 sec.	6.6%	143.8 lb/cf	5,341 psi
0.2Fiber Concrete	2.3 inch/8.0 sec	6.6%	143.8 lb/cf	5,235 psi
0.2Fiber Concrete	2.3 inch/8.0 sec	6.6%	143.8 lb/cf	5,607 psi
0.3Fiber Concrete	2.5 inch/8.0 sec	7.0%	143.8 lb/cf	4,584 psi
0.3Fiber Concrete	2.5 inch/8.0 sec	7.0%	143.8 lb/cf	4,439 psi
0.3Fiber Concrete	2.5 inch/8.0 sec	7.0%	143.8 lb/cf	4,606 psi
0.4Fiber Concrete	0.5 inch/13 sec	5.8%	141.8 lb/cf	5,320 psi
0.4Fiber Concrete	0.5 inch/13 sec	5.8%	141.8 lb/cf	5,041 psi
0.4Fiber Concrete	0.5 inch/13 sec	5.8%	141.8 lb/cf	4,245 psi

Increased Water Reducer

Increased Daravair

Table 4.3: Workability Results.

FRC	Water/Cement (w/c) Ratio	Darav AIR (oz/100lbs.)	Water Reducer (oz/100lbs.)	Slump (inches)	Air Content (%)
0% Fiber	0.40	2	2.7 (high range)	2.75	6.4
0% Fiber	0.44	1.7	5.0 (medium)	3.12	6.1
0.1% Fiber	0.44	1.9	5.0	5.5 inch (6 sec)	7.0
0.2% Fiber	0.44	1.9	5.0	1.5 inch (12 sec)	6.0
0.3% Fiber	0.44	1.9	5.5	0.25 inch (17 sec)	5.0
0.4 % Fiber	0.44	1.9	6.0	1 inch (19 sec)	5.5

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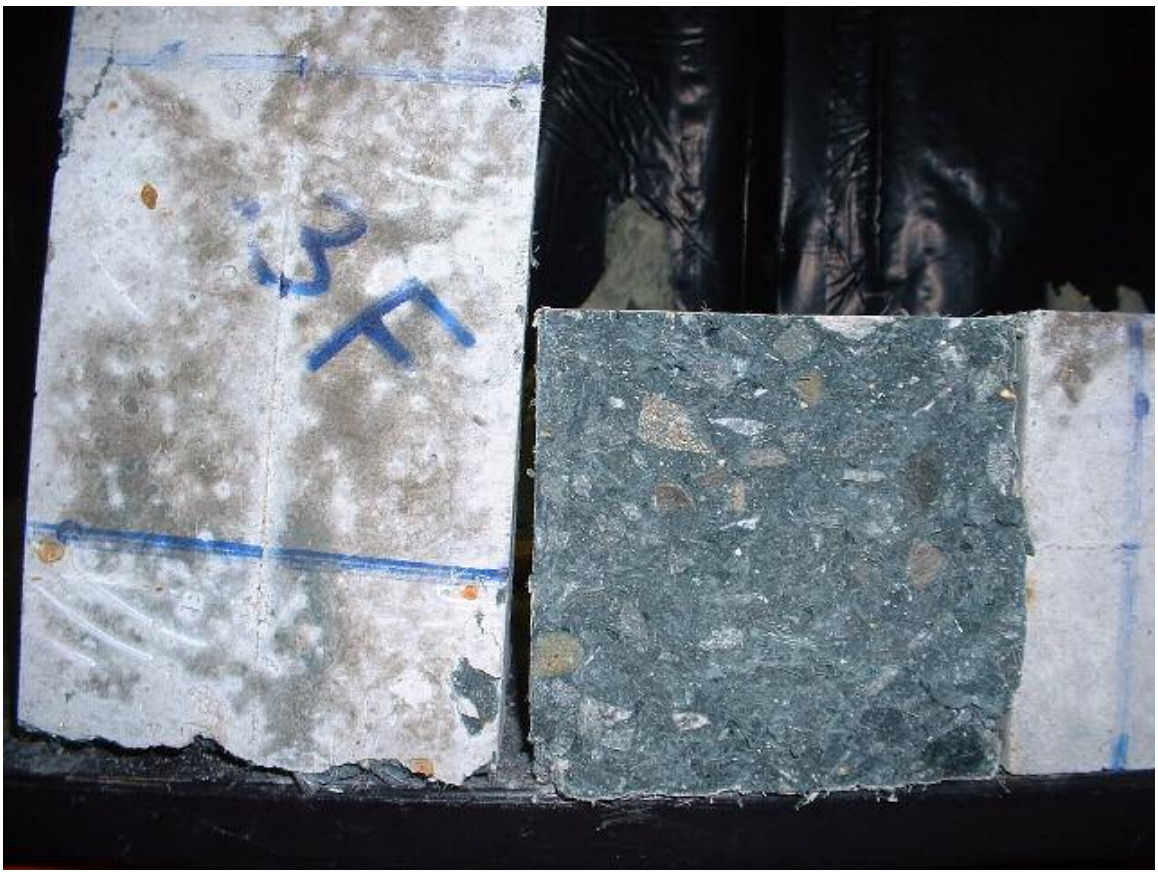

Figure 4.2: FRC Beam after Fracture (fibers visible).

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STRENGTH AND ENERGY ABSORPTION

Flexural Strength and Toughness

The preferred flexural testing of FRC is under third-point loading; ASTM C 78 or C 1018. ASTM C 78 provides maximum static flexural or peak fiber stress in tension strength. The stress at which the beam breaks is known as the Modulus of Rupture (MOR) and is a critical material property input data value in pavement design calculations. Additionally, in practice, static flexural strength is used to determine construction compliance with specifications of slabs and pavements and the calculation of the Modulus of Rupture (MOR) value is critical in establishing acceptance criteria. Essentially, the MOR replicates the tensile stress at the bottom of a concrete slab at failure due to loading. In Finite Element Models, such as KenSlabs or LEDFAA, the MOR is the input concrete strength value in determining traffic loads to failure (N) in calculating airfields' design life.

ASTM C 1018 should be used if toughness or load deflection behavior is of interest. Specimen width and depth should be three times the fiber length or maximum aggregates size. The preferred specimen size for toughness testing is a 4 x 4 x 14 inch beam. Toughness testing provides for the determination of ratios called Toughness Indices that identify the pattern of material behavior of FRC up to a selected deflection. Residual strength factors, which are derived from the indices, characterize the level of strength retained by FRC after first crack. Toughness Indices and residual strength factors determined by this test method reflect the post crack behavior of fiber reinforced concrete

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and qualitatively contribute to our understanding of the energy absorption capability of varying volumes of fibers in concrete. This manifestation of toughness or energy absorption capability is relevant in such engineering applications as the reduction of heaved pavement from explosive cratering or further serviceability of an airfield after fatigue cracking. Consider toughness, where preservation of FRC structural integrity even after severe damage is of primary concern.

Standards.

1. ASTM C-78; Flexural Strength of Concrete using Simple Beam with Third-Point Loading (Figure 4.3).
2. ASTM C1018; Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete using Beam with Third-Point Loading (Figure 4.8).
3. ASTM C 192; Making and Curing Concrete Test Specimens in the Laboratory.

   Three specimens will be made for each test age and test condition.

   Specimen width and depth should be three times the fiber length or maximum aggregate sizes (preferred specimen size 4 x 4 x 14 inches).

Aging Period. Tests are conducted at 28 days after casting the concrete.

Aging Temperature. Mixing and Curing temperature (73.4°).

Polypropylene Fiber Content. 0%, 0.1%, 0.2%, 0.3%, 0.4%

Aggregate Gradations. #57, #357 (avg. three replicates).

Slump. ASTM C 143; Slump of Hydraulic Cement Concrete. However, ASTM C 995 should also test FRC samples; Time of flow through Inverted Cone test.

Air Content. ASTM C 138. However, FRC samples should be consolidated using external vibration.

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Figure 4.3: ASTM C 78 Static Flexural Strength Testing.

Summary of Results: Static Flexural Testing

Twenty-nine, 6 inch X 6 inch X 21 inch concrete beams were tested, evaluating varying volumes of polypropylene fiber; plain (0%), 0.1%, 0.2%, 0.3%, 0.4% at normal strength (0.44 w/c) mix, using a #57 aggregate gradation. Two sets of low shrinkage concrete beams were also cast, one set using a higher strength water cement ratio (0.4 w/c) mix and the other set using a different aggregate gradation, #357. Over a range of curing times; 28 to 39 days, on average the Modulus of Rupture (MOR) for 0%, 0.1%, 0.2%, 0.3% and 0.4% fiber reinforced concrete specimens was 768 psi, 725 psi, 877 psi, 877 psi and 883 psi respectively (Figure 4.4). Modulus values for fiber beams with 0.2% to 0.4% fiber were higher, compared to plain and 0.1% fiber concrete and equivalent to

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the MOR for high strength (0.4 water-cement) plain concrete. Failure occurred at an average deflection of 0.0033”, 0.0031”, 0.0036”, 0.0037” and 0.0036” for 0% (plain), 0.1%, 0.2%, 0.3% and 0.4% fiber normal strength beams. Deflection to first crack increased with increased fiber content. Additionally, compared to plain concrete, the addition of 0.2% to 0.4% fiber to concrete increased the static flexural strength by 15 %. Static flexural testing of 6” X 6” X 21” concrete beams more than seven months old yielded different results (Figure 4.6). The average Modulus of Rupture (MOR) for plain concrete, 0.1%, 0.2%, 0.3% and 0.4% fiber reinforced concrete was 725 psi, 692 psi, 731 psi, 757 psi and 728 psi respectively. The MOR for high strength (0.4 water-cement) plain concrete was 788 psi. Compared to plain concrete, the addition of 0.3% and 0.4% fiber volumes to matured concrete increased the static flexural strength by only 5 % but retarded cracking by 15%+ at 0.4 % fiber content (Figure 4.5). Fiber concrete’s ability to retard cracking and continue to absorb energy (carry load) after first crack is best quantified in the toughness test, but is also observed during flexural and fatigue testing. Within the flexural beam testing protocol (ASTM C78) as fiber content increased, a greater percentage of each beam remained uncracked at failure (Table 4.4).

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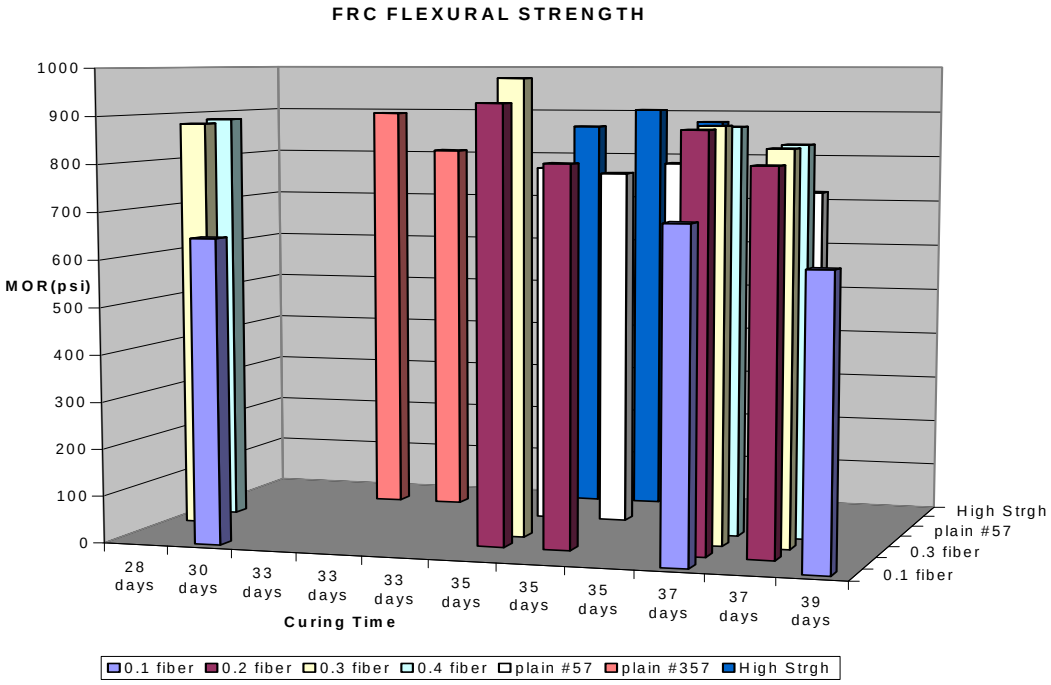
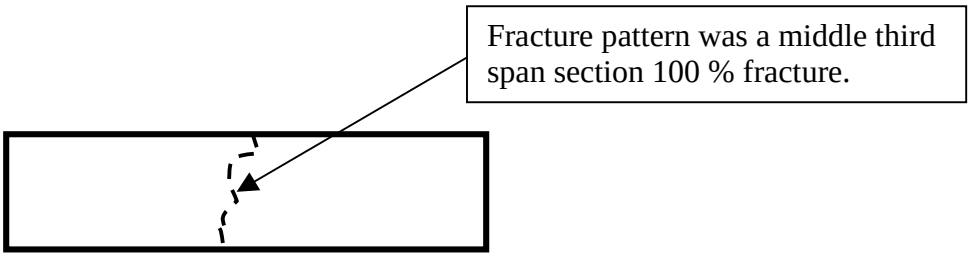
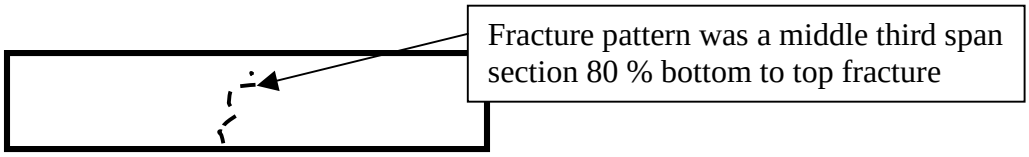


Figure 4.4: Flexural Strength Graph.



ASTM C78; Sample 3MFa-PL (plain conc. W/C =. 44).



ASTM C78; Sample 3MFa-.4F (0.4 % Fiber conc. W/C =. 44).

Figure 4.5: Typical FRC Beam Fracture.

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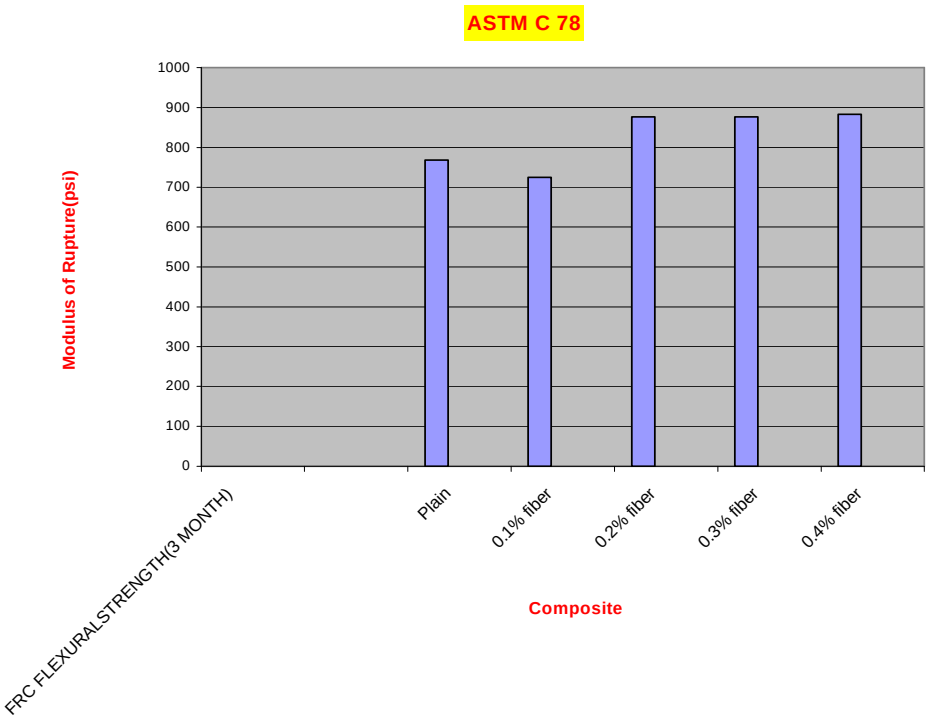

Figure 4.6:Flexural Strength Results.

Static flexural strength of 4”X 4”X14” specimens prepared for fatigue testing yielded Modulus of Rupture values for plain, 0.1%, 0.2%, 0.3% and 0.4% fiber reinforced concrete of 868 psi, 970 psi, 981 psi, 1,017 psi and 980 psi respectively. Compared to plain concrete, laboratory testing indicated the addition of 0.2% to 0.4% fiber volumes to concrete increased the static flexural strength by 15 %. Some researches reported only slight changes in static flexural strength at low volumes (<0.5% fiber) of polypropylene FRC where fatigue resistance, not static flexure was the focus of their research. However, vendors such as FORTA Corporation claim flexural strength

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increases of 17% (ASTM C-78) for 4” x 4 “ x 14” beams similar to our results. FORTA's Ultra-Net is a polypropylene, collated fibrillated alkali resistant, non-corrosive 3/4-inch to 2 1/2-inch fiber. Recommended application rate is 1.6 lbs. (0.1% fiber content) per cubic yard of concrete.

Regarding variability, ACI 544 has questioned the relevancy of flexural strength testing comparisons of polypropylene fiber volumes in concrete specimens without adjusting mix design to maintain equivalent compressive strength values at higher fiber volumes (see Chapter 2). Compressive strength testing (ASTM C39) is used as an indicator of mix design control in terms of concrete's strength. Compressive strengths decrease by as much as 10% for 0.3% and 0.4% fiber volumes in concrete as compared to 0% fiber concrete (Table 4.6). Using the compressive strength values in Table 4.6 to normalize the MOR values for 6" X 6" X 21" beams, would decrease the flexural strength values for 0.1%, 0.2% and 0.4% fiber volume FRC's and increase the Modulus value for 0.3% cases (Figure 4.7).

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Table 4.4: FRC Specimen Fracture Observations.

Fatigue Specimen	MOR	Fracture(%)	Water/Cement W/C	Fiber Content	AGE (days)
Plain Conc.	855 psi	100	.44	0%	93
Plain Conc.	868 psi	100	.44	0%	43
Plain Conc.	869 psi	100	.45	0%	49
Plain Conc.	683 psi	100	.44	0%	107
0.1% Fiber	973 psi	100	.44	0.1%	72
0.1% Fiber	970 psi	100	.44	0.1%	41
0.1% Fiber	947 psi	100	.44	0.1%	107
0.2% Fiber	860 psi	80	.44	0.2%	86
0.2% Fiber	981 psi	100	.44	0.2%	40
0.2% Fiber	973 psi	100	.44	0.2%	107
0.3% Fiber	1,061 psi	80	.44	0.3%	79
0.3% Fiber	1,017psi	98	.44	0.3%	28
0.3% Fiber	813 psi	80	.44	0.3%	107
0.4% Fiber	980 psi	80	.44	0.4%	65
0.4% Fiber	980 psi	80	.44	0.4%	29
0.4% Fiber	934 psi	80	.44	0.4%	107

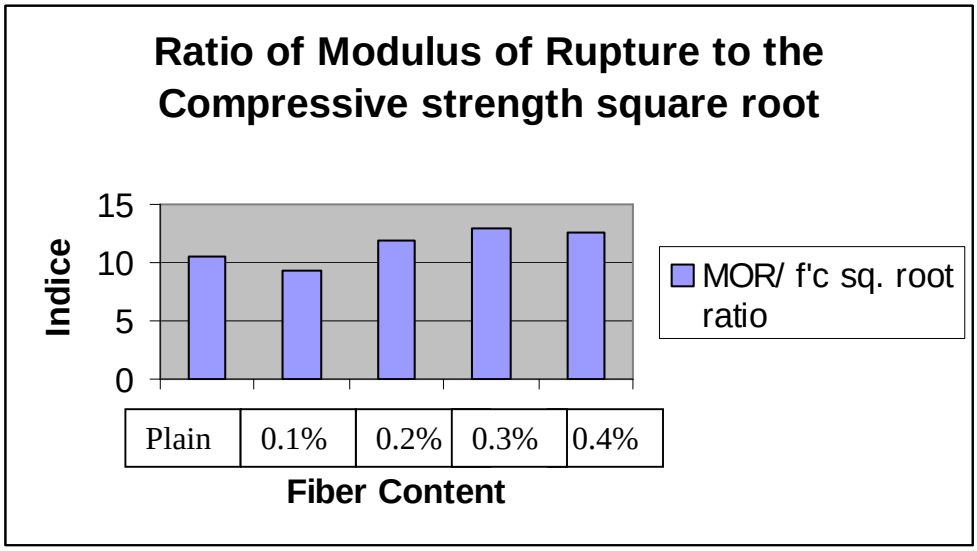

Figure 4.7: ACI FRC Flexural Strength Indices.

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Summary of Results; Toughness

The low tensile strength and brittle failure tendency of concrete airfield pavements are a major design concern in increasing the service life and minimizing slab failure. Concrete's tensile strength is typically only 275 psi, and the USAF considers slab failure as 100% thickness cracking of a 20 foot by 20 foot slab into four sections; defined as a shattered slab. Fiber reinforced concrete can increase concrete ductility and energy absorption of the slab as the high tensile strength of fiber (60 ksi) in the matrix can carry the load imposed on the pavement after the concrete fails by fibers bridging the crack after failure. Toughness testing was conducted on 12 FRC samples with at an average curing age of 95 days. Flexural strength at 1st Crack (MOR) and post first crack energy absorption (toughness) optimized in the 0.3% fiber beams (Figure 4.9) with toughness improving with increased fiber content at 0.4%, but at a descending MOR value. First crack occurred at an average deflection of 0.007", 0.01", 0.01" and 0.012" for 0.1%, 0.2%, 0.3% and 0.4% fiber content in 4" X 4" X 14 " concrete beams showing an increase in ductility. Descending flexural strength (MOR) was not the result of increased air voids or reduced compaction associated with increasing fiber content as reported by other researchers, as both our 0.3% and 0.4% fiber maintained a 6% design air void content (Table 4.5; Toughness Mix Design). Reduced Elastic Modulus values associated with fiber (600 ksi) as compared to plain concrete (3,000+ksi) likely contributed to this descending first crack strength trend at higher fiber contents.

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The toughness index (I) is a measure of the capacity of fracture energy absorption and ductility of the specimen. The toughness index is defined as the area under the load-deflection curve up to a specific deflection divided by the area under curve up to the point where concrete first cracks. Plain concrete fails immediately upon cracking, without further load carrying capacity so I is always equal to 1.0 for plain concrete. However, concrete beams reinforced with fiber continue to deflect in a ductile fashion (Figure 4.9). The beams with higher fiber contents exhibited higher energy absorption and ductility properties. Indices represent a ratio of remaining energy (load-deflection areas expressed in Foot. Lbs.-inch) at 3, 5.5 and 10.5 time's first crack deflection as compared to the energy triangle at first crack. As example, plain concrete's (0 % fiber) have I –5,10,20 values of one.

Post crack load drop is defined as the difference between the maximum load and the load recorded at a deflection equal to three times the deflection measured at first crack[9]. Laboratory derived load drops, expressed as a percentage of maximum loads, are 98 %, 97 %, 89 % and 81 % for 0.1 %, 0.2%, 0.3% and 0.4% fiber volumes respectively. The post crack load drop trend decreases with increasing fiber content indicating increased stored post crack energy in higher fiber volume concrete composites (Figure 4.10).

Laboratory derived Toughness Indices compared favorable with current research but residual strength values showed little perfect plastic behavior (R=100) of this composite at large deflections. Indices represent a ratio of remaining energy, and laboratory derived Toughness Indices at 0.3% fiber content were 3.17, 3.63 and 4.5 for

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I-5, 10, 20 respectively indicating a fourfold ability of the FRC composite to absorb energy as compared to plain concrete (Figure 4.9). Fibers' ability to absorb energy in concrete is a valuable capability to the military in terms of the amount of heaved pavement that needs to be removed from a bomb-damaged airfield. Polypropylene fiber reinforced concrete's (FRC) increased toughness can reduce the amount of heaved pavement that needs to be removed and replaced, saving invaluable time to aircraft sortie generation after an airfield attack.

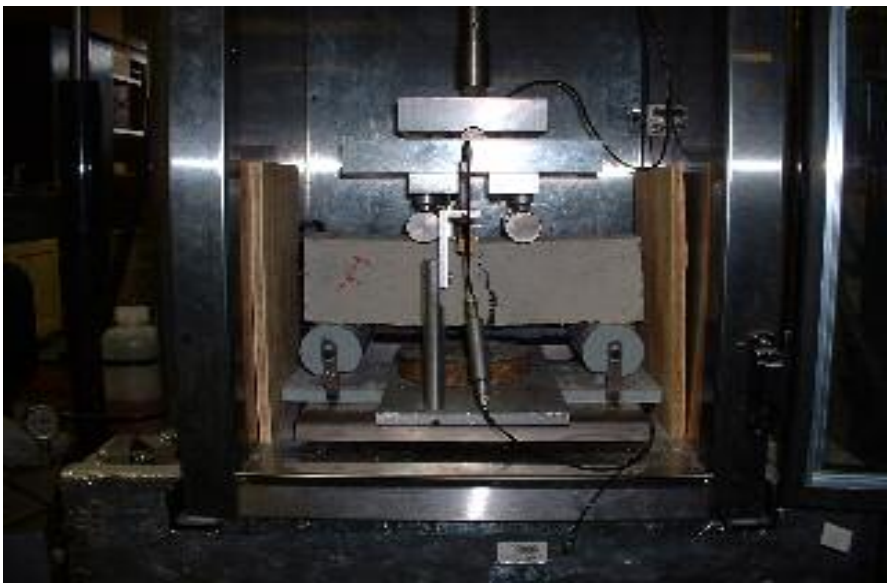

Figure 4.8: ASTM C 1018 Toughness Testing.

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Table 4.5: Toughness Mix Design (0.3% & 0.4 % Fiber).

W/C Ratio	0.44	0.44	0.44
Darav Air (ml.)	1.9 oz./100 lbs.	1.9 oz./100 lbs.	1.9 oz./100 lbs.
WRDA (ml.)	(M) 5.5 oz./100 lbs.	(M) 5.5 oz./100 lbs.	(M) 5.5 oz./100 lbs.
Fiber (%)	0.3	0.3	0.3
Slump (in./sec.)	1 / 12sec	1 / 12sec	1 / 12sec
Air Content (%)	6.1	6.1	6.1
Unit Wet. (lb./ft^3)	141.82	141.82	141.82
Temp(Celsius).	20	20	20
Curing from.	26-Oct	26-Oct	26-Oct

W/C Ratio	0.44	0.44	0.44
Darav Air (ml.)	1.9 oz./100 lbs.	1.9 oz./100 lbs.	1.9 oz./100 lbs.
WRDA (ml.)	(M) 6 oz./100 lbs.	(M) 6 oz./100 lbs.	(M) 6 oz./100 lbs.
Fiber (%)	0.4	0.4	0.4
Slump (in./sec.)	18sec	18sec	18sec
Air Content (%)	6.0	6.0	6.0
Unit Wet. (lb./ft^3)	142.82	142.82	142.82
Temp(Celsius).	26	26	26
Curing from.	26-Oct	26-Oct	26-Oct

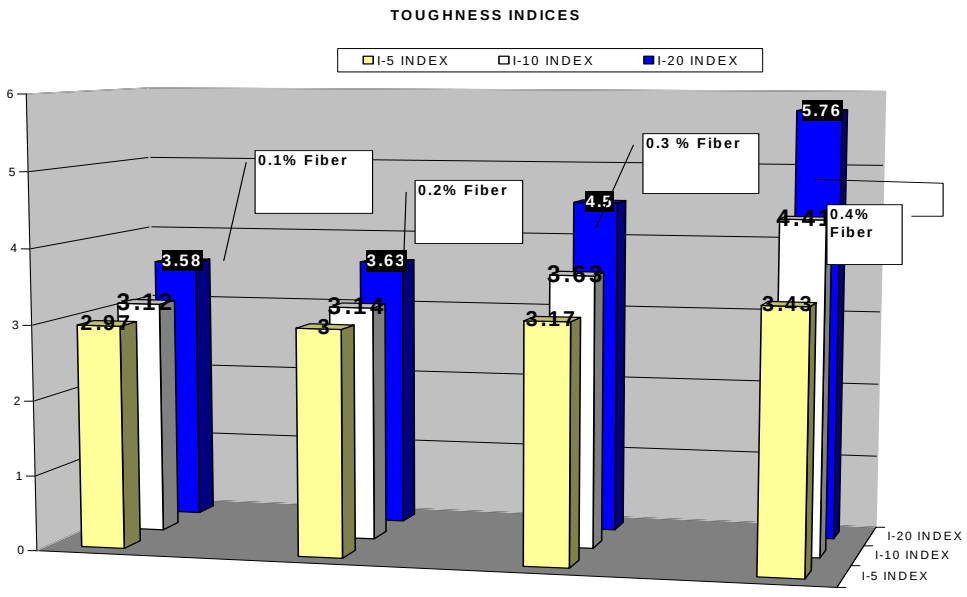

Figure 4.9: Laboratory Toughness Indices.

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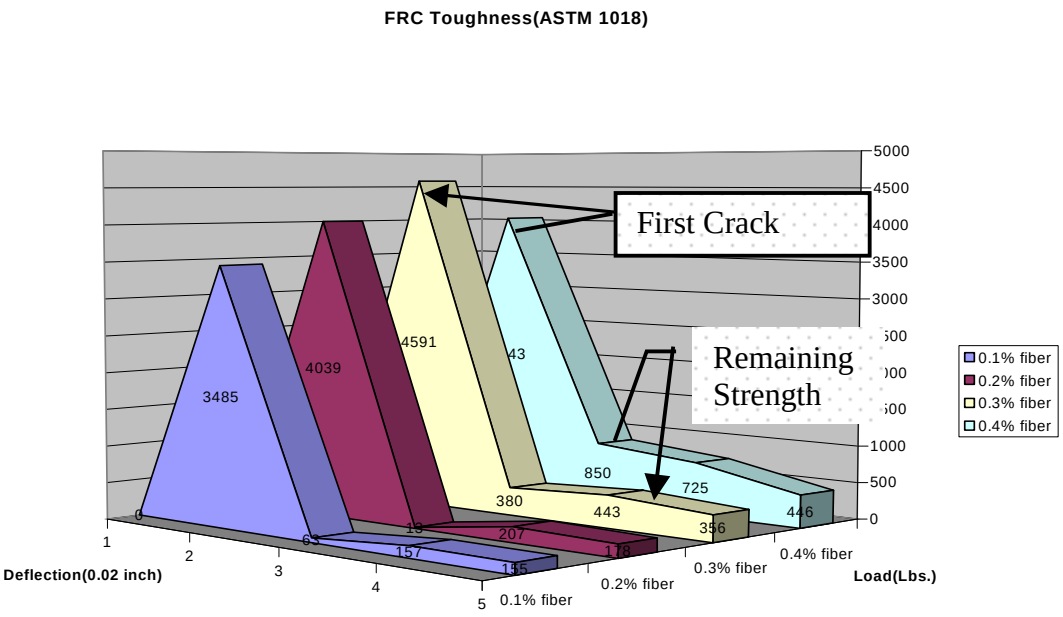

Figure 4.10: First Crack and Toughness.

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FATIGUE STRENGTH TESTING

Concrete as an airfield pavement structure is a low cost, locally available building material found anywhere in the world. However, concrete's low tensile strength and brittle nature are problematic pavement design characteristics, particularly in terms of fatigue strength and endurance limit as these structures are subject to repetitive load cycles which produce compressive transverse tensile stresses which cause concrete to crack and fail. Fibrillated polypropylene fiber has unique properties such as high tensile strength and when dispersed through the concrete matrix, retard the growth of microcracks resulting in the development of a large number of small cracks instead of a small number of large cracks which would lead to pavement failure. Theoretically, an FRC pavement that increases fatigue strength with a higher endurance limit would result in a concrete airfield with a longer life span, higher aircraft load carrying capacity or a reduced design thickness criteria as compared to a plain (0% fiber) concrete airfield pavement. Accordingly, a comparative evaluation of fatigue properties of concrete with four different volumes of fiber (0.1%, 0.2%, 0.3% and 0.4%) was undertaken to determine fatigue strength and endurance limits as compared to plain (0% fiber) concrete.

By definition, fatigue strength (fmax) is the maximum flexural fatigue stress at which a concrete beam can withstand two million cycles of repetitive loading. The 2,000,000-cycle limit is typically used to approximate the life span of a structure in concrete highway pavement fatigue testing. In terms of comparative evaluations, Endurance limit is defined as the maximum flexural fatigue stress of a beam at two

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million cycles of loading, expressed as a percentage of the modulus of rupture (MOR) of the plain concrete control specimen.

The objective of this testing is to determine fatigue strength and endurance limits of concrete with varying fiber volume (0%, 0.1%, 0.2%, 0.3% and 0.4%) subjected to 2,000,000 loading cycles at different loading stress ratios of 0.49, 0.59, 0.69 of each beam's MOR. If the beam failed before 2,000,000 cycles, then the next specimen would be tested at a lower stress ratio (Figure 4.12). All beams that survived the 2,000,000 cycles were later tested for static flexural strength to determine if microcracks had developed causing strength degradation in the concrete due to the fatigue loading. The frequency of loading was 20 Hertz (cycles per second) on a Material Test System (MTS) machine with a maximum load cell of 5,500 Lbs. (Figure 4.11). Loading was stress controlled and a sine wave frequency was selected to replicate real world pavement loading behavior. The specimens were cast in wood molds immediately after mixing the concrete, covered with plastic and cured at room temperature for 24 hours (Figure 4.13). The specimens were then removed from the wood molds and stored in water (100% humidity/73º F) for 28 days or longer prior to fatigue testing. Summary graphs are presented in Figure 4.15, showing the relationship between number of cycles (N) to failure and fatigue strengths as well as a relative comparison of endurance limits of varying volumes of FRC as compared to plain (0.0% fiber) concrete.

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Figure 4.11: Material Testing System (MTS) Machine.

Figure 4.12: FRC Fatigue Test Failure.

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Standards.

1. ASTM C 192; Making and Curing Concrete Test Specimens in the Laboratory.

   Three specimens will be made for each test age and test condition.

   Beam specimen width and depth should be three times the fiber length or maximum aggregate sizes (preferred size 4 x 4 x 14 inches).

2. Cyclic Load Testing; 5,500-lb MTS (25-kN) testing machine, stress controlled.

   Endurance Limit; 2 million cycles at 20 cycles per second loading (Figure 4.14).

Aging Period.

1. Tests are conducted at 28 days after casting the concrete.

Aging Temperature.

1. Mixing and Curing temperature (73.4°).

Polypropylene Fiber Content. 0%, 0.1%, 0.2%, 0.3%, 0.4%

Aggregate Gradations. #57

Stress Ratio. 0.69, 0.59,0.49

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Figure 4.13: Casting Beam Specimen.

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Summary of Results

Laboratory conclusions complemented literature research studies regarding increases in concrete's fatigue strength and endurance limit with increasing fiber content, when expressed as a percentage of plain concrete's modulus of rupture. Over 70, 4-inch x 4-inch x 14-inch concrete beam specimens were tested at the University of Maryland (Figure 4.16). Fatigue strength increased when fibrillated polypropylene was added to concrete. The average fatigue strength was 521 psi for plain concrete, 570 psi for 0.1% FRC and 525 psi, 567 psi and 513 psi for 0.2%, 0.3% and 0.4% FRC respectively (Figure 4.15). Fiber reinforcement clearly had a beneficial effect on fatigue strength at 0.1% and 0.3% fiber volume with an increase in strength of 6 %.

In terms of endurance limit, there was an increase of 66%, 60%, 65% and 59% for 0.1%, 0.2%, 0.3%, 0.4% fiber volumes respectively as compared to plain concrete of 60%. The endurance limit (2,000,000 cycles) was increased with the addition of fiber, which if used in airfield pavements would extend their service life. Additionally, the energy absorption capacity of fiber seem to peak at 0.1 % and 0.3%, beyond that increased fiber content resulted in a decline in strength. Polypropylene fiber strength behavior appears to also decrease rapidly with increasing stress ratio. However, testing data confirms the beneficial effect of high tensile strength ¾ inch fibrillated polypropylene fibers in bridging microcracks and improving the ability of concrete to resist repetitive cyclic loading. Of the fatigue beams that survived the 2,000,000-cycle fatigue loading, static flexural testing indicate an increase in flexural strength for FRC

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which may or may not be attributed to increased cure time. What can be said, is that fatigue loading below the endurance limit stress ratio does not degrade the flexural strength of FRC and the beam will not fail in fatigue.

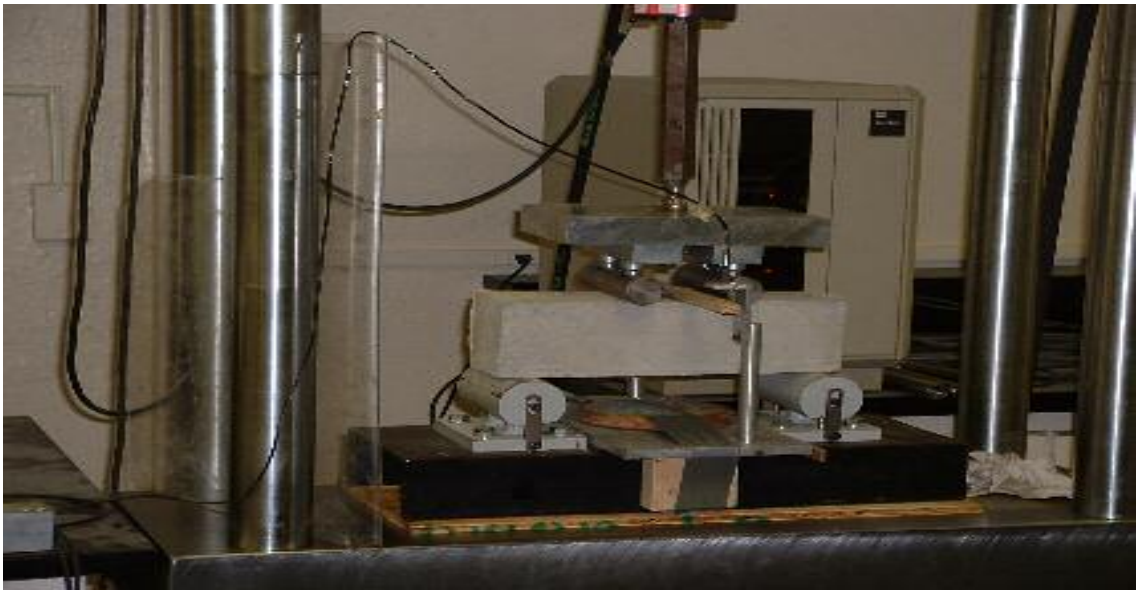

Figure 4.14: Cyclic Fatigue Loading of FRC.

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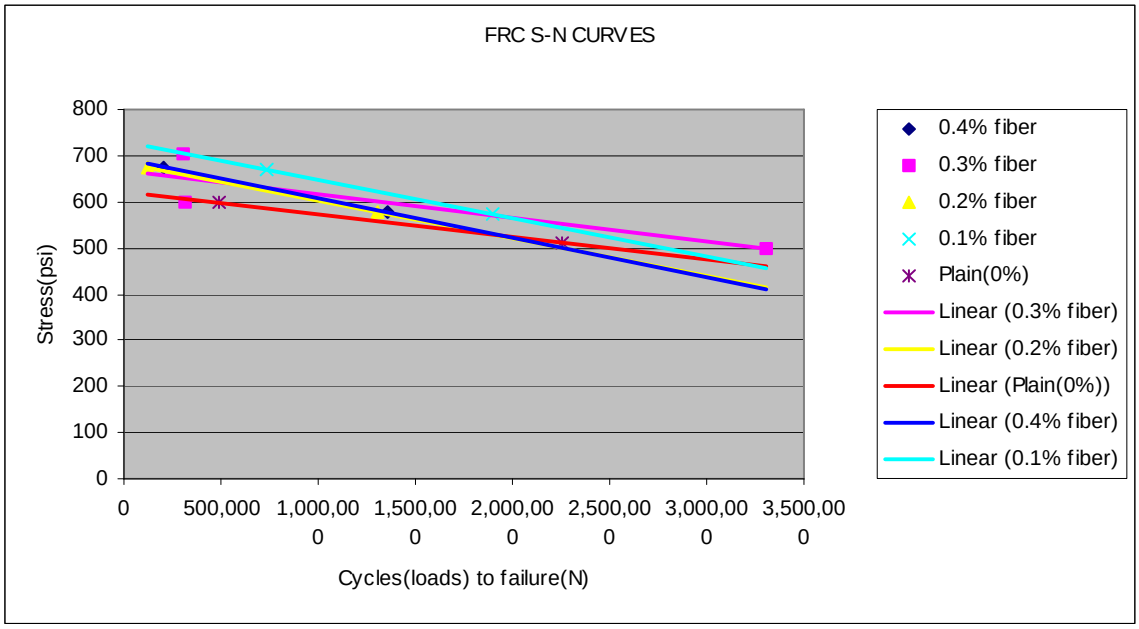

Figure 4.15: FRC Fatigue Stress/ Load Cycles to Failure Plot.

Figure 4.16: Fatigue Beam Specimens.

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COMPRESSIVE STRENGTH TESTING AND DUCTILITY OBSERVATIONS

ASTM C 39; Compressive Strength of Cylindrical Concrete Specimens determines the compressive strength of 6 inch x 12 inch concrete cylinders and is applicable to FRC. The results of this test are typically used as a basis for quality control of concrete proportioning, mixing, admixtures and placing ensuring compliance with specifications. Compressive strength is not an intrinsic property of concrete made of given materials, as it's strength value will depend on specimen size, mix proportions, temperature and curing. Therefore, interpretation of compressive strength results should be considered with limited significance[14].

Regarding FRC ductility, ACI 544.1 R-96 " Fiber Reinforced Concrete" American Concrete Institute Report by ACI Committee 544, May 1997; Chapter 4- Synthetic Fiber Reinforced Concrete (SNFRC) makes the following comments. Regarding compressive strength, polypropylene fibers at different quantities have no effect on compressive strength. However the fibers had a significant effect on the mode and mechanism of failure of concrete cylinders in a compression test. The fibers failed in a more ductile mode, particularly true for higher strength concrete where the cylinders endure large deformations without shattering[7].

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Standards.

1. ASTM C 39; Compressive Strength of Cylindrical Concrete Specimens determines the compressive strength of 6 inch x 12 inch concrete cylinders by applying a continuously increasing axial load to the specimen until failure occurs. ASTM compressive strength equipment and procedures (ASTM C31, C39, and C192) used for conventional concrete can be used for FRC. However, FRC cylinders should be made using external vibration.

2. ASTM C 192; Making and Curing Concrete Test Specimens in the Laboratory. Three specimens will be made for each test age and test condition. Specimen diameter should be three times the fiber length or maximum aggregate size.

Aging Period. Tests are conducted at 28 days after casting the concrete.

Aging Temperature. Mixing and Curing temperature (73.4°F).

Polypropylene Fiber Content. 0%, 0.1%, 0.2%, 0.3%, 0.4%

Aggregate Gradations. #57, #357

Slump. (ASTM C 143) Slump of Hydraulic Cement Concrete. However, FRC samples should also be tested by ASTM C 995; Time of flow through Inverted Cone test.

Air Content (ASTM C 138). However, FRC samples should be consolidated using external vibration.

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Summary of Results.

Compressive strength testing was undertaken on twenty-five, 6 inch X 6 inch X 12 inch concrete cylinders evaluating not only varying volumes of polypropylene fiber (0.1%. 0.2%, 0.3%, 0.4%) but the effects of varying water-cement ratio (high strength/normal strength), different aggregate gradation (#357/#57) and curing times; 28 to 37 days (Figure 4.17). On average, the compressive strength for 0.1%, 0.2%, 0.3% and 0.4% fiber reinforced concrete was 6,075 psi, 5,394 psi, 4,543 psi and 4,869 psi respectively. As compared to plain concrete strength of 5,339 psi, and high strength (0.4 water-cement) plain concrete; 5,446 psi (Table 4.6). The addition of fiber content beyond 0.2%, resulted in a corresponding decrease in compressive strength by 10% at 0.4 % fiber volume. A reduction likely due to the fiber's low elastic modulus (600 ksi) as compared to the concrete modulus (4,000 ksi). Also, the mode of cylinder failure was more ductile with increasing fiber content, crushing samples rather than failing them in shear. FRC cylinders endure large deformations without shattering, and composites with 0.4% polypropylene fiber content showed the greatest ductile behavior (Figure 4.18).

Table 4.6: Compressive Strength Values at Failure.

Cure Time	0.1 fiber	0.2 fiber	0.3 fiber	0.4fiber	plain #57	High Strength
19 days						
28 days	5,854	5,235			6,137	5,801
28 days	6,296	5,341			4,217	4,984
28 days					5,624	
28 days					5,377	
33 days		5,607	4,606	5,320		
33 days			4,439	5,041		
33 days			4,584	4,245		
37 days						5,554
Strength	6,075 psi	5,394 psi	4,543 psi	4,869 psi	5,339 psi	5,446 psi

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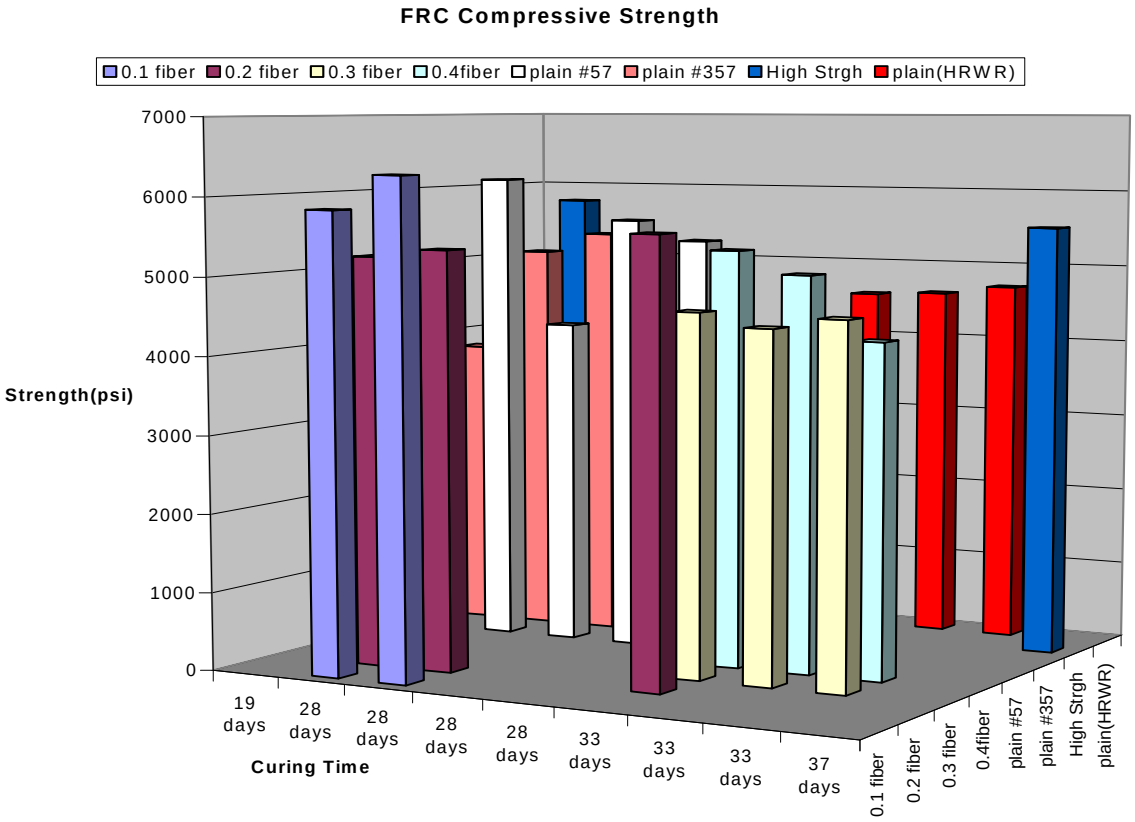

Figure 4.17: FRC Compressive Strength Test Results.

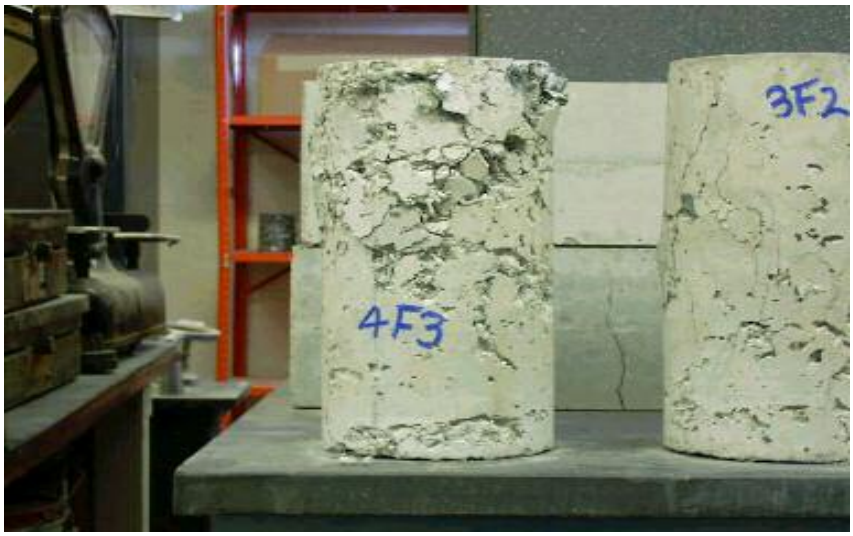

Figure 4.18: Ductile Cylinder Specimens.

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SHRINKAGE TESTING

An inherent material property of concrete when drying is shrinkage. The amount of shrinkage depends on a number of factors such as the size and age of the concrete specimen as well as environmental conditions such as temperature and humidity. If the concrete structure is restrained from shrinking, such as highway and airfield pavements, tensile stresses will develop causing the pavement to crack. Cracking is a major concern in airfield pavements due to loss of strength and degradation of the subgrade due to surface water seepage. Composite materials such as FRC have inherent properties that may resist volume change or tensile stresses and were investigated as part of this study. To obtain a quantitative indication of the ability of ¾ inch polypropylene fibrillated fibers to resist tensile stresses (cracking) by bridging shrinkage cracks the steel ring (Figure 4.19**)**, restrained shrinkage test was conducted. To obtain a relative indication of volumetric changes, the ASTM C 157 free shrinkage test was conducted for FRC specimens (Figure 4.20).

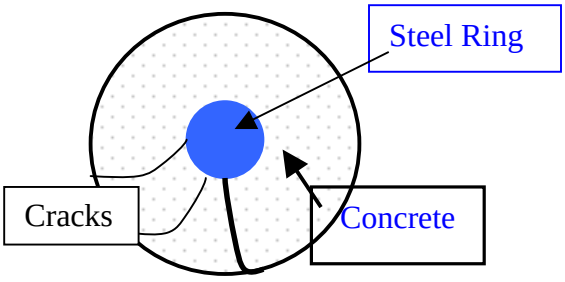

Figure 4.19: Steel Ring Test.

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Standards.

1. Unrestrained Shrinkage: ASTM C 157; Length Change of Hardened Hydraulic-Cement Mortar and Concrete.

2. Restrained Shrinkage. ACI has not declared a standard test for restrained shrinkage evaluation of FRC. The steel ring test can be used to monitor shrinkage and associated cracking that can occur within a few hours of placement. To ensure restraint cracking, specimen thickness should be 35 to 75 mm (3 inches or less) thick. Measure the number, width, location and spacing of cracks during the drying process.

Aging Period.

1. Store in the lime saturated bath for 28 days and measure length change. Additional measurements are taken at 24 hours, 8 weeks, then 16, 32, and 64 weeks for specimen water storage procedure.

2. For specimen air storage, measure length change at 24 hours, 4, 7,14 and 28 days. Additional measurements are then taken at 8 weeks, then 16, 32, and 64 week.

Aging Temperature. Temperature for curing specimens will be maintained at 73.4°F and at a relative humidity of 50 %.

Polypropylene Fiber Content. 0%, 0.1%, 0.2%, 0.3%, 0.4%

Aggregate Gradations. #57, # 357

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Free Shrinkage

ASTM C157/C 157M-99; Length Change of Hardened Hydraulic-Cement Mortar and Concrete permits assessment of potential volumetric expansion or contraction of concrete due to causes other than applied forces or temperature change. It is particularly useful in comparative evaluation of length changes in composites such as FRC under controlled laboratory conditions of temperature and humidity[14]. In our study we prepared twenty-seven, 6 inch X 6 inch X 21 inch concrete beams of varying fiber content 0%(plain), 0.1%, 0.2%. 0.3% and 0.4% using # 57 aggregate at a water-cement ratio of 0.44 and two sets (3 beams to a set) of 0.0%(plain) fiber beams using # 57 aggregate at a water-cement ratio of 0.4(high strength-low shrinkage) and at a different gradation (MD # 357) at 0.44 water-cement ratio. Beams were cured in water (100% humidity) for 28 days and then stored in a controlled 50 % humidity environment for an additional 28 days (Figure 4.20). Free shrinkage measurements were taken with a dial gage extensometer with a 10-inch gage length (comparator) on embedded brass studs in each beam (Figure 4.21). Measurements were taken in accordance with ASTM C 157 and free shrinkage was calculated on the basis of length change. It is assumed that the length of the specimen is much larger than the cross section dimensions, then shrinkage takes place only in one direction. These measurements of change in length with time are detailed and summarized in the following charts (Figures 4.24, 4.25). They provide a snapshot in time measure of one-dimensional shrinkage of this composite as compared to plain (0% fiber) concrete.

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Figure 4.20: Free Shrinkage Beam Curing.

Figure 4.21: Free Shrinkage Measurements with Extensometer.

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Restrained Shrinkage

There is presently no standardized procedure for quantifying the effects of polypropylene, or any other synthetic fiber, on plastic or drying shrinkage or on cracking that results from volume change under restrained shrinkage[7]. When concrete shrinks without being able to move, tensile stresses will arise. When the stresses cause the concrete to strain, cracking will occur. In principle, the steel ring test can be used to monitor the plastic shrinkage and associated cracking that sometimes occurs within a few hours of placement under adverse conditions of temperature, humidity, and wind speed causing high surface evaporation[4]. It can be assumed that the concrete ring is subject to approximately uniaxial stresses, when the steel ring restrains the shrinkage of the concrete annulus[7]. Twenty-one steel ring tests were conducted on plain and 0.1%. 0.2%, 0.3% and 0.4% fiber reinforced concrete samples. The steel ring was obtained by cutting a 12 inch steel pipe and the outer mold was a 16 inch cardboard Sonotube, which are typically used for column formwork in construction (Figure 4.22). Since the largest size aggregate in #57 gradation is 1 inch, the concrete ring was cast at 1.8 inch thick (< 2 inches) between the incompressible steel ring and the cardboard. Ring height was 5.5 inches, maintaining a 3 to1 ratio of ring height to thickness. The cardboard outer mold was stripped off 24 hours after casting the concrete ring and cured for 7 days in water (100% humidity). After the ring was removed from the water bath, the top surface of the concrete ring was sealed with plastic wrap and plumbers clay to promote drying in one direction only, the outer ring surface (Figure 4.23). The rings were air dried for six weeks at 35% relative humidity and a variable temperature of 80°F and cracking was monitored on the surface of the rings.

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Figure 4.22: Concrete Ring Sonotube Form.

Figure 4.23: Concrete Ring Specimen Curing.

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Summary of Results

In free shrinkage, the additions of polypropylene fibers do not significantly alter drying shrinkage as shown in the following charts (Figures 4.24/4.25). Grzybowski and Shah reported similar results and concluded that the primary advantage of fibers in relation to shrinkage is their effect in reducing the adverse width of shrinkage cracks[24]. Free shrinkage was lower for the high strength concrete due to the lower amount of water and more dense structure of the material, as most shrinkage is likely due to the loss of water during hydration. However, longer term studies (600 days) reported shrinkage strains were generally smaller for fiber (steel fiber) reinforced concrete as compared to plain concrete and shrinkage stopped at 500 days for fiber reinforced concrete whereas it continued to 600 days for plain concrete[19]. Long term, this may or may not also be true for polypropylene fiber.

The effectiveness of fibers under restrained shrinkage was observed. After the rings were air dried for six weeks at 35% relative humidity and a variable temperature of 80°F, no cracking was monitored on the surface of the rings. In order to induce cracking, we subjected the rings to a variable outside air temperature ranging from 32°F to 72°F at 35% to 40 % humidity for eight weeks with no visible sign of cracking in any samples. To induce cracking, plain and 0.2% fiber samples were then low temperature tested for seven days to –30 °Celsius, then 23° Celsius room temperature. Again no cracks were observed in any samples even after five months from casting. Indeterminate results for this test are attributed to the high strength of the concrete mix (low water-cement ratio) and size of aggregate (#357 aggregate) requiring up three inch thick concrete rings.

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Steel Ring results reported by Grzybowski and Shah[24],showed that small amounts of fiber could substantially reduce cracks and no cracking was observed during our testing. In the study, the average crack width of the specimen reinforced with 0.25% polypropylene fiber was 0.5 mm (0.016 inches) or one half the value of plain concrete, after six weeks. Additionally, the addition of very small volumes of fiber (0.1%) did not show any significant reduction in crack width or numbers of cracks. The reduction in cracking and crack width is significant in terms of the reducing the potential of FOD to high performance jet aircraft, due to deterioration of airfield surfaces, as well as loss of subgrade through cracks due to slab pumping from heavy lift cargo aircraft.

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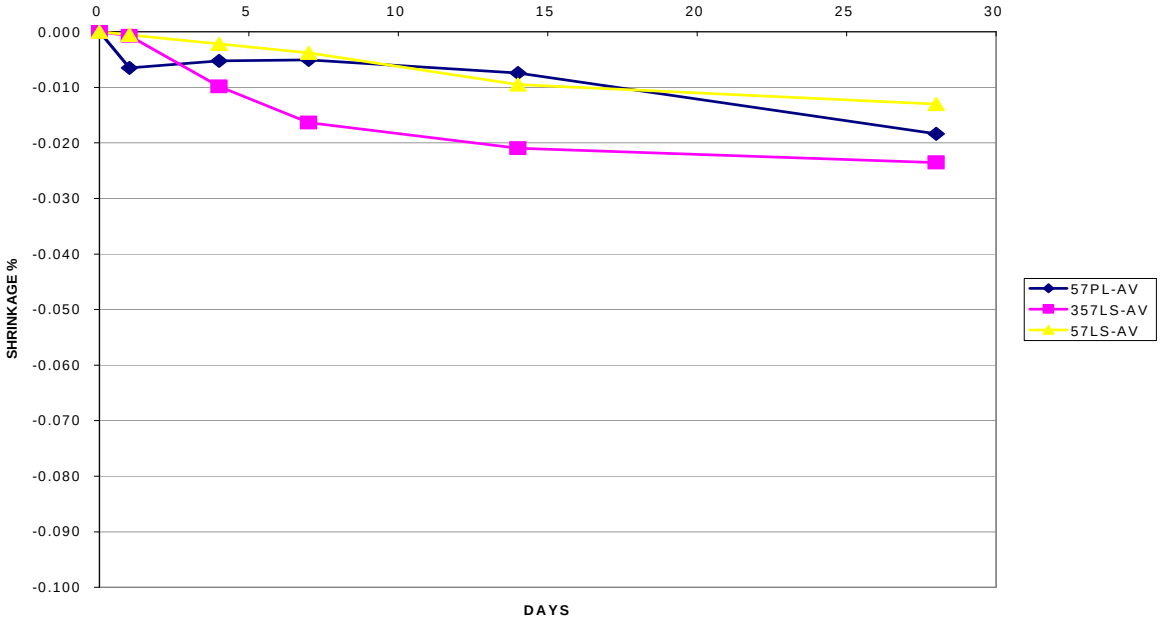

Figure 4.24: Plain (0% fiber) Free Shrinkage Test Results.
(Charts courtesy of Haejin Kim)

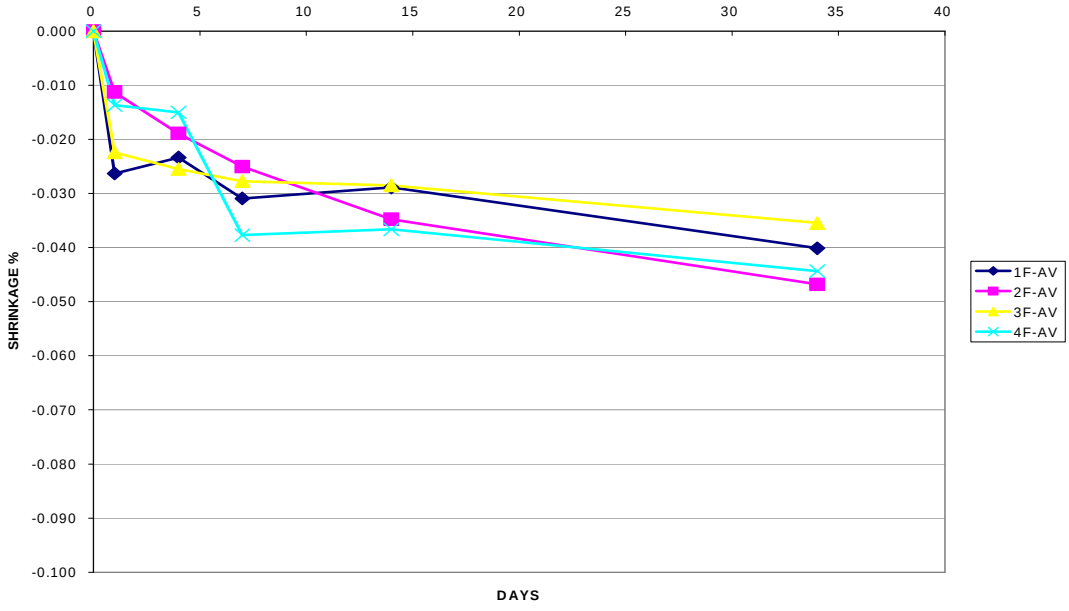

Figure 4.25: FRC (0.1%, 0.2%, 0.3%, 0.4%,) Free Shrinkage Test Results.

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CHAPTER 5. ANALYTICAL EVALUATION AND MODELING

INTRODUCTION

Although concrete is one of man's most common building materials, relatively little is known about damage accumulation to structures subjected to large numbers of load applications during their design life. Concrete deteriorates both in strength and stiffness under repeated load applications, especially if it is stressed well beyond half it's rupture modulus in tension (stress ratio > 0.5). Current research on plain and polypropylene fiber reinforced concrete (FRC) suggests that at fiber contents less than 0.5% and at stress ratios below 0.75, Miner's Rule is applicable. Miner's Rule presumes a linear accumulation of damage of materials like concrete until failure (cracking). Beyond stress ratios of 0.75 and fiber contents greater than 0.5%, damage accumulates in concrete in a pronounced, non-linear fashion and energy absorption capacity decreases almost exponentially[1].

Finite element analysis and performance modeling are detailed in this chapter for FRC pavement design thickness, corner deflections, thermal stresses, and explosive fracturing (heaved pavement). KenSlabs and LEDFAA computer programs can be used to build performance models to predict FRC material behavior and to establish minimum thickness criteria for rigid airfield pavements subjected to a specific aircraft loading for a stated design life. Through literature review and laboratory testing, material properties of

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varying volumes of low fiber content (<0.5%) concrete, such as Modulus of Elasticity (E), values for Modulus of Rupture (MOR), fatigue and toughness (1st crack strength) can be quantified to determine strength, thermal stresses, and fracture resistance characteristics of this composite. The objective of this chapter is to build performance models to evaluate FRC composites for strength, thermal stress and energy absorption at stress levels below 0.75.

FRC DESIGN THICKNESS PREDICTIONS

Conventional design (thickness) of concrete airfield pavement is based upon concrete's maximum flexural stress, the thickness and modulus of elasticity of base and subgrade soils, the aircraft's gross weight (with the load either parallel or normal to the edge of the slab), the volume of aircraft traffic, type of traffic area (runway, taxiway, apron) and allowable vertical slab deflection. Because of fiber reinforced concrete's increased fatigue strength, due to the bridging of fibers across cracks that develop, the thickness of concrete airfields can be significantly reduced. However, this results in a more flexible structure, which causes an increase in vertical deflections and potential for densification and/or shear failures in the foundation and pumping of the subgrade material. To protect against these factors, limiting deflection criteria must be applied. If the computed deflection is less than the allowable deflection, the airfield's thickness design is acceptable. If the computed deflection is larger than the allowable deflection, the thickness design for concrete must be increased or a modified value for the concrete's flexural strength or base/ subgrade modulus must be used. During this study, deflection

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and material property parameters are in accordance with TM 5-825-3/AFM 88-6 Chapter 3. Allowable vertical deflection of an airfield pavement section will not be greater than 0.05 inches and concrete's design flexural strength will be less than 900 psi for plain concrete. This ensures adequate pavement thickness to preclude subgrade pumping and design using average strength concrete mix values.

If Miner's Rule of linear damage accumulation is applicable for plain and polypropylene fiber reinforced concrete (FRC) at stress ratios below 0.75. It is reasonable to assume that a relationship exists between aircraft passes to failure (N) and the stress level as defined as the ratio of applied stress (tire contact pressure) and the static flexural strength of the concrete, the Modulus of Rupture (M.O.R.). The pavement stress level between an applied aircraft's tire contact pressure and between varying volumes of low fiber content (<0.5%) concrete, and their respective values for Modulus of Rupture (MOR) is the important input values for KenSlabs or any FEM pavement design modeling. Typically in pavement design, the applied stress value (tire contact stress) and the concrete's MOR is used to determine thickness for a specific aircraft or mix of aircraft. Such a relationships could be expressed mathematically in the form of a thickness to stress level equation to establish minimum thickness criteria for rigid airfield pavements subjected to a specific repetitive aircraft loading for a stated design life. Since damage accumulates in a linear fashion below stress ratios of 0.75, as mentioned previously, pavement failure (Nf) under a stated design wheel load (tp) for a given pavement's static flexural strength (Sc), will show a linear relationship for pavement life prediction (tp/ Sc < 0.7 stress levels).[2]

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General Form of the Derived Equation for FRC Design Thickness

Through static flexural and fatigue testing and Finite Element Method computer modeling, mathematical relationships were established to determine airfield design thickness criteria for FRC pavements at fiber contents of 0%, 0.1%, 0.2%, 0.3% and 0.4% and at stress levels of less than 0.7 for given aircraft wheel loads (see Figure 5.5). The equations were derived by using the KenSlabs' damage analysis program, inputting aircraft gear geometry, loading stress (contact pressures) at five different stress levels (0.29,0.39, 0.49,0.59,0.69) as a function of the modulus of rupture (MOR) of plain (0% fiber) concrete for a given mix (Table 4.1). Chapter two of this dissertation explains the root operating equation for the KenSlabs Damage Analysis program. The relationship of loads to failure (N), the tensile stress imposed at the base of the slab at failure and the Modulus of Rupture of the FRC material being evaluated and is expressed mathematically as equation 5.1. Similar fatigue equations and coefficients (f,f î) values have been developed by the Portland Cement Association (PCA) showing a relationship between stress ratio (σ/ Sć) and vehicle passes to failure (N)[2] . Additionally, these fatigue values and models are used by researchers, such as the PCA and the Corps of Engineers to establish a relationship between the maximum loading stress (σmax) to the modulus of rupture which they define as the stress level (S) as derived from the Wholer equation (Equation 5.2). Where a and b are experimental coefficients that vary with loading conditions, compression, tension, or flexure, to predict the fatigue life of pavements[38].

$$\text{Log } N = f\,\hat{i} - f\,(\sigma / S\acute{c}) \qquad (5.1)$$

$$S = \sigma max/MOR = a - b \log (N) \qquad (5.2)$$

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Using KenSlabs, similar a-b coefficients can be derived for a given aircraft based on its unique pavement loading characteristic in order to predict the fatigue life of a given concrete pavement based on its material properties. Essentially this is done by manipulating the KenSlabs damage analysis program by holding the failure tensile stress (σ) and loads to failure (N) values constant and determining new coefficients from modeling reflecting each aircraft's unique gear geometry and tire pressure loading similar to the Wholer equation. The output value then becomes pavement design thickness (Tc) based on aircraft gear and tire pressure as a function of the material properties (MOR, fatigue strength (fv)) of an FRC pavement (Figure 5.5). Through modeling of five different aircraft, through 80 different KenSlabs modeling runs, pavement thickness to stress level charts were developed and are presented in this chapter defining a common linear relation of stress level (0.29,0.39, 0.49,0.59,0.69) to pavement thickness properties for each given aircraft at concrete's endurance limit (Nf $\geq$ 2,000,000). This is determined through iterative KenSlabs fatigue damage design thickness modeling to determine the optimum rigid pavement thickness (Tc) that will produce a tensile strength at the base of the slab to achieve 2,000,000 passes of a given aircraft. If the airfield thickness is to small, the tensile stress will be to great and the stress ratio (Sr) to high so the endurance limit will not be reached. If the Tc is to large, the stress ratio will be to low and the aircraft loading enters a no failure condition (Nf = unlimited) indicating overdesign. This process is illustrated in Figures 5.8 and 5.12 and the resulting equations can be used to quantify pavement design thickness reduction values for any given aircraft gear geometry and tire pressure as a function of the difference in flexural strength (MOR) of any given FRC material (0.1%, 0.2%,0.3%,0.4% fiber content). Additionally, the

framework of the equation can support integration of laboratory derived endurance limit (fatigue strength/MOR plain concrete) values from 2,000,000 cycle FRC laboratory specimen fatigue testing to determine Pavement Reduction Values (PRV) using fatigue strength Indices [(f max/ fv max]½ to the general thickness equation for plain concrete presented in this Chapter. In this case, the general equation considers the actual tire contract stress and MOR for plain concrete to determine the stress level to calculate pavement thickness (Equation 5. 8). This thickness is then reduced by the fatigue strength Indices, and the PRV is then determined by comparing the results from each fiber case to plain concrete design thickness.

The value of these predictive design thickness (Tc) equations is to quantify in a rational sense the relative benefits of varying volumes (0%, 0.1%, 0.2%, 0.3%, 0.4%) of fiber reinforcement in terms of pavement thickness reduction (PRV) values under a given critical aircraft loading. This tells us the difference in pavement thickness due to fiber's contribution at a stress ratio at the endurance limit ($Nf \geq 2{,}000{,}000$) for later use in determination of an airfield design thickness for a no pavement failure condition due to aircraft loading. These derived design thickness equations (Tc) are not intended to be pavement design equations in the conventional sense, but allow development of FRC-PRV values that can then be used with any concrete pavement thickness design to reduce that design thickness. The FRC-PRV values give design thickness reduction credit for the fibers enhanced flexural and fatigue strength characteristics exhibited by fiber concrete composites as compared to plain (0% fiber) concrete. Examples of the FRC- PRV design

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thickness reduction methodology are presented in this Chapter and a case study in FRC-PRV thickness reduction for the C-17 Aircraft is contained in Chapter Six.

Constraints were placed on the KenSlab damage analysis program limiting pavement deflection to 0.05 inches and demanding a minimum of 2,000,000 aircraft passes. To determine the deflection criteria (0.05 inches) used in the above mentioned computer program, the joint use U.S. Army Technical Manuel ™ 5-825-3/ Air Force Manuel (AFM) 88-6 Rigid Pavements for Airfields [6], was consulted. Specifically, Chapter 4; Fibrous Concrete Pavement Design using the aircraft design charts and deflection tables as shown in Table 1.1. A minimum of two million aircraft passes were selected to match FEM modeling results with laboratory testing protocols for fatigue testing values at the endurance limit. Resulting design thickness for each stress level was graphed (Figure 5.5) yielding the predictive linear equation on pavement thickness as a function of a fiber-concrete composite's material properties and specific aircraft loading. Such equations establish minimum thickness (Tc) for no failure pavement design life and to limit pavement deflections that prevents subgrade failure, such as pumping. The coefficients that emerged were defined as L and D coefficients, L due to its association with the stress level design life (tp/ Sc) variable of the pavement equation and the constant was called D as the value for deflection control. These equations account for the effect of fiber reinforcement bridging microcracks in concrete under cyclic loading causing a strength increase, and the fiber's effect in increasing pore and microcrack density causing a strength decrease. This fiber effect was established as the difference between the maximum FRC composite fatigue strength (defined as fv) and the maximum

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concrete fatigue strength (defined as fmax) of plain (0%fiber) concrete. The ratio's obtained, as a percentage of the Modulus of Rupture (fv/Sc**)** is better known as the endurance limit, normalized in terms of the strength of plain concrete. Based on laboratory derived static flexural and fatigue strength values, FAA's LEDFAA v1.2 and KenSlabs finite element computer programs for rigid pavements were run to calculate thickness criteria to support a 20-year design life (Nf $\geq$ 2,000,000) for different mix of aircraft. Thickness values using polypropylene fiber concrete at 0.1%, 0.2 %, 0.3%, 0.4% volumes and plain concrete were computed. The linear equation when graphed by aircraft becomes Equation 5.3. A design thickness equation defining the relationship for a given aircraft's gear geometry and tire pressure as it pertains to the material properties of an FRC composite (MOR, fatigue strength (fv)) in terms of stress level to rigid airfield pavement thickness at the endurance limit. The purpose of the thickness equation was to create FRC pavement reduction values (PRV), not to create a new rigid pavement design equation in the conventional sense.

$$T\ (\text{concrete}) = [L\ (tp/\ Sc) + D] \qquad (5.3)$$

Derivation of the laboratory fatigue pavement reduction values; [(f max/ fv max] ½ has it's root from ASTM C-78 Modulus of Rupture equation (Equation 5.4) and the rectangular section modulus of a beam defined by the term $Z = bd^2/6$ in calculations for bending moment (Equation 5.5) to failure in a testing machine as it pertains to maximum flexural stress (fmax) obeying Hooke's law[39]. The maximum flexural stress (fmax) can be expressed as $6M/bd^2$, or Equation 5.6 where M = PL/4 . Equation 5.6 then defines the specimen thickness d, equal to $\sqrt{6PL/4b}$ (fmax). Since flexural stress varies directly with the distance of the section from the neutral axis, in this case the equation can be

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expressed as by the term $\Delta d = \sqrt{6PL/4b[(1/f\ max)½ - (1/fv)½}$] or Equation 5.7 when considering the improvement in fatigue strength due to FRC material properties. Substituting d from beam analysis for Tc from Equation 5.3, the equation then becomes Equation 5.8 for quantifying the reduction in pavement thickness for a given aircraft due to the improved material properties of a fiber-reinforced composite. Both applications of the equation, flexural and fatigue then yield design thickness values that quantify the beneficial properties of FRC under static and dynamic loading conditions relative to the design thickness for plain (0% fiber) concrete.

Determine the maximum fiber stress for third point loading

$$MOR = PL/bd^2 \text{ or } (fmax) = M/Z \quad (5.4)$$

Determine bending moment for a rectangular section

$$M = PL/4 \text{ where } Z = bd^2/6 \quad (5.5)$$

Determine maximum bending stress

$$(fmax) = 6M/bd^2 = 6PL/4\,bd^2 \quad (5.6)$$

Determine the difference in thickness due to fiber's enhanced fatigue strength yields

$$\Delta d = \sqrt{6PL/4b(fmax)\,[1 - f\ max/fv]}\ ½ \quad (5.7)$$

Apply the thickness reduction indices as a ratio of fatigue stress values (plain/fiber case)

$$T\ (concrete) = [L\ (tp/Sc) + D\ ]\ [(f\ max/fv\ max]½ \quad (5.8)$$

KenSlabs Damage Analysis Input and Output Values for Design Thickness Equation.

To determine the most critical loading case for airfield concrete slabs, three different loading positions (interior, corner and edge loading) were considered in

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accordance with Westergaard's analytical solutions for stresses and deflection prior to KenSlabs modeling. Fatigue damage based on edge stress (Figure 5.1), between the transverse joints was selected as the most critical location for tensile stress. The critical deflection occurs at the slab corner when the aircraft load is applied at that location[2].

A typical rigid airfield pavement profile for KenSlabs modeling consists of a concrete slab, treated base, stabilized granular subbase and the natural soil. Typically, the standard concrete airfield slab is 25 feet by 25 feet by 17 inches thick with a Young's Modulus (E) set at 4,000 ksi and a Poisson's Ratio of 0.15. An 8-inch Stabilized base with a Young's Modulus (E) set at 500 ksi and a Poisson's Ratio of 0.2 and an infinite subgrade with a Young's Modulus (E) set at 4,500 psi and a Poisson's Ratio of 0.35. Minimum values established by the Federal Aviation Administration (FAA) include a 20-year rigid pavement design life, a minimum six inch thick concrete surface with a base thickness of four inches[40]. According to Huang, PCA claims that freeze-thaw conditions have little significance in reducing the subgrade modulus and rigid pavement damage due to spring thaw [2], so the base thickness will be kept at eight inches. This will ensure that an adequate capillary barrier is maintained under the slab when using a seasonal adjustment factor in the KenSlab model of 0.8 or less (less than 20% damage to subgrade from spring thaw)[2]. A description of each KenSlabs model input and output parameters were discussed in Chapter 3. A description of the KenSlabs damage analysis program operating characteristics is contained in Chapter 2. In the analysis, the following input values were considered.

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1. Aircraft Gear Geometry. After slab dimensions coordinates and critical nodes are inputted into the slab grid, aircraft gear and tire pressure values are superimposed. The slab size is 24'X24', with symmetry about the Y-axis. Aircraft with high tire pressure loading were considered; Boeing 777, Boeing 747, Boeing C17, Lockheed Martin C141, and Lockheed Martin F-16 aircraft.
2. Load variables. Applied contact stress values inputted as tire pressure values, calculated to produce stress levels 0.69,0.59.0.49,0.39,0.29 of the inputted modulus of rupture values for plain concrete from laboratory testing (MOR= 868 psi). PCA default fatigue coefficients of 17.61 for plain concrete are used in KenSlabs which defines the 50% probability of fatigue failure line between stress ratio and loads to failure (N) from a wide spectrum of concrete specimen fatigue test data[2].
3. Traffic. In the analysis, minimums of 2,000,000 aircraft passes were selected to match endurance limit values for fatigue strength as determined in the laboratory. Allowable pavement deflection was set at 0.05 inches in accordance with Table 1.1, Chapter 1.
4. Material Properties. The following properties were considered. Average concrete Modulus of Elasticity (E) of 4,000,000 psi, Poisson ratio, 0.15, MOR of 868 psi for plain concrete, thermal expansion 0.000005 inch/inch, Base modulus; 500,000 ksi , Base Poisson ratio, 0.2.
5. Environmental Adjustment factor. A 15% seasonal reduction in base/subbase strength due to spring thaw was considered.
6. Iterative KenSlabs damage analysis output runs are made until a design thickness is found that allows at least 2,000,000 aircraft passes for a given gear geometry, and at five different applied contact stress values for a given tensile stress ratio. Resulting

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values are graphed and tabled (Figure 5.5 /Table 5.3) to determine the equation for predicting pavement design thickness reduction values under varying material properties (MOR, fatigue strength) and aircraft tire pressures by fiber case. Output summary of the design thickness Figures, Tables and corresponding T (concrete) = [L (tp/ Sc) +D] equations and L/D coefficients are as follows for each aircraft.

- Critical aircraft: Boeing 777 (Figure 5.5 / Table 5.3)

  T (concrete) = [16.7 ”(tp/ Sc) +4.4”]

- Boeing 747 (Figure 5.6 /Table 5.4) T c = [16.5”(tp/ Sc) + 4.5”]
- Lockheed Martin F-16 aircraft (Figure 5.8 /Table 5.5) Tc = [13.6”(tp/ Sc) +4.6”]
- Lockheed Martin C-141 (Figure 5.11 /Table 5.6) Tc = [17”(tp/ Sc) +5”]
- Boeing C-17 (Figure 5.12 /Table 5.6) T c = [17.7”(tp/ Sc) +5.9”]

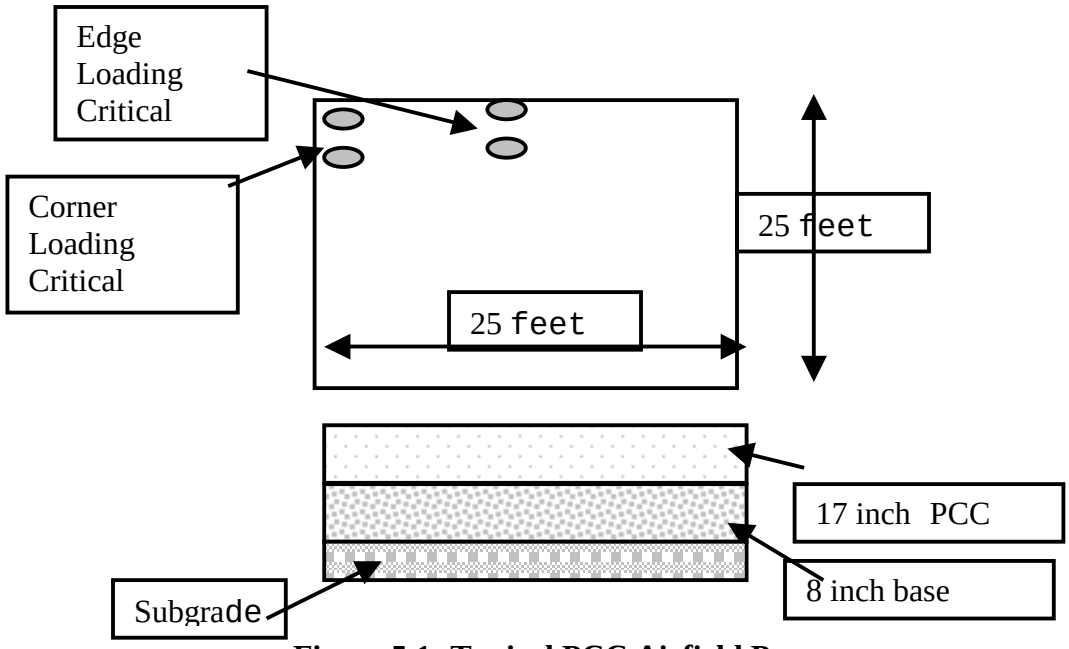

Figure 5.1: Typical PCC Airfield Pavement.

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The general form of the derived equation for FRC design thickness is then.

$$T\ (concrete) = [\ L(tp/\ Sc) + D\ ]\ [(f\ max/\ fv\ max]^{½} \qquad (5.8)$$

For $tp/\ Sc < 0.7$ stress levels [stress ratio <0.50]

Where;

T (concrete) = Rigid airfield pavement design thickness(inches).
L(tp/ Sc) +D = minimum pavement thickness(inches) to control design life (L) & deflection (D) in plain concrete(0% fiber).
tp = Aircraft tire pressure in psi.
Sc = Modulus of Rupture plain concrete (psi).
fv = fiber volume (0.1%, 0.2%, 0.3%, 0.4%) laboratory derived maximum fatigue strength (psi) at 2,000,000 cycles.
fmax = laboratory derived maximum fatigue strength (psi) at 2,000,000 cycles for plain concrete.

Constraints on the Proposed Design Thickness Equation

Fiber reinforced concrete as a structural element in airfield pavements lacks a long-term performance history. Unlike conventional plain concrete, fatigue coefficients have not evolved like those proposed by Haung and the Portland Cement Association (PCA) for fiber composites based on a wide range of differing mix designs. Additionally, fatigue coefficients are at best an approximation of concrete's failure probability due to loads to failure at different stress ratios from empirically derived data. Chapter five presents aircraft specific thickness equations used to determine average pavement thickness reduction values (PRV) at various fiber contents, derived using the concrete fatigue coefficients of 17.61 as recommended by Haung for KenSlabs. Additionally, material properties such as differing Modulus of Elasticity values for varying fiber

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volumes were averaged, as the objective was to propose generic PRVs that could be tabulated for use at any military or civilian airfield location, based on laboratory test data typically available to engineers such as modulus of rupture of a given mix design. The goal was to develop PRVs for each fiber case that could be applied to any conventional, airfield design thickness program like LEDFAA. Using only data typically available to engineers, such as an aircraft's tire pressure and gear geometry as well as a concrete's Modulus of Rupture value based on mix, pavement thickness reduction credit could be given to any conventional concrete design based on fiber volume selected.

Tables 5.1 was constructed using design mix MD-7 specific material property values to demonstrate that the above generic, average value approach produces PRVs that are conservative in estimating design thickness reduction due to fiber. The corrected FRC fatigue coefficients in these tables are based on data from only one design mix strength and do not represent a broad spectrum of mix designs and fatigue strengths as used by Huang for KenSlabs. FRC researchers (Grzybowski and Meyer[1]) do not consider it proper to use such fiber fatigue coefficients if they are based on limited test data; fatigue data from just one mix design. FRC Modulus of Elasticity and Rupture (MOR) values presented are also mix and specimen size dependent. During KenSlabs modeling, it was noted that changes in elasticity and fatigue coefficient values between fiber cases do not have the effect on design thickness as does differing values for the MOR between composites. As such, with each aircraft specific fatigue thickness equation presented in this chapter, a comparison of results is made with flexural strength values by fiber case (Equation. 5.12 through 5.26).

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Haung also concludes that loads to failure (Nf) at stress ratios (S) below a given value is infinite (ie pavement failure is not affected by additional aircraft passes). According to Haung, the Portland Cement Association states that for a stress ratio (S) $\leq$ 0.45 the allowable number of load repetitions are unlimited (Nf $\geq$ 2,000,000). Even at stress ratios of S < 0.50, no limit to loads to failure (Nf) were found to 10-20 million cycles under third point loading[2]. The results presented in Table 5.2 are at S $\leq$ 0.46 (403 psi /868 psi) which implies a no failure loading condition for the pavement is expected beyond 2,000,000 aircraft passes. As can be seen in Table 5.2, there is little impact on pavement thickness at higher load repetitions, such as three million cycles, or deviation in the slope of the pavement thickness – material behavior line (Figure 5.2, Figure 5.3).

Table 5.1: Thickness Reduction for Boeing 777; MD-7 Mix.

FRC beams 4"x 4"x14" (MD-7 mix)	**MOR**	**Modulus of Elasticity (psi)**	**FRC MD-7 Fatigue Coefficients (f 1/ f 2)**	**777 Design Thickness at 182 psi Tire Pressure (Kenslabs)**	**Design Thickness Reduction**
Plain	868 psi	4,158,817	10.24 / 6.6	7.06”	----------
0.1 % Fiber	970 psi	4,382,465	8.76 / 4.2	6.30 ”	0.76 inch
0.2 % Fiber	981 psi	4,179,904	13.05 / 11.57	6.15”	0.9 inch
0.3% Fiber	1,017 psi	3,735,295	8.88 / 5.15	< 6.0”	1.0 inch
0.4% Fiber	980 psi	3,830,317	10.97/ 8.2	6.0”	1.0 inch

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Table 5.2: Thickness Edge Stress Results - Boeing 777 Aircraft.

Stress Level (MOR = 868 psi)	Contact Stress (σmax) (Applied Stress)	Tensile stress at failure(σ) (1 st Crack Failure)	Kenslabs Computed Design Thickness (2 Million Cycles)	KenSlabs Computed Design Thickness (3 Million Cycles)
0.69	608 psi	403 psi	Tc= 15.86 inches	Tc= 15.93 inches
0.59	512 psi	403 psi	Tc= 14.29 inches	Tc= 14.50 inches
0.49	425 psi	402 psi	Tc= 12.81 inches	Tc= 13.05 inches
0.39	338 psi	402 psi	Tc= 11.08 inches	Tc= 11.15 inches
0.29	252 psi	402 psi	Tc= 8.92 inches	Tc= 8.99 inches

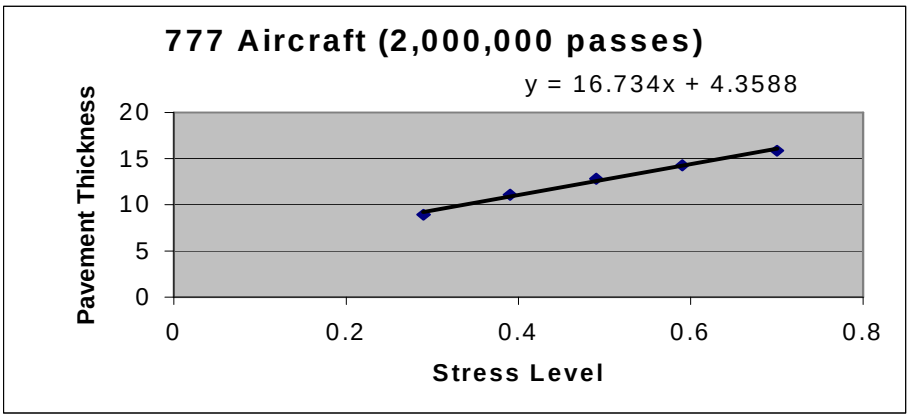

Figure 5.2: Boeing 777 Design Thickness (MD-7 Mix Design).

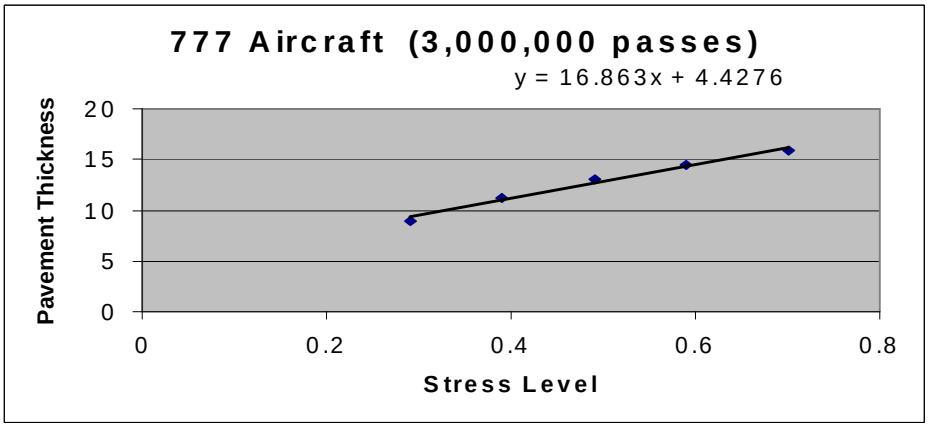

Figure 5.3: Boeing 777 Design Thickness (3,000,000 passes).

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FRC Predictive Pavement Thickness Equations; Boeing 777 and 747 Aircraft

The main landing gear of the Boeing 777 aircraft is unique, with two sets of six wheels arranged in a tridem (3 pairs of wheels in a row) configuration. The spacing between each wheel in the tridem is 57 inches. The spacing between the two-tridem rows is 55 inches. Gross aircraft weight can be 537,000 lbs, typically each wheel load equals 42,500 lbs. with a tire pressure of 182 psi and a tire contact radius area of 8.62 inches. In terms of aircraft passes, 100,000 annual departures were considered for 20 years. KenSlabs pavement responses are for a single wheel, however the principle of superposition (Figure 5.4) was utilized to determine pavement responses corresponding to the tridem gear configuration.

The main landing gear of the Boeing 747 aircraft is a four, dual tandem gear (2 pairs of wheels in a row) configuration. The spacing between each wheel in the tandem is 44 inches. The spacing between the two tandem rows is 54 inches. Dual tandem wheels were assigned a tire pressure of 189 psi, with each wheel load of 44,000 lbs. applied over a tire contact radius area of 8.62 inches[41].[42] The principle of superposition was utilized to determine pavement responses corresponding to the tandem gear configuration.

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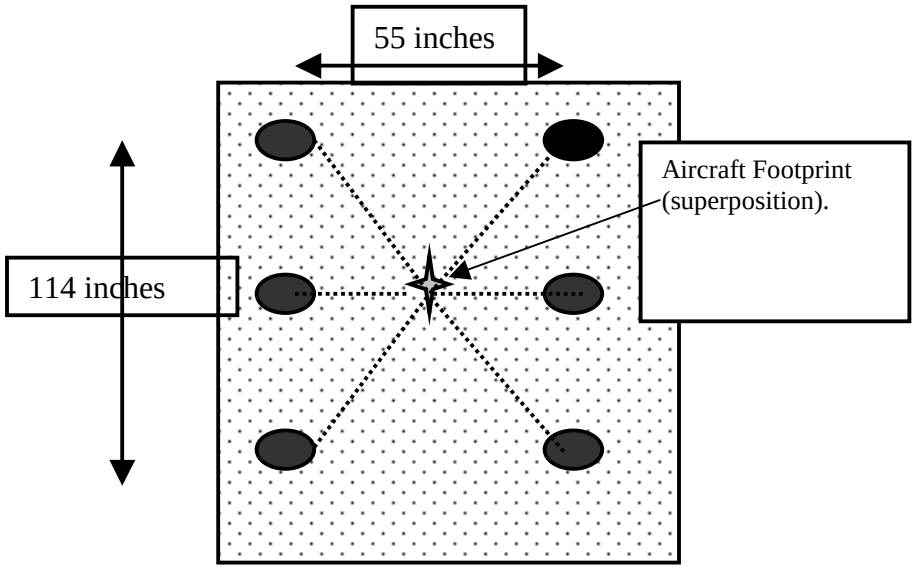

Figure 5.4: Tridem Gear Configuration (Boeing 777).

Analysis for Boeing 777 Aircraft

KenSlabs analysis confirmed a linear relationship between stress level and rigid pavement thickness subjected to the Boeing 777 aircraft footprint for edge loading for a maximum slab base tensile stress of 403 psi (Table 5.3). When graphed (Figure 5.5), yielded a design thickness to stress level trend line equation of y= 16.734x + 4.3588. Specifically, in compliance with FAA's six-inch minimum pavement thickness, adequate deflection control (< 0.05 inches) was maintained. Additionally, the design life thickness/minimum deflection L-D coefficients were defined (Figure 5.5) as 16.7 inches and 4.4 inches respectively (T = 16.734(tp/ Sc) + 4.3588) for the Boeing 777 aircraft. This equation also allows determination of airfield pavement thickness as a function of modulus of rupture value by fiber case, which is the current methodology used by most

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finite element programs or performance model building using laboratory derived fatigue strength testing results. Therefore, for predicting a 20-year design life for a rigid airfield pavement (0% fiber) for this aircraft, the equation becomes;

$$T\ (\text{concrete}) = [16.7\ ”(tp/\ Sc) + 4.4”]\ [\ f\ max/\ fv\ max)]^{½} \qquad (5.9)$$

for $tp/\ Sc < 0.7$ stress levels [stress ratio <0.50]

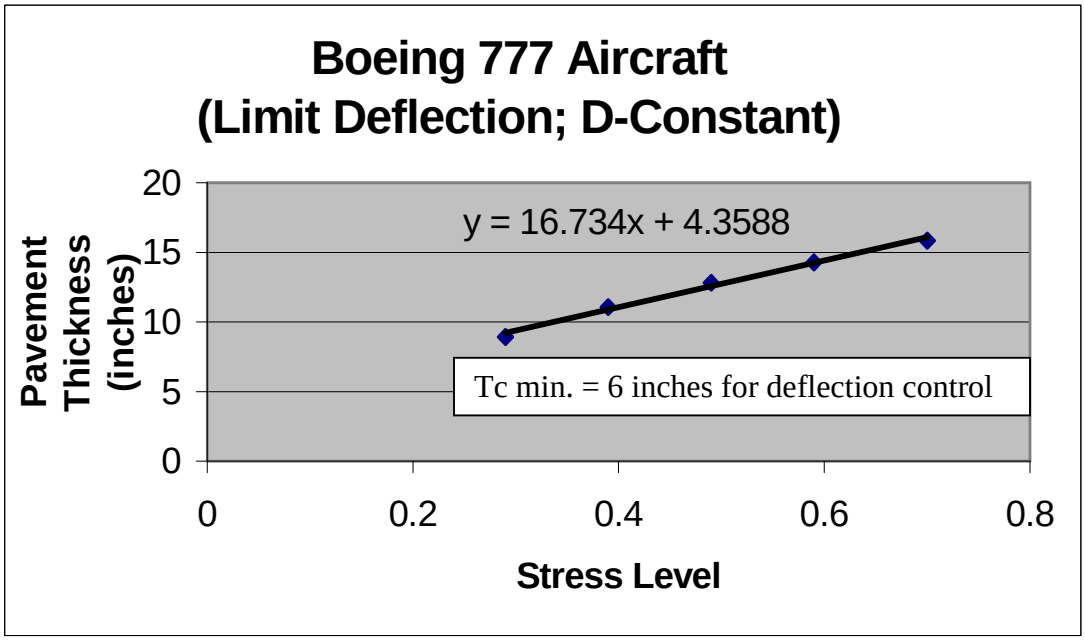

Figure 5.5: Boeing 777 Aircraft Design Thickness Graph.

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Table 5.3: KenSlabs Edge Stress Results; Boeing 777 Aircraft.

Stress Level (σmax/ MOR)	Contact Stress (σmax)	Tensile stress at failure(σ)	Modulus of Rupture(0% fiber Concrete)	KenSlab Computed Design Thickness
0.69	608 psi	403 psi	868 psi	Tc= 15.75 inches
0.59	512 psi	403 psi	868 psi	Tc= 14.29 inches
0.49	425 psi	402 psi	868 psi	Tc= 12.81 inches
0.39	338 psi	402 psi	868 psi	Tc= 11.25 inches
0.29	252 psi	402 psi	868 psi	Tc= 9.25 inches

Pavement Thickness in Function of the Static FRC Flexural Strength

This equation allows determination of airfield pavement thickness as a function of static flexural strength (Sc). The equation for the Boeing 777 Aircraft simply becomes;

T (concrete) = [16.7"(tp/ Sc) +4.4"]; for plain (0% fiber) concrete (inches). (5.10)

And for fiber reinforced concrete;

T (concrete) = [16.7"(tp/ Sc-fiber) +4.4"]; (5.11)
Sϵ fiber = fiber volume (0.1%, 0.2%, 0.3%, 0.4%) MOR (psi).

As example, using ASTM C-78 laboratory testing results the static flexural strength of 0%, 0.1%, 0.2%, 0.3%, 0.4% fiber reinforced concrete in 4"X4"X14" concrete specimen beams was established as 868 psi, 970 psi, 981 psi, 1,017 psi and 980 psi respectively. Based on KenSlabs analysis, airfield pavement thickness for edge loading of a Boeing 777 aircraft for 2,000,000 passes is as follows:

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T (plain concrete) = [16.7”(182 psi/ 868 psi) +4.4”] = 7.9 inches (5.12)

T (0.1% fiber concrete) = [16.7”(182 psi/ 970 psi) +4.4”] = 7.5 inches (5.13)

T (0.2% fiber concrete) = [16.7”(182 psi/ 981psi) +4.4”] = 7.5 inches (5.14)

T (0.3% fiber concrete) = [16.7”(182 psi/ 1,017 psi) +4.4”] = 7.4 inches (5.15)

T (0.4% fiber concrete) = [16.7”(182 psi/ 980 psi) +4.4”] = 7.5 inches (5.16)

Other laboratory testing results for static flexural strength of 0%, 0.1%, 0.2%, 0.3%, 0.4% fiber reinforced concrete in 6”X6”X21” concrete specimen beams was established as 725 psi, 692 psi, 731 psi, 757 psi and 728 psi respectively. In this case, airfield pavement thickness for the Boeing 777 aircraft would be.

T (plain concrete) = [16.7”(182 psi/ 725 psi) +4.4”] = 8.6 inches (5.17)

T (0.1% fiber concrete) = [16.7”(182 psi/ 692 psi) +4.4”] = 8.8 inches (5.18)

T (0.2% fiber concrete) = [16.7”(182 psi/ 731psi) +4.4”] = 8.6 inches (5.19)

T (0.3% fiber concrete) = [16.7”(182 psi/ 757 psi) +4.4”] = 8.4 inches (5.20)

T (0.4% fiber concrete) = [16.7”(182 psi/ 728 psi) +4.4”] = 8.6 inches (5.21)

Analysis has shown up to a ½ inch reduction in airfield pavement thickness by use of 0.3% polypropylene fiber as compared to plain (0%) concrete (Equation 5.15). In construction of a 10,000 foot- 300-foot wide runway, this equates to a reduction in 4,630 cubic yards of concrete for a 20-year design life rigid pavement for this aircraft. In terms of present economics, $ 694,444 savings in construction costs using a $150/ Cubic Yard (CY) unit cost.

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Pavement Thickness in Function of FRC Fatigue Strength (fv max)

As example, repetitive load testing established the fatigue strength of 0%, 0.1%, 0.2%, 0.3%, 0.4% fiber reinforced concrete in 4”X4”X14” concrete specimen beams as 521 psi, 570 psi, 525 psi, 567 psi and 513 psi respectively at 2,000,000 cycles. Based on the KenSlabs analysis, airfield pavement thickness for edge loading of a Boeing 777 aircraft for 2,000,000 passes is as follows:

T (plain concrete) = [16.7 ”(182 psi/ 868 psi) + 4.4”][521/ 521psi)] ½ = 7.9” (5.22)

T (0.1% fiber conc.) =[16.7 ”(182 psi/ 868 psi) + 4.4”] [521/ 570psi)] ½ = 7.5” (5.23)

T (0.2% fiber conc.) = [16.7 ”(182 psi/ 868 psi) +4.4”] [521/ 525psi)] ½ = 7.9” (5.24)

T (0.3% fiber conc.) = [16.7 ”(182 psi/ 868 psi) + 4.4”] [521/ 567psi)] ½ = 7.6” (5.25)

T (0.4% fiber conc.) = [16.7 ”(182 psi/ 868 psi) + 4.4”] [521/ 513psi)] ½ = 8.0” (5.26)

Dynamic loading has shown a 0.4-inch reduction in airfield pavement thickness for the 0.1% polypropylene FRC and a 0.3-inch reduction at 0.3% fiber content in concrete. Over a 10,000 foot- 300-foot wide runway alone, reductions of 3,241 cubic yards of concrete for construction of a 20-year design life rigid pavement for this aircraft. In terms of present economics, $ 486,111 savings in construction costs.

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Analysis for Boeing 747 Aircraft

Kenslabs modeling defined the relationship between stress level and rigid pavement thickness subjected to the Boeing 747 aircraft footprint for edge loading (Table 5. 4). The L-D coefficients were defined (Figure 5.6) as 16.5 inches and 4.5 inches respectively (T = 16.45(tp/ Sc) + 4.5434) with FAA's six inch minimum pavement thickness deflection control (< 0.05 inches) being maintained. Therefore, for predicting a 20-year design life for a rigid airfield pavement (0% fiber) for this aircraft, the equation is:

$$T\ (\text{concrete}) = [16.5"(tp/\ Sc) + 4.5"]\ \ [\ f\ max/\ fv\ max]^{1/2} \qquad (5.27)$$

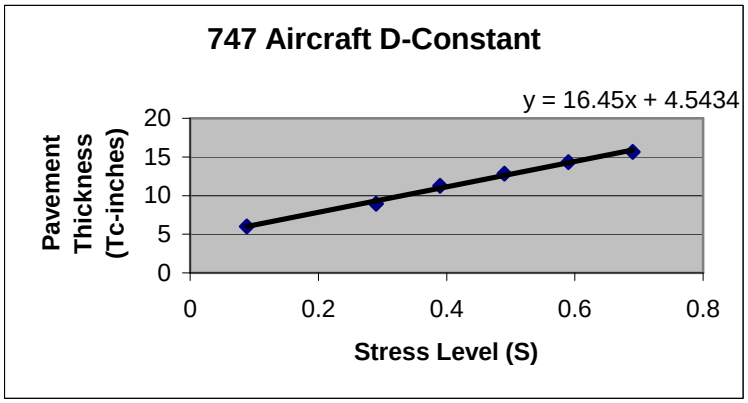

Figure 5.6: Boeing 747 Design Thickness Graph.

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Table 5.4: KenSlabs Edge Stress Results; Boeing 747 Aircraft.

Stress Level (σmax/MOR)	Contact Stress (σmax)	Tensile stress at failure(σ)	Modulus of Rupture (0% fiber Concrete)	KenSlab Computed Design Thickness
0.69	599 psi	404 psi	868 psi	Tc =15.65 inch.
0.59	512 psi	403 psi	868 psi	Tc =14.32 inch.
0.49	425 psi	402 psi	868 psi	Tc =12.84 inch.
0.39	338 psi	403 psi	868 psi	Tc =11.25 inch.
0.29	252 psi	403 psi	868 psi	Tc = 8.96 inch.

Pavement Thickness in Function of the Static FRC Flexural Strength

T (plain concrete) = [16.5"(189 psi/ 868 psi) +4.5"] = 8.1 inches (5.28)

T (0.1% fiber concrete) = [16.5"(189 psi/ 970 psi) +4.5"] = 7.7 inches (5.29)

T (0.2% fiber concrete) = [16.5"(189 psi/ 981psi) + 4.5"] = 7.7 inches (5.30)

T (0.3% fiber concrete) = [16.5"(189 psi/ 1,017 psi) + 4.5"] = 7.6 inches (5.31)

T (0.4% fiber concrete) = [16.5"(189 psi/ 980 psi) + 4.5"] = 7.7 inches (5.32)

Analysis has shown a ½ inch reduction in airfield pavement thickness by use of 0.3% polypropylene fiber for Boeing 747 operations. For a 10,000 foot- 300-foot wide runway alone, this equates to a reduction of 4,630 cubic yards of concrete. In terms of present economics, $ 694,444 savings in construction costs. Similar results as the Boeing 777 aircraft analysis, a 0.4-inch decrease in pavement thickness across all fiber concrete samples. But greater design thickness due to the different gear configuration and slight difference in the T ~ σmax/ Sc relationship.

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Pavement Thickness in Function of Fatigue Strength (fv max)

T (plain concrete) = [16.5”(189 psi/ 868 psi) + 4.5”] [521/ 521 psi] ½ = 8.1” (5.33)

T (0.1% fiber conc.) = [16.5”(189 psi/ 868 psi) + 4.5”] [521/ 570 psi] ½ = 7.7” (5.34)

T (0.2% fiber conc.) = [16.5”(189 psi/ 868 psi) + 4.5”] [521/ 525 psi] ½ = 8.1” (5.35)

T (0.3% fiber conc.) = [16.5”(189 psi/ 868 psi) + 4.5”] [521/ 567 psi] ½ = 7.7” (5.36)

T (0.4% fiber conc.) = [16.5”(189 psi/ 868 psi) + 4.5”] [521/ 513 psi] ½ = 8.2” (5.37)

KenSlabs has shown a 0.4 inch reduction in airfield pavement thickness by use of 0.1% and 0.3% polypropylene fiber concrete under dynamic loading. Constructing a 10,000 foot- 300-foot wide runway alone, this equates to a reduction of 3,704 cubic yards of concrete, a $ 555,600 cost savings.

FRC Predictive Pavement Thickness Equations; Military Aircraft F-16

Analysis for F-16 Aircraft.

The Lockheed Martin F-16 military aircraft is a unique, single wheel, high tire pressure-landing gear system arranged in a triangular (tricycle) gear configuration (Figure 5. 7). Dimensionally, the aircraft is only 49’ 5” long and has a wingspan of 32’. The spacing between each wing wheel is less than ten feet (120 inches). Gross aircraft weight can be as much as 42,300-lbs (Block 25 model), with each wing wheel load equal to 21,150 lbs. on takeoff, with a tire pressure of 200 psi and a tire contact radius area of only

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5.8 inches[43]. In terms of aircraft passes, 100,000 annual departures were considered. KenSlabs pavement responses are for a single wheel, however the principle of superposition was utilized to determine pavement responses corresponding to the F-16 gear configuration.

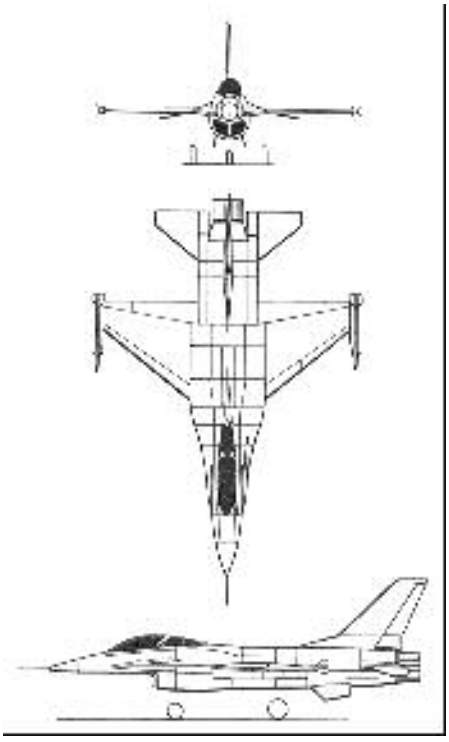

Figure 5.7: The F-16 Fighting Falcon.

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Kenslabs analysis confirmed a linear relationship between stress level and rigid pavement thickness subjected to the Lockheed-Martin F-16 aircraft footprint for edge loading (Table 5.5). Specifically, in compliance with FAA's six inch minimum pavement thickness adequate deflection control (< 0.05 inches) was maintained. Additionally, the L-D coefficient were defined as 13.6 inches and 4.6 inches respectively (T = 13.576 (tp/ Sc) + 4.6041) for the F-16 aircraft (Figure 5.8). Therefore for predicting a 20-year design life for a rigid airfield pavement (0% fiber) for this aircraft, the equation becomes:

$$T\ (\text{concrete}) = [13.6"(tp/\ Sc) + 4.6"]\ \ [(f\ \max/\ fv\ \max)]\ ½ \qquad (5.38)$$

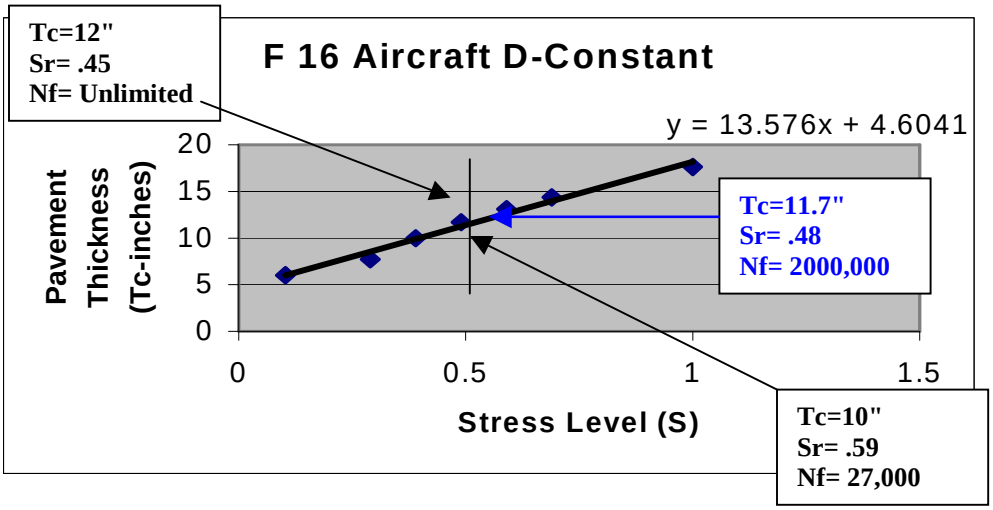

Figure 5.8: F-16 Aircraft Design Thickness Graph.

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Table 5.5: KenSlabs Edge Stress Results; F-16 Aircraft.

Stress Level (σmax/MOR)	Contact Stress (σmax)	Tensile stress at failure(σ)	Modulus of Rupture (0% fiber Concrete)	KenSlab Computed Design Thickness
0.69	599 psi	416 psi	868 psi	Tc =14.35 inch.
0.59	512 psi	415 psi	868 psi	Tc =13.10 inch.
0.49	425 psi	413 psi	868 psi	Tc =11.68 inch.
0.39	338 psi	417 psi	868 psi	Tc = 9.98 inch.
0.29	252 psi	414 psi	868 psi	Tc = 7.72 inch.

Pavement Thickness in Function of Static FRC Flexural Strength

Based on Kenslabs, airfield pavement thickness for edge loading of an F-16 military aircraft for a minimum of 2,000,000 passes is as follows:

T (concrete) = [13.6”(tp/ Sc) + 4.6”] (5.39)
Sc= maximum static flexural strength 0% fiber (plain) concrete.
tp = Aircraft tire contact stress (psi)

T (concrete) = [13.6”(tp/ Sc-fiber) + 4.6”] (5.40)
Sc-fiber = fiber volume (0.1%, 0.2%, 0.3%, 0.4%) MOR (psi).

T (plain concrete) = [13.6”(200 psi/ 868 psi) + 4.6”] = 7.7 inches (5.41)

T (0.1% fiber concrete) = [13.6”(200 psi/ 970 psi) + 4.6”] = 7.4 inches (5.42)

T (0.2% fiber concrete) = [13.6”(200 psi/ 981psi) + 4.6”] = 7.4 inches (5.43)

T (0.3% fiber concrete) = [13.6”(200 psi/ 1,017 psi) + 4.6”] = 7.3 inches (5.44)

T (0.4% fiber concrete) = [13.6”(200 psi/ 980 psi) + 4.6”] = 7.4 inches (5.45)

-

Analysis has shown a 3/8-inch reduction in airfield pavement thickness by use of 0.3% polypropylene fiber under static flexural loading. Over a 10,000 foot- 300-foot wide runway alone, this equates to a reduction of 3,704 cubic yards of concrete in construction of a 20-year design life rigid pavement for this aircraft. In terms of present economics, $ 555,556 savings in construction costs. As compared to the Boeing 777/747 aircraft analysis, a 0.3 inch pavement thickness reduction across all fiber concrete samples due to the increased tire pressure but smaller contact area and a different aircraft gear geometry resulting in the different T ~ σmax/ Sc linear relationship.

Pavement Thickness in Function of FRC Fatigue Strength (fv max)

As example, laboratory testing (Chapter 4) of concrete specimen beams established the flexural fatigue strength of 0%, 0.1%, 0.2%, 0.3%, 0.4% fiber reinforced concrete at 2,000,000 load cycles as 521 psi, 570 psi, 525 psi, 567 psi and 513 psi respectively. Based on KenSlabs modeling, airfield pavement thickness for edge loading of a F-16 fighter aircraft for 2,000,000 passes is as follows.

T (plain conc) = [13.6”(200psi/ 868 psi) + 4.6”][521/ 521 psi)] ½= 7.7” (5.46)

T (0.1% fiber conc.) =[13.6”(200 psi/ 868 psi) + 4.6”] [521/ 570 psi)] ½= 7.4” (5.47)

T (0.2% fiber conc.) = [13.6”(200 psi/ 868 psi) + 4.6”] [521/ 525 psi)] ½= 7.7” (5.48)

T (0.3% fiber conc.) = [13.6”(200psi/ 868 psi) + 4.6”] [521/ 567 psi)] ½= 7.4” (5.49)

T (0.4% fiber conc.) = [13.6”(200 psi/ 868 psi) + 4.6”] [521/ 513 psi)] ½= 7.8” (5.50)

-

KenSlabs has shown a 0.3-inch reduction in airfield pavement thickness by use of 0.1% or 0.3% polypropylene fiber. Over a 10,000 foot- 300-foot wide runway, this equates to a reduction of 2,778 cubic yards of concrete in construction of a 20-year design life rigid pavement for this aircraft. Twice that figure, if you considered follow-on taxiway and apron construction. In terms of present economics, $ 416,667 savings in construction costs considering a $150/CY unit cost.

FRC Predictive Pavement Thickness Equations; C141 Starlifter and C-17 Globemaster Military Airlift Aircraft

Kenslabs modeling confirmed a linear relationship between stress level and rigid pavement thickness subjected to the Lockheed-Martin C141 and C-17 aircraft footprint for edge loading. FAA's six inch minimum pavement thickness, adequate deflection control (< 0.05 inches) was maintained (Table 5.6). The L-D coefficients were defined as 17 inches and 5 inches respectively (T = 17 (tp/ Sc) + 5) for the C141 aircraft (Figure 5.11). The L-D coefficients were defined as 17.73 inches and 5.9 inches respectively (T = 17.7 (tp/ Sc) + 5.9) for the C-17 aircraft (Figure 5.12). Therefore for predicting a 20-year design life for a rigid airfield pavement (0% fiber) for these aircraft, the equation becomes:

C-141 Aircraft

$$T\ (\text{concrete}) = [17"(tp/\ Sc) + 5"][f\ max/\ fv\ max)]\ ½ \qquad (5.51)$$

C-17Aircraft

$$T\ (\text{concrete}) = [17.7"(tp/\ Sc) + 5.9"]\ [f\ max/\ fv\ max)]\ ½ \qquad (5.52)$$

-

The Lockheed Martin C141 Starlifter (Figure 5.9) is the “workhorse” of the Air Mobility Command. The Starlifter fulfills the vast spectrum of airlift requirements through its ability to airlift combat forces over long distances, deliver those forces and their equipment either by air, land or airdrop, resupply forces and transport the sick and wounded from the hostile area to advanced medical facilities. Deliveries can be made through the side paratroop doors or via the rear-loading ramp. The C-141 can also carry medical patients and supplies, and several have been outfitted to transport ballistic missiles. Dimensionally, it’s wingspan is 48.74 meters (159 feet, 11 inches), length: 51.29 meters (168 feet, 4 inches), 11.96 meters (39 feet, 3 inches) in height with a maximum weight of 155,582 kilograms (343,100 pounds). Gear configuration is tandem, dual wheels with tandem spacing of 48 inches and 32.5 inch spacing between dual tires. Tire pressure is 190 psi[44].

Figure 5.9: Lockheed Martin C141 Starlifter.

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The C-17 Globemaster III (Figure 5.10) is the newest, most flexible cargo aircraft to enter the military airlift force. The C-17 is capable of rapid strategic delivery of troops and all types of cargo to main operating bases or directly to forward bases in the deployment area. The aircraft is also capable of performing tactical airlift and airdrop missions when required[45]. The C-17 is a high-wing, four-engine, T-tailed cargo aircraft with a rear-loading ramp. It is 174 feet in length, has a height of 55.08 feet and a wingspan of 169.75 feet. Maximum takeoff gross weight is 585,000 pounds, maximum payload is 169,000 pounds. With a payload of 160,000 pounds, the C-17 can take off from a 7,600-foot airfield, fly 2,400 nautical miles and land on a small, austere airfield in 3,000 feet or less. Gear configuration is tandem, dual wheels with tandem spacing of 97 inches and 41.5 inch spacing between dual tires. Tire pressure is 138 psi.

Figure 5.10: Boeing C-17 Globemaster III.

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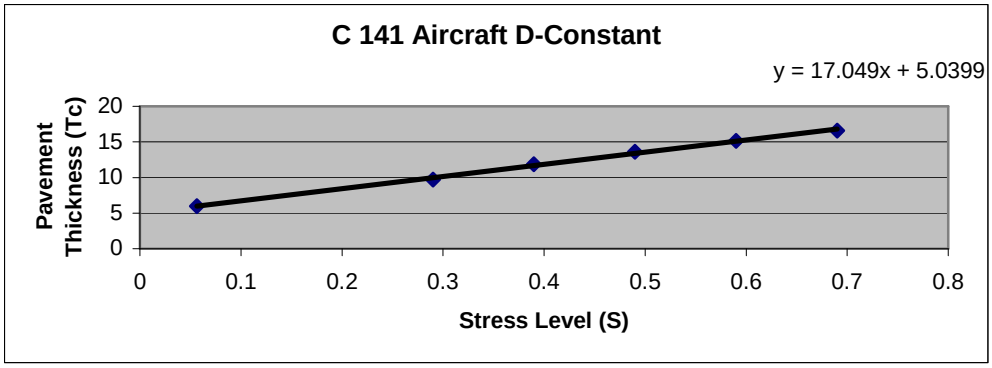

Figure 5.11: KenSlabs Edge Stress Results; C-141 Aircraft.

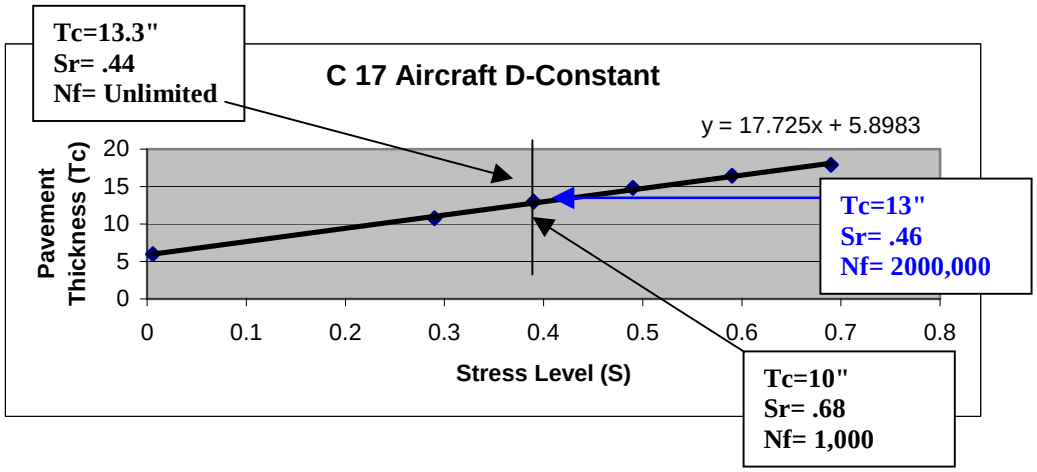

Figure 5.12: KenSlabs Edge Stress Results; C-17 Aircraft.

Table 5.6: KenSlabs Edge Stress Results; C-141/C-17 Aircraft.

Contact Stress (σmax)	Tensile stress at failure(σ)	Modulus of Rupture (0% fiber Concrete)	KenSlab (C-141) Computed Design Thickness	KenSlab (C-17) Computed Design Thickness
599 psi	404 psi	868 psi	Tc =16.57 inch.	Tc =17.90 inch.
512 psi	405 psi	868 psi	Tc =15.15 inch.	Tc =16.45 inch.
425 psi	403 psi	868 psi	Tc =13.65 inch.	Tc =14.83 inch.
338 psi	401 psi	868 psi	Tc = 11.87 inch.	Tc = 12.98 inch.
252 psi	399 psi	868 psi	Tc = 9.71 inch.	Tc = 10.77 inch.

-

Pavement Thickness in Function of the Static FRC Flexural Strength; C-141 Aircraft

T (concrete) = [17 ”(tp/ Sc) +5 ”] for 0% fiber (plain) concrete. (5.53)

T (concrete) = [17 ”(tp/ Sc-fiber) +5 ”] (5.54)
Sc-fiber = fiber volume (0.1%, 0.2%, 0.3%, 0.4%) MOR (psi).

As example, ASTM C-78 laboratory testing established the static flexural strength of 0%, 0.1%, 0.2%, 0.3%, 0.4% fiber reinforced concrete in 6”X 6”X21” concrete beams as 725 psi, 692 psi, 731 psi, 757 psi and 728 psi respectively. Based on KenSlabs analysis, airfield pavement thickness for edge loading of a C141 military aircraft for 2,000,000 passes is as follows:

T (plain concrete) = [17 ”(190 psi/ 725 psi) + 5 ”] = 9.5 inches (5.55)

T (0.1% fiber concrete) = [17 ”(190 psi/ 692 psi) + 5”] = 9.7 inches (5.56)

T (0.2% fiber concrete) = [17 ”(190 psi/ 731 psi) + 5”] = 9.4 inches (5.57)

T (0.3% fiber concrete) = [17 ”(190 psi/ 757 psi) + 5”] = 9.25 inches (5.58)

T (0.4% fiber concrete) = [17 ”(190 psi/ 728 psi) + 5”] = 9.5 inches (5.59)

Using ASTM C-78 laboratory testing values of 868 psi, 970 psi, 981 psi, 1,017 psi and 980 psi for static flexural strength of 0%, 0.1%, 0.2%, 0.3%, 0.4% fiber reinforced concrete in 4”X 4”X14” concrete beams respectively, airfield pavement thickness for a C141 military aircraft is;

-

T (plain concrete) = [17 ”(190 psi/ 868 psi) + 5 ”] = 8.7 inches (5.60)

T (0.1% fiber concrete) = [17 ”(190 psi/ 970 psi) + 5”] = 8.3 inches (5.61)

T (0.2% fiber concrete) = [17 ”(190 psi/ 981 psi) + 5”] = 8.3 inches (5.62)

T (0.3% fiber concrete) = [17 ”(190 psi/ 1,017 psi) + 5”] = 8.2 inches (5.63)

T (0.4% fiber concrete) = [17 ”(190 psi/ 980 psi) + 5”] = 8.3 inches (5.64)

Calculations have shown a 1/4-inch reduction in airfield pavement thickness by use of 0.3% polypropylene fiber using different laboratory testing data for flexural strength (Equation 5.58). This equates to a reduction of 2,315 cubic yards of concrete in construction of rigid airfield pavement for this aircraft. In terms of present economics, $ 347,222 savings in construction costs.

Determination of Pavement Thickness in Function of FRC Fatigue Strength; C-141 Aircraft

As example, over 70, 4-inch x 4-inch x 14-inch concrete beam specimens were tested at the University of Maryland for fatigue strength. Fatigue strength at the endurance limit increased when fibrillated polypropylene was added to concrete. The average fatigue strength was 521 psi for plain concrete, 570 psi for 0.1% FRC and 525 psi, 567 psi and 513 psi for 0.2%, 0.3% and 0.4% FRC respectively. Analysis has shown a 0.4 inch reduction in airfield pavement thickness by use of 0.1% or 0.3% polypropylene fiber. Over a 10,000 foot- 300-foot wide runway alone, this equates to a reduction of 3,704, cubic yards of concrete in construction of a 20-year design life rigid pavement for this aircraft. In terms of present economics, $ 555,555 savings in construction costs.

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T (plain concrete) = [17 ”(190 psi/ 868 psi) + 5”] [521/ 521psi] ½ = 8.7" (5.65)

T (0.1% fiber concrete) = [17 ”(190 psi/ 868 psi) + 5”] [521/ 570 psi] ½ =8.3" (5.66)

T (0.2% fiber concrete) = [17 ”(190 psi/ 868psi) + 5”] [521/ 525 psi] ½ = 8.7" (5.67)

T (0.3% fiber concrete) =[17 ”(190 psi/ 868 psi) + 5”] [521/ 567 psi] ½ = 8.3" (5.68)

T (0.4% fiber concrete = [17 ”(190 psi/ 868 psi) + 5”] [521/ 513 psi] ½ = 8.8" (5.69)

Tabulation and Use of FRC Pavement Reduction Values in Thickness Design

In Chapter 6, a case study and calculations are presented deriving pavement thickness reduction values for fiber reinforced concrete under C-17A aircraft loading using the methodology presented in this chapter. Based on these thickness calculations, FRC Composite Pavement Thickness Reduction Values (PRV) are summarized in Table 5.8. The pavement thickness reduction values quantify the increase in concrete pavement strength, due to fiber reinforcement, as it pertains to specific aircraft.

Table 5.8: Design Thickness Reduction Values (C-17A Aircraft).

FRC Composite C-17 Aircraft	Pavement Design Thickness; Flexural Strength	Pavement Design Thickness; Fatigue Strength	Design Thickness Reduction Value as Compared to plain (0%) fiber concrete
Plain(0%) fiber Concrete	8.7 inches	8.7 inches	----------
0.1% Fiber Concrete	8. 4 inches	8.3 inches	3/8 inch
0.2% Fiber Concrete	8. 4 inches	8.7 inches	1/8 inch
0.3% Fiber Concrete	8.3 inches	8.4 inches	3/8 inch
0.4% Fiber Concrete	8. 4 inches	8.8 inches	1/8 inch

-

Conventional airfield design thickness results from LEDFAA multi-aircraft analysis meeting FAA criteria are presented in Table 5.9. KenSlabs and LEDFAA pavement design thickness results and PRV's are shown in Table 5.10. Table 5.10 could be used to reduce an airfield pavement design thickness based on the fiber content and the known properties of a given fiber concrete composite mix. As example, to meet FAA's 20 year design thickness criteria for a Boeing 777, Boeing 747, C-141, C-17A airfield traffic mix, when a 0.3% FRC is used, the airfield would have to be 19.22"-0.4"(PRV) or 18.82" thick as compared to 19.22" for plain concrete. To meet the Military's requirement for C-141 operations, the airfield would have to be 8.7" - 0.4"(PRV) or 8.3" thick. If the design mix with the 725 psi MOR were used, the airfield thickness would have to be 9.5" -0.3"(PRV) or 9.2" thick for class C traffic areas. TM 5-825-3/AFM 88-6 for Fibrous Concrete Pavement Design requires FRC airfield design thickness for Traffic Area A and B surfaces to be 10.5 inches in order to maintain an allowable deflection (0.05 inches) and design life for a heavy lift C-141military aircraft[6]. Therefore, the airfield design thickness for the C-141 aircraft would be 10.5 "- 0.4" (PRV) or 10.1".

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Table 5.9: LEDFAA Multi-Aircraft Design Thickness Results.

Traffic	Annual Departures	Modulus of Elasticity	PCC Design Thickness	Poisson's ratio	Subbase Thickness & E Subgrade E
Boeing 777 Boeing 747	50,000 50,000	4,000,000 psi	19.85 inches	0.15	8 inches 500,000 psi 4,500 psi
Boeing 777 Boeing 747 C-141	33,000 33,000 33,000	4,000,000 psi	19.44 inches	0.15	8 inches 500,000 psi 4,500 psi
Boeing 777 Boeing 747 C-141 C-17A	25,000 25,000 25,000 25,000	4,000,000 psi	19.22 inches	0.15	8 inches 500,000 psi 4,500 psi
Boeing 777 Boeing 747 C-141 C-17A	25,000 25,000 25,000 25,000	4,000,000 psi	17.80 inches	0.15	16 inches 500,000 psi 4,500 psi
Boeing 777 Boeing 747 C-141 C-17A	25,000 25,000 25,000 25,000	4,000,000 psi	14.26 inches	0.15	16 inches 500,000 psi 13,500 psi

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Table 5.10: Single/ Multi-Aircraft FRC Design Thickness Results.

Traffic	Annual Departures	Military Standard (KenSlabs) Design	LED-FAA Design Thickness	Fiber Content/ thickness reduction values.
Boeing 777 Boeing 747	50,000 50,000		19.85 inches (MOR;800psi)	0.1%/0.4”reduction 0.2%/0.2” reduction 0.3%/0.5” reduction 0.4%/0.2” reduction
Boeing 777 Boeing 747 C-141	33,000 33,000 33,000		19.44 inches (MOR;800psi)	0.1%/0.3”reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
Boeing 777 Boeing 747 C-141 C-17A	25,000 25,000 25,000 25,000		19.22 inches (MOR;800psi)	0.1%/0.3”reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
Boeing 777	100,000	8.3 inches thickness (MOR;868 psi)		0.1%/0.4”reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
Boeing 747	100,000	8.1 inches thickness (MOR;868 psi)		0.1%/0.4”reduction 0.2%/0.2” reduction 0.3%/0.5” reduction 0.4%/0.2” reduction
C-141	100,000	8.7 inches thickness (MOR;868 psi)		0.1%/0.4” reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
C-141	100,000	9.5 inches thickness (MOR;725 psi)		0.1%/no reduction 0.2%/0.1” reduction 0.3%/0.3” reduction 0.4%/no reduction
C-17A	100,000	8.7 inches thickness (MOR;868 psi)		0.1%/0.4” reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
F-16	100,000	7.7 inches thickness (MOR;868 psi)		0.1%/0.3”reduction 0.2%/0.2” reduction 0.3%/0.3” reduction 0.4%/0.1” reduction

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FRC THERMAL STRESS AND DEFLECTION

FRC Modeling with Respect to Rigid Slab Temperature Curling

Stresses are induced in large dimensional slabs by the temperature differential between the top and bottom of the slab due to climate. Typical temperature gradient changes can be as much as 3.5º F per inch of slab thickness. During the day these stresses are in addition to the aircraft load as the slab curls down due to the longer dimension of the warmed surface as compared to the base of the slab. There is debate whether these stresses should be added to the aircraft load stresses during damage analysis, typically these stresses are evaluated separately [2]. To evaluate the impact of FRC pavements to curling stresses, a four-slab arrangement with doweled joints, with dowels placed every 12 inches (on centers) was considered (Figure 5.13). The thermal coefficient of expansion (α), as recommend by PCA, that was used was 0.0005", and a temperature difference of 20˚F was assumed in each KenSlab run between the top and bottom of the slab. The same foundation conditions were used as in the damage analysis model (Figure 5.1). Based on the calculated pavement thickness for fatigue cracking at 2,000,000 cycles for each fiber case, the unit weight and Modulus of Elasticity of 0%, 0.1%, 0.2%, 0.3% and 0.4% fiber concrete as derived from compressive strength tests[46], the curling stresses were determined (Table 5.11). Quantifiably, at a temperature differential of 20˚F, a reduction of 17.4 psi of temperature related stresses at 0.3% fiber concrete as compared to plain (0%fiber) concretes.

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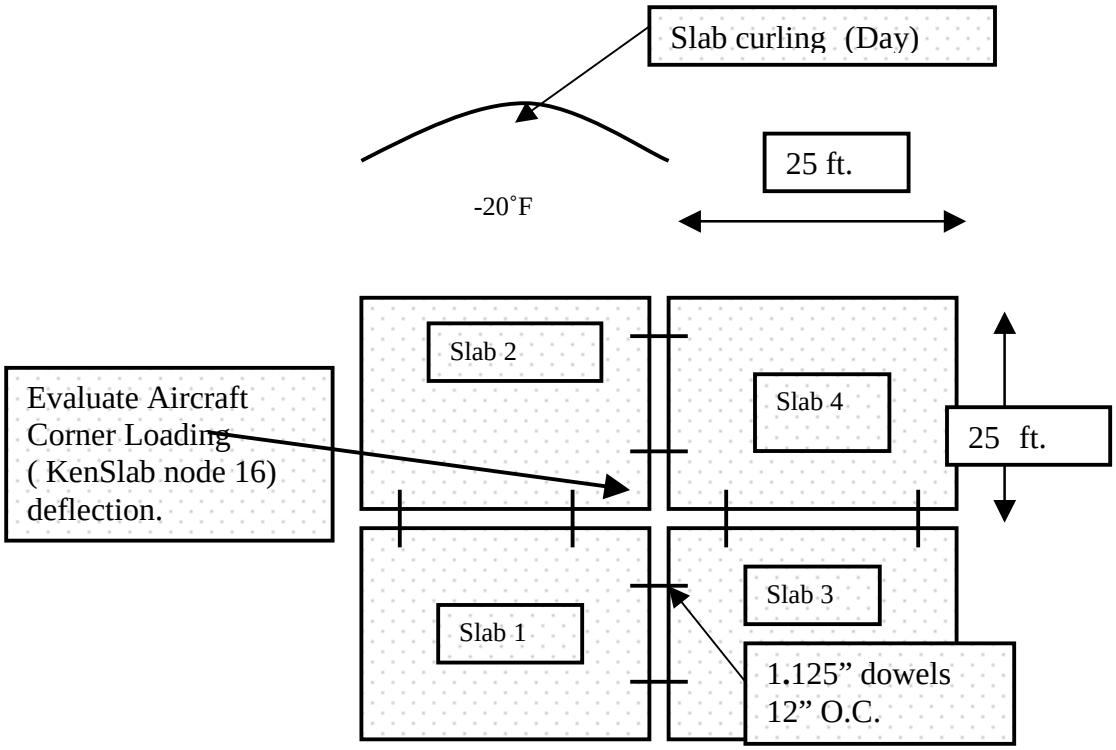

Figure 5.13: Curling Stress.

Table 5.11: Curling Stresses; 25’X 25’ Slab (Δ 20˚F).

Fiber Case	**Modulus E** (psi)	**Unit wt. (pcf)**	**Fatigue Design Thickness**	**Curling Stress (psi)**
Plain	4,177,328	142.82	9.0 inches	182.25
0.1%	4,663,892	147.82	8.7 inches	199.47
0.2%	4,180,341	143.82	8.6 inches	179.28
0.3%	3,836,315	143.82	8.5 inches	164.85
0.4%	3,888,886	141.82	8.6 inches	167.58

-

Temperature curling stresses were also calculated using KenSlabs based on a 25'X12' single slab analysis. Material properties from laboratory testing and temperature curling stress results are tabulated below (Tables 5.12 to 5.14). The thermal coefficient of expansion (α) used was 0.0005", and three temperature differentials (10˚F, 20˚F, 30˚F) were considered in each KenSlabs run between the top and bottom of the slab. Same foundation conditions were used as in the damage analysis model (Figure 5.1). Analysis showed that there is a decrease in temperature curling stresses with increasing fiber volume, a function of decreasing Modulus value and fiber related slab thickness, which reduces total slab stresses (loading and thermal) during daylight aircraft operations. Quantifiably, at a temperature differential of 20˚F, a reduction of 26.3 psi was observed at 0.3 % fiber concrete (Table 5.13) to a reduction of 39.4 psi of curling stresses between plain and 0.3 % fiber concrete (Table 5.14) at a temperature differential of 30˚F.

Table 5.12: Thermal Stress Values on 25'X 12' Slab (Δ 10˚F).

Fiber Case	**Modulus E(psi)**	**Unit wt. (pcf)**	**Fatigue Design Thickness**	**Curling Stress (psi)** Slab edge	**Curling Stress (psi)** Slab interior(center)
Plain	4,158,817	143.8	9 inches	113.5 psi	125.1 psi
0.1% fiber	4,482,465	144.8	8 inches	120.7 psi	135.5 psi
0.2% fiber	4,179,904	143.8	8 inches	112.1 psi	126.4 psi
0.3% fiber	3,735,295	141.8	8.4 inches	100.4 psi	112.9psi
0.4% fiber	3,830,317	142.8	8.8 inches	103.8 psi	115.5 psi

-

Table 5.13: Thermal Stress Values; 25'X 12' slab (Δ 20˚F).

Fiber Case	**Modulus E(psi)**	**Unit wt. (pcf)**	**Fatigue Design Thickness**	**Curling Stress (psi)** Slab edge	**Curling Stress (psi)** Slab interior(center)
Plain	4,158,817	143.8	9 inches	227 psi	250.1 psi
0.1% fiber	4,482,465	144.8	8 inches	241.4 psi	270.9 psi
0.2% fiber	4,179,904	143.8	8 inches	224.2 psi	252.9 psi
0.3% fiber	3,735,295	141.8	8.4 inches	200.7 psi	225.9 psi
0.4% fiber	3,830,317	142.8	8.8 inches	207.6 psi	231.1 psi

Table 5.14: Thermal Stress Values; 25'X 12' slab (Δ 30˚F).

Fiber Case	**Modulus E(psi)**	**Unit wt. (pcf)**	**Fatigue Design Thickness**	**Curling Stress (psi)** Slab edge	**Curling Stress (psi)** Slab interior(center)
Plain	4,158,817	143.8	9 inches	340.5 psi	375.2 psi
0.1% fiber	4,482,465	144.8	8 inches	362 psi	406.4 psi
0.2% fiber	4,179,904	143.8	8 inches	336.3 psi	379.3 psi
0.3% fiber	3,735,295	141.8	8.4 inches	301.1 psi	338.8 psi
0.4% fiber	3,830,317	142.8	8.8 inches	311.4 psi	346.6 psi

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Corner Deflections and Slab Pumping Reduction

Corner deflection in airfield slabs under repetitive loading is always problematic for aircraft parking aprons due to foundation soils pumping. Pumping being the ejection of base/subgrade fine-grained soils at slab corners due to the dynamic nature of aircraft wheel loading and excessive slab deflections. Typically, this results in a void under apron slab corners due to loss of foundation material, eventually resulting in slab fracture. The military design deflection criteria (AFM 88-6) for airfields are based on edge loading, which simulates runway and taxiway travel lane conditions, not corner loading. KenSlabs corner loading modeling using the most critical aircraft loading condition, the Boeing 777 and Boeing 747 aircraft on a 25 square foot concrete airfield slab yielded the results shown in Table 5.15. KenSlabs analysis suggests that for these aircraft, apron corner deflection can be significant, by as much as seven times the allowable edge loading design deflection. KenSlabs analysis shows that foundation improvement, not slab thickening is a better approach to reducing deflections, as slab thickening adds to the deflection problem (Table 5.15). According to Huang, corner deflection is reduced by 50% if there is a threefold increase in subgrade modulus[2] and KenSlabs analysis suggests this (Table 5.16). Since publication of this AFM 88-6 in 1988, significant advancements in polymer technology and geosynthetics engineering have occurred, making foundation strength improvement achievable and cost effective. Installation of a non-woven geotextile separator in the foundation soils and FRC would be a better approach to eliminating pumping problems rather than the traditional approach of slab thickening[47] .

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Corner Deflection was evaluated on the same four-slab system (Figure 5.13), using laboratory derived FRC material properties under aircraft load but independent of temperature curling. Worst case deflection condition was assumed by placing the Boeing 777 and Boeing 747-gear load over the doweled corner at node 16. Material properties, design thickness and deflection results are shown in Tables 5.15 and 5.16. Corner deflection decreases with a decrease in pavement thickness and Modulus value (Table 5.15) and an increase in subgrade value (Table 5.16). The inherent nature of fiber reinforcement to contribute to reduction in the stiffness and thickness required of a concrete airfield pavement also reduces the stress on the slab foundation and quantifiably reduces corner deflection and the eventual detrimental effects of pumping.

Table 5.15: FRC Corner Deflections; 25'X 25' Slab.

Fiber Case	**Modulus E** (psi)	**Unit wt. (pcf)**	**Flexural Design Thickness (inches)**	**Corner Deflection (inches)**
Plain(0%)	4,177,328	142.82	24	0.477
Plain(0%)	4,177,328	142.82	17	0.422
Plain(0%)	4,177,328	142.82	9.0	0.36
0.1%	4,663,892	147.82	8.7	0.36
0.2%	4,180,341	143.82	8.6	0.357
0.3%	3,836,315	143.82	8.5	0.356
0.4%	3,888,886	141.82	8.6	0.356

Table 5.16: Corner Deflection Subgrade Effect.

Airfield Slab 25'X 25'	**Modulus E (psi)**	**Fatigue Design Thickness**	**Contact Pressure(psi)** (aircraft tire)	**Subgrade E (psi)**	**Corner Deflection; inch**
Plain(0%)	4,177,328	24 inches	189psi	4,500	0.477
Plain(0%)	4,177,328	24 inches	10psi(no load)	4,500	0.322
Plain(0%)	4,177,328	24 inches	189psi	6,000	0.363
Plain(0%)	4,177,328	24 inches	189psi	9,000	0.249
Plain(0%)	4,177,328	9 inches	189psi	4,500	0.36
Plain(0%)	4,177,328	9 inches	10psi(no load)	4,500	0.17
Plain(0%)	4,177,328	9 inches	189psi	6,000	0.274
Plain(0%)	4,177,328	9 inches	189psi	9,000	0.186

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FRACTURE MODELING FOR HEAVED PAVEMENT REDUCTION

Polypropylene fiber possesses material properties that increase concrete's ductility and dynamic energy absorption capability, which are performance characteristics desired by the military in reducing bomb damaged airfield pavement. A significant concern by the United States Air Force is the time to repair battle damaged airfields in which current criteria requires repair of three, 50 foot diameter craters within 4 hours[36]. A significant part of that repair effort is removal of heaved and fractured pavement around the crater requiring removal and replacements of concrete twice the crater's diameter (Figure 5.14). Polypropylene fiber reinforced concrete's (FRC) ability to absorb energy will reduce the amount of heaved pavement required to be removed, saving invaluable time to aircraft sortie generation after an attack. Laboratory toughness testing demonstrated that FRC has four times the energy absorption capability of plain concrete, a significant characteristic suggesting the amount of heaved pavement needing to be replaced can be reduced and that reduction is quantifiable.

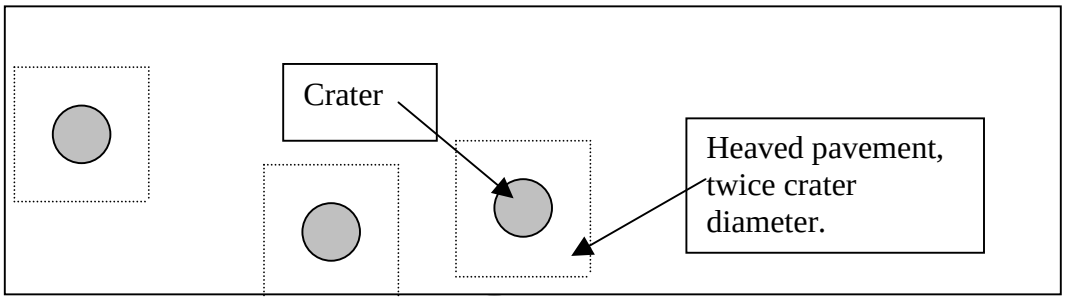

Figure 5.14: Bomb Damage Repair; Airfield Concrete Runway.

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Predicting the mechanism of blast fractures of concrete has to do with stress wave theory. In which the magnitude and shape of this rapidly moving wave depends on such factors as the type of explosive (explosive weight and detonation velocity), blast depth, relationship of detonation velocity to wave propagation velocity of concrete's material properties (unit weight-γ, Modulus of Elasticity-E), bore hole diameter, and the distance from the hole where the stress measurement is taken. We know wave propagation is faster in hard rock than soft rock and the majority of the fracturing produced in the rock is radial from the hole and associated with the propagating stress wave. The fragmenting process occurs in a relatively short time, five to 10 milliseconds with cracks forming at a rate of 1,500 to 8,000 feet-per-second[48]. A considerable amount of laboratory data has been collected on the material properties of plain and polypropylene fiber reinforced concrete during laboratory testing (Table 5.17). However, information regarding current military munition capabilities such as explosive weight, detonation velocity and depth are classified and varied between munitions. According to AFMAN 10-219, pavement upheaval continues up to 25 feet beyond the crater lip of a 50-foot diameter crater[35] and that stress wave velocity (Vc) through a given linear-elastic material is a function of that materials properties (E, γ) and mathematically expressed as $Vc = \sqrt{E \text{ plain concrete}/\gamma \text{ plain concrete}/\text{gravity (g)}}$ where γ / g = the material's density (ρ).[37] Air Force Pamphlet 10-219 states the diameter of radial heaved pavement fracturing from a bomb-damaged airfield is twice the 50-foot apparent crater diameter (Figure 5.16). The importance of this relationship is not to estimate crater diameter from a given explosive. But to understand the amount of heaved pavement that needs to be removed as a result of the cratering. Normalized for fiber reinforcement material properties for materials with similar

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Poisson's ratios [49] and considering the relationship of fracture diameter (RD) to crater diameter (D) the equation could be expressed as:

$$RD = \frac{2D\,[\sqrt{E_{\text{fiber concrete}}/\gamma_{\text{fiber concrete}}/(g)}]}{[\sqrt{E_{\text{plain concrete}}/\gamma_{\text{plain concrete}}/(g)}]} \qquad (5.70)$$

In terms of Kinetic energy, any explosive energy (Q) as it travels through a material (mass-m) at ever-greater distance (d) from its source will result in a loss of stress wave (a) intensity. After the initial detonation pressure, the amplitude of the stress wave will decay as it travels through the concrete and encounters more material mass. This decrease in energy density with distance from the source is known as geometrical damping[37]. According to the Dupont Blaster's Handbook, pressure-time recordings made at different distances from blast centers during quarry operations of granite indicate an average rate of decay of the compressive stress wave as 4,533 psi – 383.33psi(L feet) from the explosive borehole[48]. Granite is a suitable material to compare to concrete in this regard, due to their similar Poisson's ratios[4].

We have a rational way of predicting the amount of energy a given FRC composite must be able to absorb in order to resist heaving. When a material is tested in toughness, a force is applied in order to deform the specimen. Force times distance is work. Dividing the force by the cross-section of the specimen provides stress, divide the deformation by the length of the specimen you have the strain. The resulting force-displacement diagram is now a stress-strain diagram and the area under the stress-strain

-

diagram equals the work per unit volume of material required to deform or fracture the material (see Figure 5.15)[50]. This quantifies the amount of energy any given FRC composite can absorb based on its unique material properties (Toughness). The vertical axis value (stress) on the diagram, at 1st crack is defined as the first crack strength ($\propto$) of a given material and is determined by using the modulus of rupture formula in ASTM C78[14]. The amount of heaved pavement deformed, radiating from the crater center (L) is the strain. The value ($\propto$) was selected to define the "strength characteristic" of FRC as used by other researchers in material property crater analysis[52].

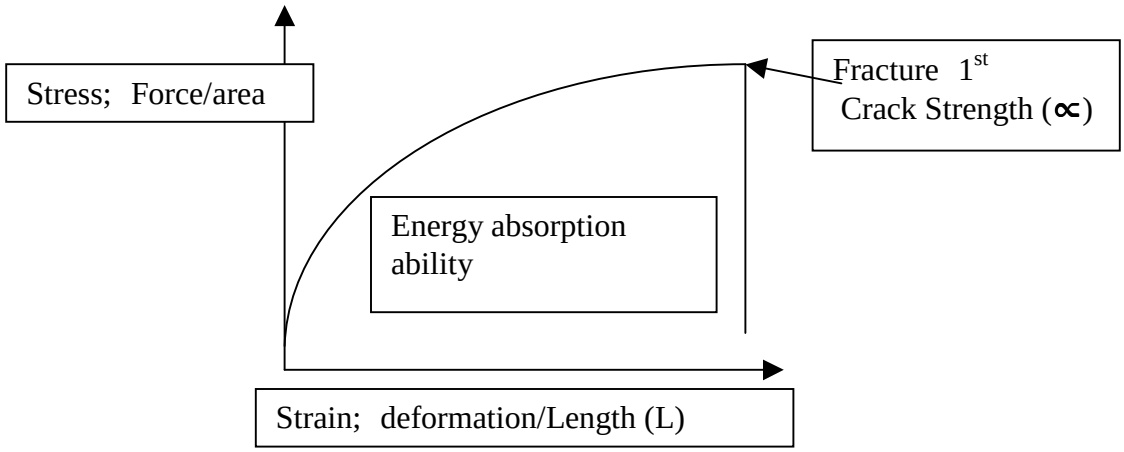

Figure 5.15: Toughness.

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Equation 5.71 can be used to predict the distance (L) from the crater center in which the energy absorption capacity of a given FRC material will be greater than the remaining energy in the decaying stress wave. This will be the limit of heaved pavement damage. This L relationship is a function of material properties (1st crack strength, volume of material for damping) for any given explosive energy and can be used to compare the difference in energy absorption characteristics of different FRC material.

If we consider that the 1st Crack strength values from ASTM C1018 toughness testing of plain, 0.1%, 0.2%, 0.3% and 0.4% fiber reinforced concrete specimens defines the strength characteristic of each composite, and will determine the limit of the ruptured pavement from a stress wave. Scaled to match a given cratering charge, we can mathematically predict the amount of fracturing (L) from explosive catering for varying amounts of polypropylene fiber reinforcement considering tensile stresses. Another correction needs to be considered here, normalizing the p wave amplitude decay as a function of distance (1/L) to that of a wave acting in the tensile direction ($1 / \sqrt{L}$).These geometrical damping relationships were derived from studies done by Ewing, Jardetzky and Press in 1967[51]. Calculation for heaved pavement reduction are presented in detail for 0.1%, 0.2%, 0.3%, and 0.4% polypropylene fiber concrete later in this chapter using Equation 5.71 as a correction to Equation 5.70.

($\propto$)= 1st crack strength (toughness) (5.71)

$$(\propto) = [4{,}533.33\text{psi} - 383.33\text{psi}(L \text{ feet})]\left[\frac{\sqrt{E \text{ fiber concrete}}/\gamma \text{ fiber concrete}/(g)}{\sqrt{E \text{ granite}}/\gamma \text{ granite}/(g)}\right]\left[\frac{\sqrt{W}}{2}\right]\left[\frac{1/\sqrt{L}}{1/L}\right]$$

-

Table 5.17: Laboratory and Calculated Material Properties.

Material	M.O.R.	Unit Weight	Modulus E.
Granite	**N/a**	**170 #/cf**	**8,249,224 psi**
Plain Concrete	**868 psi**	**143.82 #/cf**	**4,158,817 psi**
0.1% FRC	**970 psi**	**144.82 #/cf**	**4,382,465 psi**
0.2% FRC	**981 psi**	**143.82 #/cf**	**4,179,904 psi**
0.3% FRC	**1,017 psi**	**141.82 #/cf**	**3,735,295 psi**
0.4% FRC	**980 psi**	**142.82 #/cf**	**3,830,317 psi**

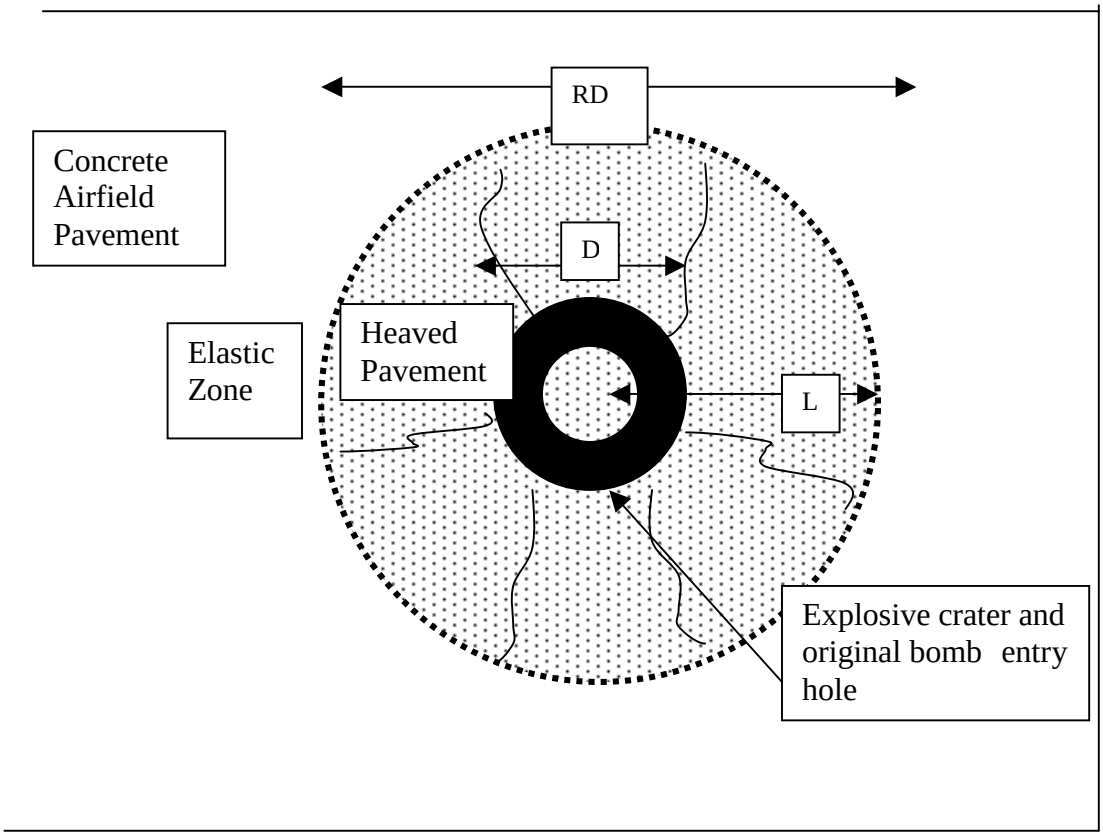

Figure 5.16: FRC Heaved Pavement Fracturing Schematic.

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Calculations; The following example is provided to illustrate the use of the aforementioned equations to determine the reduction in heaved concrete that needs to be removed around a runway crater due to the improvement in the energy absorption characteristics of low volume polypropylene fiber in airfield concrete. Material values were taken from laboratory testing of polypropylene fiber-concrete specimens at 0.1%, 0.2%, 0.3 % and 0.4% mix volumes. Values for other materials were taken from DuPont de Nemour's Blaster's Handbook based on accumulated empirical data regarding explosive testing in quarry operations.

Given the 100' diameter of heaved pavement surrounding a 50' crater on a plain concrete runway with a 1st crack strength =868 psi. If we added fiber to the mix during construction, could we reduce the amount of heaved pavement?

Known material properties

RD = 100'(0% fiber) plain concrete for 50' crater; $\propto$= 868psi; (5.72)
E= 4,158,817 psi@143.82#/cf. (g= 32.2 ft./sec-sec)
E granite = 8,249,224 psi@170 #/cf. (g= 32.2 ft./sec-sec)

Determine the stress wave decay for plain concrete. (5.73)

$$868 \text{ psi} = (4{,}533 \text{ psi} - 383.33 \text{ psi } L)\left[\frac{\sqrt{4{,}158{,}817 \text{ psi}/ 143.82 \text{ \#/cf/g}}}{\sqrt{8{,}249{,}224 \text{psi} /170 \text{\#/cf/g}}}\right] L$$

$L^2 - 11.83 L + 2.93 = 0$ (Quadratic Equation) (5.74)

L = 11.58'(stress wave decay for a given 4 # explosive weight).

Use of the Square root scaling rule for 50' crater charge ($\frac{\sqrt{W}}{\sqrt{4 \text{ Lbs.}}}$)
where d is the distance from blast center.[53]

L (scaled) = (11.58')(11.73) < 135.83' [Limit of pavement cracking] (5.75)

1. 0.1% fiber case; $\propto$ = 970 psi ; E= 4,482,465 psi @ 144.82 #/cf.

Determine heaved pavement limit based on fiber case.

$$RD = 2 (50') \left[\frac{\sqrt{4{,}482{,}465 \text{psi}/ 144.82 \text{ \#/cf/g}}}{\sqrt{4{,}158{,}817 \text{psi}/ 143.82 \text{\#/cf/g}}}\right] = 103.45'$$ (5.76)

-

Determine the stress wave decay for 0.1 % fiber concrete. (5.77)

$$970 \text{ psi} = (4{,}533 \text{ psi} - 383.33 \text{ psi } L)\left[\frac{\sqrt{4{,}482{,}465 \text{psi}/ 144.82 \#/cf/g}]L}{[\sqrt{8{,}249{,}224} \text{psi} /170 \#/cf/g]}\right.$$

$L^2 - 11.83\ L + 3.17 = 0$ (Quadratic Equation) (5.78)

L = 11.56' (stress wave decay for a given explosive weight).

L (scaled) = (11.56')(11.73) < 135.6' (5.79)

ΔL (pl.-0.1%)= 135.83'- 135.6' =0.23'(difference in wave decay between materials)

Determine 0.1 % FRC heaved pavement diameter around crater. (5.80)

$$RD = 2\ (50') \left[\frac{\sqrt{4{,}482{,}465 \text{psi}/ 144.82\ \#/cf/g}]}{[\sqrt{4{,}158{,}817} \text{psi}/ 143.82 \#/cf/g]}\right. = 103.45' - 2(\Delta L) = 103'$$

Area RD (plain) – Area RD (0.1% fiber); Reduction in fractured pavement = -478 sq.ft (< 0 %) with 0.1% fiber concrete as compared to plain concrete. Not recommended.

2. 0.2% fiber case; $\propto$ =981 psi ; E= 4,179,904 psi @ 143.82 #/cf.

Determine heaved pavement limit based on fiber case. (5.81)

$$RD = 2\ (50') \left[\frac{\sqrt{4{,}179{,}904 \text{ psi}/ 143.82\ \#/cf/g}]}{[\sqrt{4{,}158{,}817} \text{ psi}/ 143.82 \#/cf/g]}\right. = 100.25'$$

Determine the stress wave decay for 0.2 % fiber concrete. (5.82)

$$981 \text{ psi} = (4{,}533 \text{ psi} - 383.33 \text{ psi } L)\left[\frac{\sqrt{4{,}179{,}904 \text{ psi}/ 143.82 \#/cf/g}] L}{[\sqrt{8{,}249{,}224} \text{psi} /170 \#/cf/g]}\right.$$

$L^2 - 11.83\ L + 3.31 = 0$ (Quadratic Equation) (5.83)

L= 11.54' (stress wave decay for a given explosive weight).

L (scaled) = (11.54')(11.73) < 135.36' (5.84)

ΔL (pl.-0.2%)= 135.83'- 135.36' =0.47'(difference in wave decay between materials).

Determine 0.2 % FRC heaved pavement diameter around crater. (5.85)

$$RD = 2\ (50') \left[\frac{\sqrt{4{,}179{,}904 \text{ psi}/ 143.82\ \#/cf/g}]}{[\sqrt{4{,}158{,}817} \text{ psi}/ 143.82 \#/cf/g]}\right. = 100.25' - 2(\Delta L) = 99.32'$$

-

Area RD (plain) – Area RD (0.2% fiber); Reduction in fractured pavement = 106.6 sq.ft (1.4 %) with 0.2% fiber concrete as compared to plain concrete. Similar to plain concrete.

3. 0.3% fiber case; $\propto$ =1,017 psi ; E= 3,735,295 psi @ 141.82 #/cf.

Determine heavied pavement limit based on fiber case. (5.86)

$$RD = 2\,(50') \left[\frac{\sqrt{3{,}735{,}295 \text{ psi}/ 141.82 \#/cf/g}}{\sqrt{4{,}158{,}817 \text{ psi}/ 143.82 \#/cf/g}} \right] = 95.44' - 2(\Delta L) = 94.04'$$

Determine the stress wave decay for 0.3 % fiber concrete. (5.87)

$$1{,}017 \text{ psi} = (4{,}533 \text{ psi} - 383.33 \text{ psi } L)\left[\frac{\sqrt{3{,}735{,}295 \text{ psi}/ 141.82 \#/cf/g}\, L}{\sqrt{8{,}249{,}224 \text{psi}/170 \#/cf/g}} \right]$$

$L^2 - 11.83\,L + 3.6 = 0$ (Quadratic Equation) (5.88)

L= 11.52' (stress wave decay for a given explosive weight).
L (scaled) = (11.52')(11.73) < 135.13'

ΔL (pl.-0.3%)= 135.83'- 135.13'=0.7'(difference in wave decay between materials).

Determine 0.3 % FRC heaved pavement diameter around crater. (5.89)

$$RD = 2\,(50') \left[\frac{\sqrt{3{,}735{,}295 \text{ psi}/ 141.82 \#/cf/g}}{\sqrt{4{,}158{,}817 \text{ psi}/ 143.82 \#/cf/g}} \right] = 95.44' - 2(\Delta L) = 94.04'$$

Area RD (plain) – Area RD (0.3% fiber); Reduction in fractured pavement = 908.31sq.ft (11.56 %) with 0.3% fiber concrete as compared to plain concrete. Recommended.

4. 0.4% fiber case; $\propto$ =980 psi ; E= 3,830,317 psi @ 142.82 #/cf.

Determine heaved pavement limit based on fiber case. (5.90)

$$980 \text{ psi} = (4{,}533 \text{ psi} - 383.33 \text{ psi } L)\left[\frac{\sqrt{3{,}830{,}317 \text{ psi}/ 142.82 \#/cf/g}\, L}{\sqrt{8{,}249{,}224 \text{psi}/170 \#/cf/g}} \right]$$

Determine the stress wave decay for 0.4 % fiber concrete.

$L^2 - 11.83L + 3.44 = 0$ (Quadratic Equation) (5.91)

L = 11.52' (stress wave decay for a given explosive weight).
L (scaled) = (11.52')(11.73) < 135.13' (5.92)

ΔL (pl.-0.4%)= 135.83'- 135.13'=0.7' (difference in wave decay between materials).

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Determine 0.4% FRC heaved pavement diameter around crater. (5.93)

RD = 2 (50') [√ 3,830,317 psi/ 142.82 #/cf/g] = 96.3'- 2(ΔL) = 94.9'
[√ 4,158,817 psi/ 143.82#/cf/g]

Area RD (plain) – Area RD (0.4% fiber); Reduction in fractured pavement = 780.7 sq.ft (10 %) with 0.4% fiber concrete as compared to plain concrete. Recommended.

Calculations comparing FRC material behavior as a function of a shear (Sh) wave without considering stress wave decay are also presented and tabulated for comparison to p wave calculations (Table5.14). Material property comparison from the perspective of a shear (S) wave without considering wave decay; Vs =√ G plain concrete/ γ plain concrete/gravity (g) where γ / g = the material's density (ρ) [37]. G (Shear Modulus)= E/ 2(1 + .15), where Poisson's ratio is assumed as 0.15 for concrete[49].

0.1% Fiber Concrete. (5.94)
RD=2(50')[√ 4,482,465psi/ 2.3/ 144.82 #/cf/g]= 103.5'(no reduction; heaved pavement)
[√ 4,158,817psi/2.3 /143.82#/cf/g]

0.2% Fiber Concrete. (5.95)
RD=2(50')[√ 4,179,904 psi/ 2.3/ 143.82 #/cf/g]= 100.2'(no reduction; heaved pavement)
[√ 4,158,817psi/2.3 /143.82#/cf/g]

0.3% Fiber Concrete. (5.96)
RD=2(50')[√ 3,735,295psi/ 2.3/ 141.82 #/cf/g]= 95.4'(9% reduction; heaved pavement)
[√ 4,158,817psi/2.3 /143.82#/cf/g]

0.4% Fiber Concrete. (5.97)
RD=2(50')[√ 3,830,317psi/ 2.3/ 142.82 #/cf/g]= 96.3'(7% reduction; heaved pavement)
[√ 4,158,817psi/2.3 /143.82#/cf/g]

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Explosive Fracture Modeling Summary.

Fracture energy reduction under high-speed transit motion waves (explosives) improved as a result of fibers tendency to reduce the stiffness and density of concrete. Fiber concrete is better able to resist fracturing with an increase in fiber content due to a lower Modulus of Elasticity value and increased energy absorption capacity through damping. Improved damping and increased toughness properties, such as an increased 1st crack strength value exhibited by polypropylene fiber even in small volumes (<0.5%) in concrete, demonstrates an ability to reduce pavement heave up to 11.6 %(Figure 5.17). Reduction in heaved pavement is an important material property capability for the U.S. Military in Rapid Runway Repair of Airfields. The presented calculations are applicable for any fiber-concrete composite material, as it evaluates the composite's response (based on its unique material properties) to any given detonation. In terms of its contribution to quantifying reduction in heaved pavement, FRC damping (less stiffness due to reduction in Modulus of Elasticity) is the dominate factor, as compared to reductions contributed by fiber-concrete's other material property, 1st crack strength (Table 5.18). However, the precedence of considering the strength of a material to resist cratering from wave energy exists with the empirically derived, Maxwell Z model used by NASA engineers from impact crater observations. The Maxwell Z model is defined with a dimensionless "strength characteristic" value ($\propto$) =V (velocity of the mass) R^3 (crater radius)/t (time) [52]. The results regarding heaved pavement reduction are similar, and match well with the laboratory testing values for toughness (Figure 5.17).

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Table 5.18: Heaved Pavement Reduction Summary.

Fiber Content	Material (p wave) Properties	Stress wave Decay(1st Crack Strength)	Sum of Material and Decay Values	Shear(Sh) Wave
Plain	No reduction	No reduction	No reduction	No reduction
0.1%	No reduction	No reduction	No reduction	No reduction
0.2%	No reduction	1.4 % reduction	1.4 % reduction	No reduction
0.3%	8.9% reduction	2.7 % reduction	11.56 % reduction	9 % reduction
0.4%	7.3% reduction	2.7% reduction	10 % reduction	7% reduction

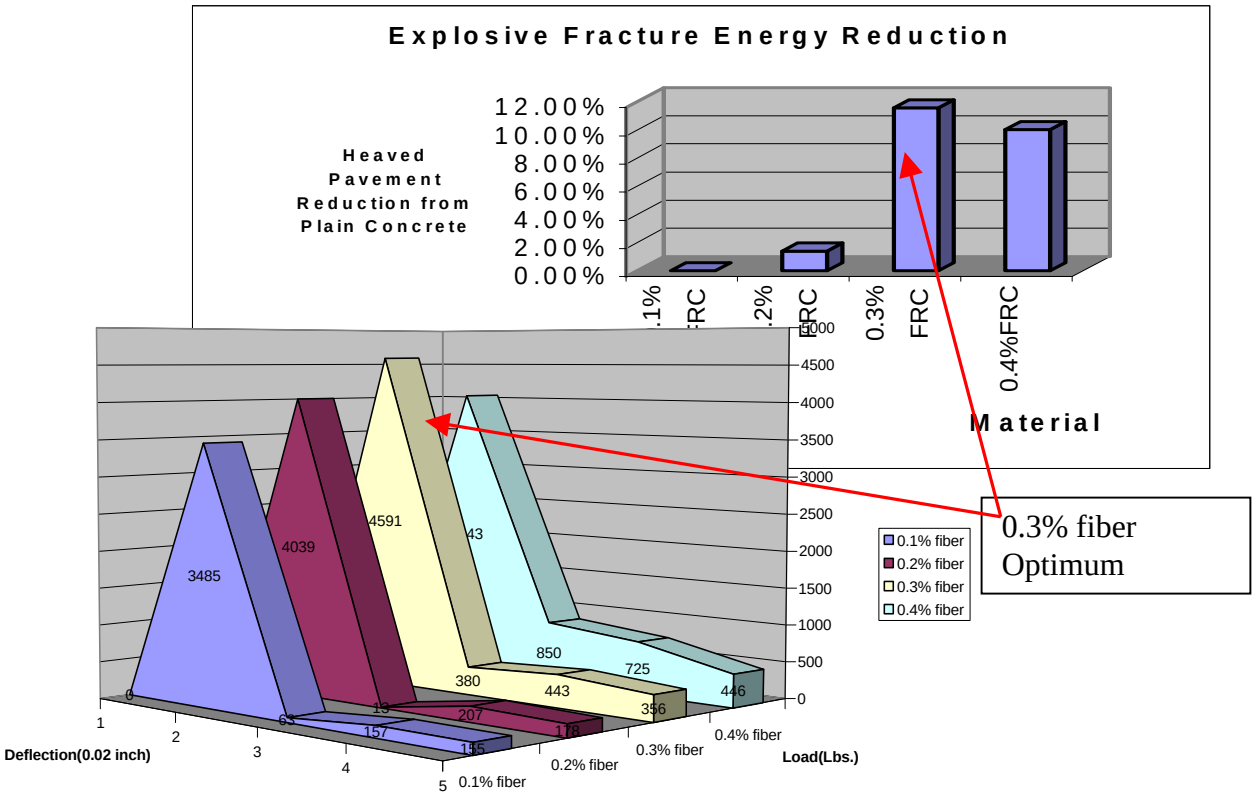

Figure 5.17: Heaved Pavement Reduction Toughness Results.

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CHAPTER 6. CASE STUDY ANALYSIS OF THE INTEGRATED DESIGN AND SELECTION METHODOLOGY FOR FRC AIRFIELDS.

INTRODUCTION

A case study is presented in this chapter for demonstrating the different steps and analysis of this methodology. Consider a foreign policy scenario not unlike the Berlin Airlift after World War II. A democratic, landlocked sub-Saharan nation is in conflict with its neighbors who have closed off their borders to all commerce including food to a now starving population. This now starving democratic nation has asked the United States for help and a marginal amount of food is being flown in on C-130 cargo aircraft due to the limited number of short asphalt airstrips located throughout this impoverished nation. United States military engineers have been sent to the capital of this nation to consider the feasibility in building a 3,000-foot concrete runway for C-17A operations. Sustained airlift operations with the C-17A aircraft, to replace the C-130 Aircraft, can provide the needed logistics to avert a famine crisis occurring in this nation prior to a settlement of this conflict, which will take at least a year. The engineers have determined that there is a ready source of sand, aggregate and cement for concrete production meeting MD-7 specifications. Engineering units and equipment are now in country to begin construction, with a 30 day tasking to complete the runway and another 30 days to construct parking aprons and taxiways. After construction, the runway will be expanded for civilian aircraft. At this time, there is a threat of air strikes with conventional munitions from hostile military aircraft.

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CASE STUDY

Step 1. Evaluate and Select New Fiber Material.

In this step fiber reinforced concrete selection should meet four targeted properties of High Performance Airfield Concrete (HPAC) outlined in Chapter three.

1. Reduce deflections, compressive stresses and horizontal strains reflected through the FRC composite to underling pavement surfaces due to aircraft gear geometry and repetitive loading. Accomplish this through optimized FRC material strength properties such as MOR and fatigue strength.

2. Reduce airfield pavement surface deterioration and minimize foreign object debris (FOD) damage. Accomplish this through FRC material properties that reduce pavement shrinkage, cracking and scaling potential due to construction, maintenance, traffic abrasion and thermal stresses.

3. Enhance energy absorption characteristics of the composite such as toughness, ductility, and impact resistance to minimize heaved pavement damage generated by explosive catering.

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4. Enhance constructability of rigid airfield pavements in terms of ease of placement (workability), and thickness reduction. Optimize FRC material properties to reduce design thickness, yet maintain workability to reduce construction time and cost.

As concluded in the literature research detailed in Chapter two, there is significant indication from past studies that less than 0.5% by volume polypropylene fiber enhances the fatigue and flexural strength of rigid airfield pavements without excessive deflections. Fatigue strength and flexural strength are the dominant material characteristics in achieving a 20-year pavement design life as specified by the FAA and the military. The goal of this selected fiber is that at optimized polypropylene fiber content, concrete airfields designed for a specified aircraft mix and design life can have a smaller equivalent thickness as compared to plain (0.0% fiber) concrete pavement. The high tensile strength of polypropylene and its ability to bridge microcracks results in higher fatigue endurance limits for concrete. This composite pavement will also have a smaller Modulus of Elasticity value, which will contribute to a reduction in thermal stresses due to a less stiff, thinner rigid pavement section. At volumes of less than 0.5%, historical problems associated with fiber concrete at greater volumes, 0.5 to 2.0 percent by volume such as excess deflection, creep, workability and durability becomes insignificant[6]. If you consider a 10,000-foot long, 300-foot wide military runway, whose design thickness can be reduced by even one half inch by use of this composite, the economics are significant. In terms of material costs and construction time, in the magnitude of 4,650 Cy at $150/Cy or $697,500. Additionally, this composite exhibits superior crack control characteristics, which in military and civilian airfields not only enhances pavement longevity and surface

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serviceability, but also reduces foreign object debris (FOD) damage to high performance aircraft engines. Polypropylene also possesses material properties that increase concrete's ductility and dynamic energy absorption capability (toughness), which are performance characteristics desired by the military in reducing bomb damaged airfield pavement. Polypropylene fiber reinforced concrete (FRC) increased toughness can reduce the amount of heaved pavement required to be removed and replaced, saving invaluable time to aircraft sortie generation after an attack. Literature review and laboratory testing suggests that FRC has four times the energy absorption capability of plain concrete and the impact is significant. Under these conditions, the amount of heaved pavement needing to be replaced can be reduced, and the reduction is quantifiable.

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Table 6.1 summarizes material properties of low volume (< 0.5%) polypropylene fiber reinforced concrete as compared to plain (0% fiber) concrete, as determined through extensive literature search in Chapter two. Table 6.1 also identifies HPAC properties (highlighted) governing airfield pavement performance that are selected for further evaluation.

Table 6.1:Polypropylene Fiber Concrete Properties.

Material Property/Behavior	Polypropylene reinforced concrete; average values	Plain (unreinforced) concrete; average values
Static flexural strength	Increase (< 15%)	720 psi
Tensile strength	Increase (<10%)	620 psi
Dynamic fatigue strength	Significant (18%+ increase)	450 psi
Endurance limit	Significant (18% + increase)	2 million cycles
Flexural Toughness	Significant (I = 4.1)	I = 1(first crack)
Compressive strength	Ductile failure/6,100 psi	Shatter failure/6,050 psi
Creep strain	Increase (+10%)	Stress /strength ratio > 0.55
Plastic/ shrinkage cracking	Reduced crack width/cracking	12%+ more cracked surface
Freeze-thaw resistance	Function of air entrainment	80% weight/ 1000 cycles
Impact resistance	¼ - ½ inch fibers/ Increase at Failure	65 blows (ACI 544)
Permeability	Silica fume additive/increase	2.6% water migration
Abrasion Resistance	Same	Same(ASTM C 944/C799)
Workability	Superplasticizers/ same	Better workability
Elastic modulus	Matrix same/fiber (500 ksi)	E > 3.5 x 10^6 psi
Poisson's Ratio	No research	0.2
Thermal expansion	No research	0.0000055 per °F

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Step 2. HPAC Laboratory Testing.

Targeted material properties of a FRC composite that would be characteristic of a High Performance Airfield Concrete (HPAC) would be those properties that reduce pavement surface deterioration and foreign object debris (FOD) damage to aircraft. Also, material properties that enhance constructability, such as workability and reduce design thickness and subsequently reduce agency costs, such as construction time and materials. Most importantly for the military, material properties that enhance survivability such as toughness and impact resistance are considered in HPAC. The material properties identified for HPAC in Step one would be selected for laboratory testing as in Chapter four and evaluated for their potential contribution to pavement performance.

Quantify the workability characteristics of 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete through optimized mix design, slump cone and air content testing using concrete mix design MD-7 (Table 4.1) .

Laboratory testing in Chapter four confirmed cast in place concrete will accommodate up to 0.4 percent by volume of polypropylene fibers with minimal mix proportion adjustments. Good workability can be maintained in polypropylene fiber reinforced concrete (FRC) by adding an appropriate amount of admixtures. Slump and air content values provide an indication of workability of a concrete mix. Given a limited

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slump range; 1 –1/2 to 3 inches and fixed air content of 6.5%, adequate mix design was maintained using water reducers and air entraining admixture (Tables 4.2, 4.3).

Quantify the energy absorption characteristics of 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete through toughness, ductility and impact resistance testing.

Toughness testing provides for the determination of ratios called Toughness Indices that identify the pattern of material behavior of FRC up to a selected deflection. Indices represent a ratio of remaining energy (load-deflection areas expressed in Foot. Lbs.-inch) at 3, 5.5 and 10.5 times first crack deflection as compared to the energy triangle at first crack. As example, plain concrete has I –5,10, 20 values of one. This manifestation of toughness or energy absorption capability is relevant in such engineering applications as the reduction of heaved pavement from explosive cratering, where preservation of structural integrity even after severe damage is of primary concern. Toughness testing was conducted on 12 FRC samples at the University of Maryland and is detailed in Chapter 4. Toughness Indices compared favorable with current research, but residual strength values showed little perfect plastic behavior of these composite at large deflections. Laboratory Toughness Indices at 0.3% fiber content were 3.17, 3.63 and 4.5 for I-5, 10, 20 respectively. Indicating a fourfold ability of the FRC composite to absorb energy as compared to plain concrete after cracking (Figure 4.9). The toughness of concrete improves with increases in fiber volume, and first crack strength optimized at a fiber content of 0.3% (Figure 4.10).

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In the “Investigation of Fiber-Reinforced Concrete for Use in Transportation Structures” [13] the results for impact resistance indicated the number of blows to first crack and ultimate failure increases with increasing fiber volume as tabulated in Table 2.6.

ASTM C 39; Compressive Strength of Cylindrical Concrete Specimens determines the compressive strength of 6 inch x 12 inch concrete cylinders by applying a continuously increasing axial load to the specimen until failure occurs. We tested twenty-five, 6 inch X 6 inch X 12 inch concrete cylinders as discussed in Chapter four, evaluating varying volumes of polypropylene fiber. On average, the compressive strength for plain, 0.1%, 0.2%, 0.3% and 0.4% fiber reinforced concrete was 5,339 psi, 6,075 psi, 5,394 psi, 4,543 psi and 4,869 psi respectively. The addition of fiber beyond 0.2% resulted in a corresponding decrease in compressive strength by 10% at 0.4 % fiber content. However, the fibers had a significant effect on the mode and mechanism of failure of concrete cylinders in the compression test. The mode of failure was more ductile, crushing samples rather than failing them in shear, where the cylinders endure large deformations without shattering (Figure 4.18). Evaluation and observation of all flexural, fatigue, compressive and toughness specimens showed an increase in energy absorption and ductility of concrete possessing greater volumes of polypropylene fiber as compared to plain concrete (Figures 6.1, 6.2).

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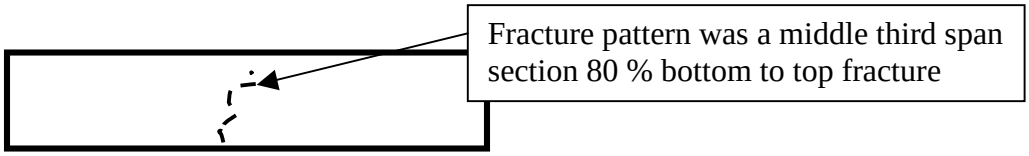
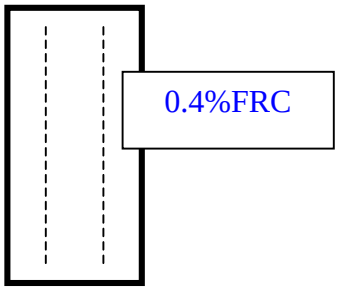
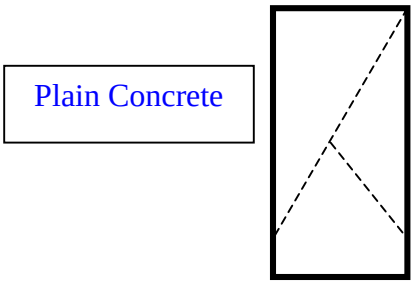


Fatigue Beam Specimen (0.4 % FRC-w/c = 0.44).

Figure 6.1: Fracture Reduction Observation.



Fracture pattern columnar at 4,869 psi .



Fracture pattern cone and shear at 5,339 psi.

Figure 6.2: Cylinder Specimen Failure.

Shrinkage Prediction.

Quantify the shrinkage characteristics of 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete through restrained and free shrinkage testing .

Characterize surface distress (cracking).

- Evaluate unrestrained shrinkage (ASTM 157) for 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete.

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- Evaluate restrained cracking (Steel Ring test) for 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete.

An inherent material property of concrete when drying is shrinkage. The amount of shrinkage depends on a number of factors such as the size and age of the concrete sample as well as environmental conditions such as temperature and humidity. If the concrete structure is restrained from shrinking, such as highway and airfield pavements, tensile stresses will develop causing the pavement to crack. Cracking is a major concern in airfield pavements due to FOD generation, loss of strength, durability and degradation of the subgrade through pumping.

Laboratory testing at the University of Maryland was conducted on twenty-seven, 6 inch X 6 inch X 21 inch free shrinkage concrete beams of varying fiber content 0%(plain), 0.1%, 0.2%. 0.3% and 0.4%. Results indicated the additions of polypropylene fibers do not significantly alter drying shrinkage (Figures 4.24, 4.25). Grzybowski and Shah reported similar results and concluded that the primary advantage of fibers in relation to shrinkage is their effect in reducing the adverse width of shrinkage cracks.[24] The ACI has not declared a standard test for plastic or restrained shrinkage evaluation of FRC. However, FRC results using the steel ring test indicate a 20%-90% reduction in cracking and crack width as compared to a plain concrete (Figure 6.3). No cracking was observed in laboratory steel ring tests over a temperature range of -30 to 23 degrees Celsius.

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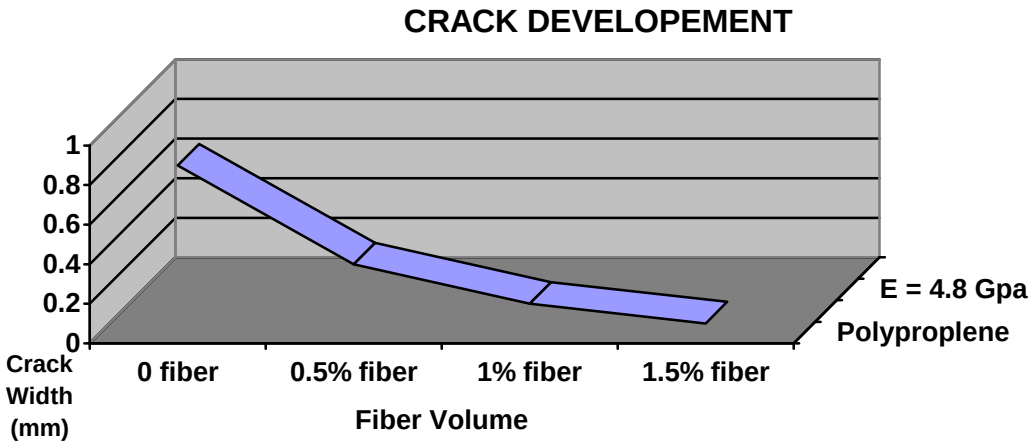

Figure 6.3: Restrained Shrinkage Cracking (ref. Grzybowski, Shah 1990).

Step 3. FRC Design Thickness Predictions. For carrying out the analysis, a finite element method using KenSlabs was selected. KenSlabs has great versatility in validating improvements in FRC strength through design thickness reduction and reduction in thermal stresses by evaluating the material properties for different mixtures. The inputs to consider in the analysis are:

1. Aircraft Geometry. The gear and tire footprint of a specific military aircraft, which is considered the critical contributor to airfield pavement damage. In this case, the Boeing C-17 Globemaster III aircraft.

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Example; Design Aircraft. The C-17 is capable of rapid strategic delivery of troops and all types of cargo directly to forward bases into the deployment area outlined by this scenario. The aircraft is also capable of performing tactical airlift and airdrop missions when required[45]. Maximum takeoff gross weight is 585,000 pounds with a maximum payload of 169,000 pounds. With a payload of 160,000 pounds, the C-17 can take off from a 7,600-foot airfield, fly 2,400 nautical miles and land on a small, austere airfield of 3,000 feet or less in length. Gear configuration is tandem, dual wheels with tandem spacing of 97 inches and 41.5 inch spacing between dual tires. The tire pressure is 138 psi.

2. Traffic. A fixed number of aircraft takeoffs and landings. In this case, at least 2,000,000 passes in this analysis.

3. Material Properties. Essentially, the Modulus of Rupture values, Modulus of Elasticity values, Poisson's ratio and maximum flexural strength (fmax) values as determined from literature review or laboratory testing of plain, 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber content are considered. Moduli of Rupture values for FRC from Chapter four are 868 psi, 970 psi, 981 psi, 1,017 psi and 980 psi respectively. Flexural strength (fmax) values are 521 psi, 570 psi, 525 psi, 567 psi and 513 psi. An average Poisson’s Ratio value of 0.15 and an average Modulus of Elasticity value of 4,000,000 psi is selected.

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4. Seasonal adjustment factors. Adjustments (15 % reduction) to a standard set of subgrade strength values due to environmental conditions such as spring thaw. The selected subgrade strength values are a Young's Modulus of 5,000 psi, and a Poisson's ratio 0.2.

5. Load Variables. Generally an increasing range of contact tire pressure stress values per aircraft, that determines the relationship between stress levels and pavement thickness for a given FRC material for a given aircraft, the C-17 (Table 5.6).

As shown in Chapter five, KenSlabs analysis provided a linear relationship between stress level and rigid pavement thickness for the Boeing C-17 aircraft footprint and for edge loading conditions at a slab tensile stress of 405 psi (Table 5.6). When graphed, the relationship yielded a design thickness to stress level equation of y = 17.73x + 5.898 (Figure 5.12, Constant D C-17A Aircraft). In compliance with the Military and FAA's six-inch minimum pavement thickness, adequate deflection control (< 0.05 inches) was maintained. The L-D constants were defined as 17.73 inches and 5.90 inches respectively. As indicated previously, this equation allows determination of airfield pavement thickness as a function of static flexural strength. Therefore for predicting the 20-year design life for a rigid airfield pavement for this aircraft the equation becomes:

T (concrete) = [17.7”(tp/ Sc) +5.9”] ; Sc for plain concrete. (6.1)

T (concrete) = [17.7”(tp/ Sc-fiber) +5.9”] **;** Sϵ fiber = fiber volume (0.1%, 0.2%, 0.3%, 0.4%) MOR (psi).

-

T (plain concrete) = [17.7”(138 psi/ 868 psi) +5.9 ”] = 8.7 inches (6.2)

T (0.1% fiber concrete) = [17.7”(138 psi/ 970psi) +5.9 ”] = 8.4 inches (6.3)

T (0.2% fiber concrete) = [17.7”(138 psi/ 981psi) +5.9 ”] = 8.4 inches (6.4)

T (0.3% fiber concrete) = [17.7”(138 psi/ 1017 psi) +5.9 ”] = 8.3 inches (6.5)

T (0.4% fiber concrete) = [17.7”(138 psi/ 980 psi) +5.9 ”] = 8.4 inches (6.6)

This equation also allows determination of pavement thickness as a function of fatigue strength. Based on KenSlabs analysis, airfield pavement thickness for edge loading of a C-17 military aircraft for 2,000,000 passes is as follows.

T (concrete) = [17.7 ”(tp/ Sc) +5.9”] [f max/ fv max]½ (6.7)
for tp/ Sc < 0.7 stress levels[S < 0.5 stress ratio]

Where:
T (concrete) = Rigid airfield pavement design thickness (inch).
L(tp/ Sc) +D = minimum pavement thickness(inches) for plain concrete.
tp = Aircraft tire pressure in psi.
Sc = Modulus of Rupture of 0% fiber (plain)Concrete (psi).
fv = Fatigue strength (psi) at 2,000,000 cycles for FRC.
fmax = Fatigue strength (psi) at 2,000,000 cycles for plain concrete.

T (plain concrete) = [17.7 ”(138 psi/ 868 psi) +5.9”] [521/ 521psi)] ½ = 8.7" (6.8)

T (0.1% fiber concrete) =
[17.7”(138 psi/ 868 psi) +5.9”] [521/ 570 psi)] ½ = 8.3 inches (6.9)

T (0.2% fiber concrete) =
[17.7”(138 psi/ 868psi) +5.9”] [521/ 525 psi)] ½ = 8.7 inches (6.10)

T (0.3% fiber concrete) =
[17.7”(138 psi/ 868 psi) +5.9”] [521/ 567 psi)] ½ = 8.4 inches (6.11)

T (0.4% fiber concrete) =
[17.7”(138 psi/ 868 psi) +5.9”] [521/ 513 psi)] ½ = 8.8 inches (6.12)

-

KenSlabs showed a quantifiable improvement in FRC pavement strength by a reduction in design thickness. In this case, 0.3 inch reduction for 0.1 % -0. 4% FRC as compared to plain concrete in the flexural strength. Fatigue strength at 2,000,000 cycles increased when fibrillated polypropylene was added to concrete. In this case, 0.4-inch reduction for 0.1% and, 0.3 inch reduction for 0.3% FRC in design thickness as compared to plain concrete.

Conventional airfield design thickness is computed for plain concrete and then reduced by the appropriate PRV listed in Table 6.2. Boeing 777, Boeing 747, Boeing C-17, Lockheed Martin C-141 design thickness values were determined in Chapter five based on LED-FAA standards or military standards by traffic area using KenSlabs and are tabulated (Table 6.2). In this case, enter Table 6.2 at the C-17A aircraft, select the appropriate design thickness traffic area. As example, for runways (traffic area A) the minimum design thickness is 10.5”. Subtract the PRV for 0.1% or 0.3% fiber content which is 0.4”, then the final design thickness is 10.1” for an FRC military runway for the C-17 aircraft operations.

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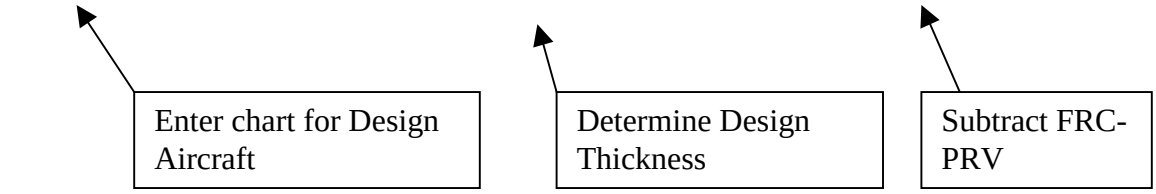
Table 6.2: Single/Multi-Aircraft Design Thickness.

Aircraft	Annual Departures	Mil.Std.(Kenslab) Design Thickness By Traffic Area	LED-FAA Design Thickness	Fiber Content/PRV thickness reduction value(avg.)
Boeing 777 Boeing 747 C-141	33,000 33,000 33,000		19.44 inches (MOR;800psi)	0.1%/0.3”reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
Boeing 777 Boeing 747 C-141 C-17A	25,000 25,000 25,000 25,000		19.22 inches (MOR;800psi)	0.1%/0.3”reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
Boeing 777	100,000	8.3 inches Class C traffic areas (MOR;868 psi) Class A/B traffic Areas; 10.5 inches		0.1%/0.4”reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
C-141	100,000	8.7 inches Class C traffic areas (MOR;868 psi) Class A/B traffic Areas; 10.5 inches		0.1%/0.4” reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction
C-17A	100,000	8.7 inches Class C traffic areas (MOR;868 psi) Class A/B traffic Areas; 10.5 inches		0.1%/0.4” reduction 0.2%/0.2” reduction 0.3%/0.4” reduction 0.4%/0.2” reduction



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Thermal Stress and Deflection Predictions.

KenSlabs modeling using the C-17 aircraft design thickness and a 20° F temperature differential between the base and top of the 25 foot concrete airfield slab yielded the following thermal stress results quantified in Table 6.3. There is a decrease in temperature curling stresses with increasing fiber volume, which reduces total slab stresses during typical daylight aircraft loading conditions. This appears to be a function of decreasing Modulus value and thickness associated with FRC composites. Quantifiably, a reduction of 19.8 psi of curling stresses between plain and 0.3% fiber concrete. Based on Table 5.15, no significant reductions in corner deflection can be expected in design thickness difference of 0.4 inches or less.

Table 6.3: KenSlabs Thermal Stress Results.

Fiber Case	**Modulus of Elasticity**[46] (psi)	**Unit wt.** (**pcf)**	**Fatigue Design Thickness**	**Curling Stress (psi)**	**Thermal Stress reduction; psi**
Plain	4,177,328	142.82	8.7 inches	247.90	baseline
0.1%	4,663,892	147.82	8.3 inches	276.80	--------
0.2%	4,180,341	143.82	8.5 inches	248.30	--------
0.3%	3,836,315	143.82	8.3 inches	228.10	19.8 psi
0.4%	3,888,886	141.82	8.5 inches	231.10	16.8 psi

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Agency Costs (Construction time and materials).

Adequate FRC workability for 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber concrete as compared to plain (0%fiber) concrete can be maintained using admixtures. Therefore, determination of reduction in agency costs by pavement thickness reduction model is the only relevant cost criteria (Table 6.4).

Table 6.4:Agency Cost Matrix -Mix Design # 7.

Specimen	**C-17Aircraft Design Thickness**	**FRC Pavement Reduction Value (PRV)**	**Material savings; C.Y.s of Concrete 150'x 3,000' runway**	**Material savings (dollars)**
Plain Concrete	8.7 inches	----------	----------	----------
0.1% FRC	8.3 inches	0.4 inches	556 cy	$83,400.00
0.2% FRC	8.5 inches	0.2 inches	278 cy	$41,667.00
0.3% FRC	8.3 inches	0.4 inches	556 cy	$83,400.00
0.4% FRC	8.5 inches	0.2 inches	278 cy	$41,667.00

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Step 4. FRC Heaved Pavement Predictions.

Reduction in heaved pavement is an important material property capability for the U.S. Military in Rapid Runway Repair of airfields. The calculation of reduction in heaved pavement fracturing based on 0.3 % polypropylene fiber concrete as compared to plain concrete are shown next. Chapter five provides modeling for all fiber cases, showing reduction in heaved pavement crater diameter (RD) in function of FRC material properties.

Given the 100' diameter of heaved pavement surrounding a 50' crater on a plain concrete runway with a 1st crack strength =868 psi. If we added 0.3% fiber to the mix during construction, could we reduce the amount of heaved pavement?

$$RD = \frac{2D\,[\sqrt{E\ 0.3\%\text{fiber concrete}}/\ \gamma\ \text{fiber concrete}/(g)]}{[\sqrt{E\ \text{plain concrete}}/\ \gamma\ \text{plain concrete}/(g)]} - 2(\Delta L) \quad (6.13)$$

RD = 100’(0% fiber) plain concrete for 50’ crater; 1st Crack = 868psi;
E= 4,158,817 psi@143.82#/cf. (g= 32.2 ft./sec-sec)

Determine the stress wave decay for plain concrete.

$$868\ \text{psi} = (4{,}533\ \text{psi} - 383.33\ \text{psi}\ L)\frac{[\sqrt{4{,}158{,}817\ \text{psi}}/\ 143.82\ \#/\text{cf}/g\ ]}{[\sqrt{8{,}249{,}224\text{psi}}\ /170\#/\text{cf}/g]}\ L \quad (6.14)$$

E granite = 8,249,224 psi@170 #/cf. (g= 32.2 ft./sec-sec)

$$L^2 - 11.83\ L + 2.93 = 0 \text{ (Quadratic Equation)} \quad (6.15)$$

L = 11.58’(stress wave decay for a given 4 # explosive weight).

Use of the Square root scaling rule for 50' crater charge ($\frac{\sqrt{W}}{\sqrt{4\ \text{Lbs.}}}$)
where d is the distance from blast center.[53]

$$L\ (\text{scaled}) = (11.58')(11.73) < 135.83' \quad (6.16)$$

-

Determine heaved pavement limit based on fiber case.

0.3% fiber case; 1st Crack =1,017 psi ; E= 3,735,295 psi @ 141.82 #/cf.

$$RD = 2\,(50') \left[\frac{\sqrt{3{,}735{,}295 \text{ psi}/ 141.82 \text{ \#/cf/g}}}{\sqrt{4{,}158{,}817 \text{ psi}/ 143.82 \text{\#/cf/g}}} \right] = 95.44' \quad (6.17)$$

Determine the stress wave decay for 0.3 % fiber concrete. (6.18)

$$1{,}017 \text{ psi} = (4{,}533 \text{ psi} - 383.33 \text{ psi L}) \left[\frac{\sqrt{3{,}735{,}295 \text{ psi}/ 141.82 \text{\#/cf/g}}}{\sqrt{8{,}249{,}224 \text{psi}/170 \text{\#/cf/g}}} \right] L$$

$$L^2 - 11.83\,L + 3.6 = 0 \text{ (Quadratic Equation)} \quad (6.19)$$

L= 11.52' (stress wave decay for a given 4 # explosive weight).

$$L \text{ (scaled)} = (11.52')(11.73) < 135.13' \quad (6.20)$$

ΔL (pl.-0.3%)= 135.83'- 135.13'=0.7' (difference in wave decay between materials)

Determine 0.3 % FRC heaved pavement diameter around crater.

$$RD = 2\,(50') \left[\frac{\sqrt{3{,}735{,}295 \text{ psi}/ 141.82 \text{ \#/cf/g}}}{\sqrt{4{,}158{,}817 \text{ psi}/ 143.82 \text{\#/cf/g}}} \right] = 95.44' - 2(\Delta L) = 94.04' \quad (6.21)$$

Area RD (plain) – Area RD (0.3% fiber); Reduction in fractured pavement = 908.31 sq.ft (11.56 %) with 0.3% fiber concrete as compared to plain concrete.

As the calculations show, heaved pavement reduction is improved as a result of fibers tendency to reduce the stiffness and density of concrete and in its increased strength properties (Figure 5.17). Both reduced stiffness and increased strength properties exhibited by polypropylene fiber, even in small volumes (<0.5%) in concrete, demonstrates an ability to reduce pavement heave by 11 % as a result of explosive cratering (Table 5.18). Also, this analysis methodology is iterative for any concrete composite material, as it measures the composite's response based on its unique material properties to any given detonation.

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Step 5. Field-Testing. Implementation (construction) of optimized FRC slabs for actual field-testing. Feedback from field-testing becomes input data for iterative system engineering analysis (Figure 3.9: System Engineering Schematic). Field data acquisition yields improvements in test methods, data collection as well as deterioration modeling.

- **Aircraft Loading.** Control (0%fiber) and FRC slabs are constructed on an airfield for actual load testing by passing aircraft**.** Measure deflection and strain under load and determine FRC's actual material properties (Modulus value) from compressive strength testing. Install horizontal strain gages and calculate horizontal tensile stress using Hooke's law for specific aircraft passes. Calculate number of aircraft passes and measure deflection and compare to analytically derived KenSlabs tensile stress of 405 psi for the C-17 aircraft at design thickness. Determine which FRC slab performs the best under load for a specific aircraft.

- **Environmental testing**. Control (0%fiber) and FRC slabs are constructed by the airfield for shrinkage testing; record cracking, thermal stresses and volumetric changes. Record cracking using the pavement condition index (PCI) visual method. Conduct pulse velocity testing to determine slab deterioration. Record thermal stress induced slab measurements and using the deflectometer, record density changes due to weathering and stresses (internal cracking). Install thermal couples and determine FRC's actual material properties such as the coefficient of thermal expansion (α), then calculate thermal stresses using KenSlabs. Determine which FRC slab performs the best under a specific local environment.

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- **Explosive testing.** Control (0%fiber) and FRC slabs should be constructed for Ammonium Nitrate-Fuel Oil (ANFO) explosive testing. After explosive testing, record the reduction in radial fractured FRC pavement from a given charge as compared to plain concrete. Chart relationship between explosive type/net explosive weight, bore hole diameter and radial distance of heaved pavement from crater center. The United States Air Force (USAF) defines the Repair Quality Criteria (RQC) for heaved pavement as a pavement with greater than ¼ inch vertical displacement. Determine which FRC slab provides the greatest reduction in heaved pavement based on its material properties.

Conclusion.

Considering both the U.S. Military's and commercial aviation's global reach, similar to SuperPave, FRC rigid pavement design may be regionally specified based on local desired performance criteria due to mission, environment and threat as well as local material (design mix) properties. In our sub-Saharan construction scenario, expediency and survivability are the critical mission requirements. Table 6.3 suggests that use of 0.3% fiber reinforced concrete will reduce over 556 cubic yards of concrete from our initial construction of a 150' wide, 3,000' runway for initial C-17A operations, twice that for follow on apron and taxiway construction. Using material costs as a metric, a savings of over $83,000 (Table 6.4). Selection of the 0.3% fiber reinforcement also provides up to 11 % reduction in airfield heaved pavement, as a result of any air attack with conventional munitions, as determined in the Step three calculations. From our literature

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search summary in Step one, we can also expect good workability with superplasticiters and good crack control, as 0.3 % fiber reinforcement reduces adverse crack width in half (Table 2.7). Even though we expect the conflict to end in a year, long term benefits offered by higher volumes of fiber content includes thermal stress reduction (Table 6.3), enhanced toughness (Figure 4.9), ductility (Figure 4.18) and impact resistance (Table 2.6) as characterized in step two and Chapter four laboratory testing. Final mixture selection is both available material and scenario driven, but rapidly determined by thoughtful research, analysis and building of planning tables like Table 6.5 ahead of time. As example, if the U.S. Military were considering short term basing and airfield construction in Eastern Europe's predominately wet, but low air threat environment, a 0.1 % polypropylene fiber mix might be considered due to lower costs.

Table 6.5: FRC Selection based on HPAC Performance Results.

HPAC Performance Criteria; C17Aircraft. (FRC Mix # 7)	Plain Concrete	0.1% FRC	0.2% FRC	0.3% FRC	0.4% FRC
Fatigue Strength Design thickness	-------	**0.4 inch reduction**	no reduction	0.3 inch reduction	--------
Flexural Strength Design thickness	-------	0.3 inch reduction	0.3 inch reduction	**0.4 inch reduction**	0.3 inch reduction
Thermal Stresses	-------	-------	-------	**19.8 psi reduction**	16.8 psi reduction
Explosive Model Heaved Pavement	-------	no reduction	1.4% reduction	**11.6 % reduction**	10 % reduction
Toughness			I-5; 1.7	**I-5; 2.4**	I-5; 2.8
Ductility					**Optimum**
Impact Resistance	Blows to failure; 68	Blows to failure; 68	Blows to failure; 69	Blows to failure; 69	**Blows to failure; 94**
Crack Reduction			**Optimum**		
Workability	**Optimum**				
Agency Cost		**Least cost**			

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CHAPTER 7. SUMMARY, CONCLUSIONS AND FUTURE RECOMMENDATIONS

SUMMARY

The main objective of this research is development of an integrated concrete material design/selection methodology for fiber reinforced concrete composite pavements. The task was to quantify the structural and energy absorption potential of low volume (<0.5%) polypropylene fiber reinforced concrete in structures such as rigid airfield pavements. This was accomplished through concrete laboratory testing, literature research and finite element modeling with specific airfield or pavement computer programs that lead to the development of performance based design equations. The function of these predictive equations is to quantify the effect of different volumes of polypropylene fiber in reducing airfield pavement thickness or reducing the damage to a pavement structure through dynamic loading, such as repetitive aircraft passes or explosive bomb damage. Through the same venue, an offset study was conducted on workability, durability, deflection, creep, thermal stresses, shrinkage and cracking to ensure none of the historical problems associated with larger volumes (>0.5%) of fibers in concrete composites occur. The end result of this study is a performance-based, integrated mixture design/selection methodology coupled with pavement design requirements. It is recognized that computer and performance modeling, laboratory testing or any literature research can not capture the real life aircraft loading conditions or replace explosive testing. These performance models or pavement thickness reduction equations and values require further evaluation in the field under real world conditions.

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Essentially, the objective proposed in this dissertation was to construct a rational framework for comprehensively evaluating all facets of fiber-reinforced concrete's (FRC) materials' behavior and design as it applies to improving the performance of the airfield pavement as a system. Much of the Military's current rigid pavements design methodology focuses on structural thickness determination, a single criteria approach to design, independent of concrete mix properties and their behavior over a range of other performance requirements.

Chapters three proposed an integrated mix design methodology for fiber reinforced concrete (FRC) as a high-performance airfield concrete (HPAC) pavement. In brief, the five steps of the methodology are:

Step 1. Conduct extensive literature research to determine the FRC material properties for HPAC.

Step 2. Establish laboratory-testing protocols to evaluate desired HPAC-FRC material behavior and obtain data values, which then could be analyzed to predict rigid airfield pavement performance.

Step 3. Through finite element programs, establish prediction equations estimating design pavement thickness reduction based on aircraft footprint and FRC material properties.

Step 4. Determine heaved pavement reduction based on the rheological properties of FRC containing up to 0.4% by volume of polypropylene fiber concrete.

Step 5. Propose a process for field testing analytically derived airfield pavement performance models with actual conditions in an iterative model improvement process.

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CONCLUSIONS

To be significant, in terms of contribution to the engineering community, research must be geared towards application otherwise it just serves itself. Innovation in pavement design management has and will clearly involve the interaction of universities, industry and public agencies such as the Defense Department to exploit future innovations in pavement design research[34]. In addition to traditional academic sources of research such as the Transportation Research Board (TRB) and American Concrete Institute (ACI), the Internet is a powerful research tool on reviewing ongoing FRC research at other universities and with polymer vendors. Most important, is the analysis of this data by military engineers with the practical experience and academic acumen to sort through tremendous amount of data on emerging composite material technology and recognize the HPAC potential for selection of an FRC composite for further analytical evaluation. Generic tabular data is important to the military in making engineering decisions in remote locations with limited material testing data or available design time. Final mixture selection is both available material and scenario driven, but rapidly determined by thoughtful research, analysis and building of such planning tables ahead of time. Table 6.5 provides an example of its application and is proposed for use in determining and tabulating identified high performance airfield concrete material characteristics for a given aircraft, mix design and environment (location).

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Through laboratory testing of material properties such as fatigue, toughness and static flexural strength, polypropylene FRC showed a modest but consistent increase in those tensile strength properties that would increase the life of the pavement structure under repetitive aircraft traffic. Through computer modeling, this composite also showed a reduction in thermal stresses due to lower modulus of elasticity values. This increase in strength and reduction in stiffness could reduce required pavement design thickness by ¼ inch to ½ inch for a fixed aircraft traffic loading and design life. In terms of economics, if you consider constructing an entire airfield the implications are significant, in the magnitude of saving $ 700,000 for the runway construction alone if you can reduce the runway's design thickness as stated. The increase in toughness of this composite as compared to conventional concrete not only increases pavement life, but is significant to the military in mitigating heaved pavement around bomb damaged runway craters during Rapid Runway Repair (RRR). During Rapid Runway Repair, time to repair heaved pavement being the single most important criteria to air base survivability by the United States Military.

Essentially, there were six tasks supporting the stated research objective.

1. Characterize the workability of small volume (<0.5%) polypropylene FRC composites.

- Laboratory testing confirmed that cast in place concrete will accommodate up to 0.4 percent by volume of polypropylene fibers with minimal mix proportion adjustments. Good workability can be maintained in polypropylene fiber reinforced concrete (FRC) by adding an appropriate amount of admixtures.

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2. Characterize the fatigue and static flexural strength of small volume (<0.5%) polypropylene FRC composites.

- Research studies complemented our laboratory conclusions regarding increases in concrete's fatigue strength and endurance limit with increasing fiber, when expressed as a percentage of plain concrete's Modulus of Rupture. Fiber reinforcement has a clear beneficial effect on the fatigue behavior of concrete as long as the fiber content is not much larger than 0.3 percent. At 0.3 %, the beneficial effect of polypropylene on the total energy-absorption capacity of concrete seems to peak, irrespective of the stress level. The fatigue strength at the endurance limit (2,000,000 cycles) was increased with the addition of 0.1% and 0.3% fiber, which if used in airfield pavements would extend their service life or could reduce the pavement thickness.
- Compared to plain concrete, laboratory testing indicated the addition of 0.2% to 0.4% fiber volumes to concrete increased the static flexural strength by 5 to 15 %.

3. Characterize the toughness, ductility and impact resistance of small volume (<0.5%) polypropylene FRC composites. Qualitatively and quantitatively examine the energy absorption capability of low volume (<0.5%) polypropylene fiber composites to resist dynamic loading.

- Laboratory derived Toughness Indices at 0.3% fiber content were 3.17, 3.63 and 4.5 for I-5, 10, 20 respectively, indicating a fourfold ability of the FRC composite to absorb energy as compared to plain concrete after cracking.
- In compressive strength testing of FRC composites, polypropylene fibers at different quantities have an effect on compressive strength and a significant effect on the mode

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and mechanism of failure of concrete cylinders. The fiber concrete composites failed in a more ductile mode, particularly true for higher strength concrete where the cylinders endure large deformations without shattering. As compared to plain concrete, the addition of fiber beyond 0.2% resulted in a corresponding decrease in compressive strength by 10% for 0.4 % fiber content.

- Fiber concrete has excellent impact resistance, which increases with an increase in fiber content and fiber length. For all fiber concrete (0.1%, to 0.5%) the number of blows to first crack and final failure was higher than that of plain concrete, by as much as 20%.

4. Characterize the unrestrained shrinkage, restrained shrinkage and cracking stresses of small volume (<0.5%) polypropylene FRC composites. Study the cracking and thermal stresses associated with small volume (<0.5%) polypropylene FRC composites.

- The results of our laboratory testing revealed additions of polypropylene fibers do not significantly alter drying shrinkage.
- Steel Ring results reported showed that small amounts of fiber could substantially reduce cracks. The average crack width of the specimen reinforced with 0.25% polypropylene fiber was 0.5 mm (0.016 inches) or one half the value of plain concrete after six weeks. No cracking was observed during FRC Steel Ring laboratory testing.
- KenSlabs modeling confirmed there is a reduction in thermal stresses with increasing fiber content due to decreases in slab thickness and stiffness (Table 7.1).

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5. Quantify the fatigue and static flexural strength of small volume (<0.5%) polypropylene FRC composites through pavement thickness reduction values by predicting FRC design thickness at 0.1%, 0.2%, 0.3% and 0.4% polypropylene fiber contents as compared to plain concrete.

- Through Finite Element Method computer modeling, this dissertation derived equations to predict airfield design thickness criteria for FRC pavements at fiber contents of 0%, 0.1%, 0.2%, 0.3% and 0.4% and at stress levels of less than 0.7 (0.29,0.39.0.49,0.59.0.69) for given aircraft wheel loads based on laboratory derived fatigue strength values. These equations yielded aircraft specific performance models that established minimum thickness (L-D coefficients) parameters for design life (L) and to limit pavement deflection (D) to levels that prevents subgrade failure from pumping. These equations allowed determination of FRC airfield pavement thickness reduction values (PRV) as a function of static flexural strength, which is the current methodology used by most finite element programs, as well as, fatigue strength airfield pavement thickness reduction values.

6. Determine the reduction in heaved pavement around a bomb-damaged crater as a result of FRC material properties.

- Fracture Energy reduction was improved as a result of fibers tendency to reduce the stiffness of concrete and in it's increased strength properties. Both reduced stiffness and increased fracture strength properties exhibited by polypropylene fiber, even in small volumes (<0.5%) in concrete, demonstrates an ability to reduce pavement heave by as much as 11 % as a result of explosive cratering.

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Table 7.1: Thermal Stress Values; 25'X 12' slab (Δ 20˚F).

Fiber Case	**Modulus E(psi)** (stiffness)	**Unit wt. (pcf)**	**Fatigue Design Thickness**	**Curling Stress (psi)** Slab edge	**Curling Stress (psi)** Slab interior(center)
Plain	4,158,817	143.8	9 inches	227 psi	250.1 psi
0.1% fiber	4,482,465	144.8	8 inches	241.4 psi	270.9 psi
0.2% fiber	4,179,904	143.8	8 inches	224.2 psi	252.9 psi
0.3% fiber	3,735,295	141.8	8.4 inches	200.7 psi	225.9 psi
0.4% fiber	3,830,317	142.8	8.8 inches	207.6 psi	231.1 psi

FUTURE RECOMMANDATIONS

1. Identify range of criteria for acceptance of FRC mixtures.

- This dissertation focused on one type of fiber concrete composite, polypropylene within a specific strength range, water/cement ratio of 0.40 to 0.44 (medium strength). To be useful, tabular data would have to be compiled at both high and low strength mix designs within this fiber group to determine a range of material performance as an airfield pavement.
- When considering a new fiber group, detailed literature review of past research would again have to be accomplished to determine those material properties that would enhance the performance of an airfield pavement. Tabular data would first be compiled by fiber concrete composite group, then by strength (low, medium, high).

2. Automate methodology with software development.

- The objective of this dissertation was development of an integrated concrete material design and selection methodology for airfield pavements. To be useful, a database of

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material characteristics must be compiled by fiber group and by strength as it pertains to airfield performance. That database would be considerable, requiring software development across a range of fibers and strength to rapidly determine the best composite for a given location, aircraft and mix design.

3. Improve and further develop pavement thickness reduction models.

- Continued refinement of the design thickness reduction model will require better characterization of fiber concrete's material properties across a spectrum of mix designs and their compressive strengths. More ASTM C39 test data of low volume (<0.5% fiber) fiber reinforced concrete's strengths at different water/cement ratios will need to be researched to arrive at an average compressive strength value for each fiber case. That average strength value would allow determination of an average Modulus of Elasticity value for fiber concrete in KenSlabs modeling.
- Continued refinement of the design thickness reduction model will require better characterization of fiber concrete's material properties across a spectrum of mix designs and their fatigue strengths. More fatigue test data of low volume (<0.5% fiber) fiber reinforced concrete's strengths at different water/cement ratios will need to be researched to establish a range of fatigue strength values for each fiber case. The average fatigue value of this range of strength values would allow determination of the fatigue line by fiber content and their respective coefficient values (f1, f2) for fiber concrete in KenSlabs modeling.

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4. Improve and further develop pavement-testing protocols.

- On–site test pad construction of optimized FRC composite slabs provides feedback from field testing as revised data for iterative airfield design analysis. Considering both the U.S. Military's and commercial aviation's global reach, similar to SuperPave, FRC rigid pavement design may be regionally specified based on local desired performance criteria due to mission, environment and threat as well as available local materials (Mix Design) properties. Chapter three recommends those field tests.

5. Expand methodology for any PCC materials and mix.

- There is a real need to institutionalize a system-engineering research methodology within the Department of Defense to evaluate emerging fiber concrete composite materials or any concrete for airfield pavement design. As example, fibers such as Kevlar (Armid) are becoming commercially available, at less cost and have great potential as they posses material properties, such as tensile strength many times that of polypropylene.
- Judgment criteria for adopting a new FRC airfield materials research and design methodology would have to be established. Those criteria should be performance, reliability and flexibility in that weighted order. Chapter three recommends the criteria of selecting such a methodology for new materials in rigid airfield pavement design.

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