GUIDELINES AND SPECIFICATIONS FOR THE USE OF RECLAIMED AGGREGATES IN PAVEMENT

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The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the State of Florida Department of Transportation.

EXECUTIVE SUMMARY

In 1996, the production of crushed stone (virgin aggregate) in the USA was 2.2 billion metric tonnes (Grogan 1996). According to Grogan, the nation's highway system accounted for over 40% of the aggregate market in 1996. Thus, the public sector is the largest single consumer of aggregates in the nation.

The Portland Cement Concrete Pavement (PCCP) constitutes about 3-4% of the USA highway system. One strategy of rehabilitating deteriorated PCCP is to remove the old concrete and reconstruct the pavement. The removed concrete may either be reclaimed and used for other purposes, or disposed in landfills.

Landfilling demolished concrete is becoming less favorable due to, among other things, dwindling number of landfills, increasing costs of disposal, and environmental concerns. As a result, recycling remains a better alternative. At present, recycled concrete aggregate (RCA) is mostly used in pavement bases (both unstabilized and cement treated), shoulder concrete, and porous granular fill; and to a limited extent, as aggregates in new PCCP. For the increased use of RCA in new pavement construction, the characteristics of RCA have to be well understood and documented, and standards for their use have to be developed.

The FDOT as one of the most active state highway agencies in the recycling efforts sponsored this research project in fiscal year 1996-1997 to develop guidelines and specifications for the use of RCA in new pavement construction. The project focused on evaluating the performance of recycled concrete for use as a base material under hot mix asphalt pavements and

as an aggregate in Portland cement concrete pavements. In order to meet this objective, several goals were established. First, published literature on RCA was reviewed and a survey of State Highway Agencies (SHA) was performed to determine the extent of use of RCA in highway projects. Second, the RCA was tested at the FDOT Materials Lab in Gainesville, Florida, to determine the material properties. Third, by using the output from the falling weight deflectometer test along with the KENSLABS and KENLAYER computer programs (Huang, 1993), a theoretical analysis was performed to predict the number of repetitions before the pavements failed in both the fatigue and permanent deformation criteria. Lastly, nine design sections involving HMA and PCC pavements were constructed at the University of Central Florida's Circular Accelerated Test Track (UCF-CATT) to evaluate the response of the pavement sections made with RCA under actual dual-wheel loading.

Following is the summary of the results obtained from this research project:

Literature Search and Survey of SHA

Information from the literature review suggest that when compared to virgin aggregate (VA), RCA has lower density, higher water absorption, higher soundness mass loss, and higher content of foreign matters. However, in most cases the properties of RCA is within limits of the specifications for base course or concrete aggregates. Some countries in Europe and Japan have developed guidelines for use of RCA in pavement construction. These guidelines have been reviewed in Chapter 8.

Responses from SHAs showed that 24% of the 46 SHAs that responded did not allow the use of RCA in their projects. Those who allow RCA, use it mostly for base and sub-base courses, backfill, and as aggregate for asphalt and cement concrete pavements. The results of the survey also, revealed that nine SHAs have developed specifications for use of RCA in concrete that covered issues of processing, mix design, and acceptable conditions of old pavement. Chapter 3 summarizes the results of the US highway agencies.

Laboratory Testing

Due to the fact that RCA has mortar bonded to the aggregate, its water absorption capacity when compared to virgin aggregate is much higher. For this reason, it is recommended to pre-wet recycled material before using it in the concrete mix. In so doing, the possibility for premature stiffening of concrete is reduced, increasing the mechanical properties of the rigid pavement. It is also advised to avoid use of recycled fine aggregates because their capacity to absorb water can induce excessive shrinkage in concrete and they affect the workability of the mix. Further, an abundance of fines can affect the particle bonding since the cement paste that should adhere to the aggregate will be attached to the fine particles instead.

When mixing the RCA concrete, plasticizing admixtures and water reducing agents should be employed. These products aid the concrete in achieving higher strengths, therefore increasing the workability and durability of the rigid pavement. Once the RCA concrete pavement has been placed, it must be protected against shrinkage by either spraying curing compound over the finished surface or by using a 24-hour water irrigation system to help minimize evaporation.

Laboratory tests performed on forty concrete specimens made of different percentages of RCA and virgin aggregate verified the fact that even though the slump of all mixes were approximately the same, the higher the percentage RCA material, the lower the compressive, flexural, and tensile strengths. As Figure 4.2 illustrates, the compressive strength ranged between 82% and 100%, the flexural strength between 81% and 100%, and the tensile strength between 96% and 100%, where 100% corresponds to the virgin concrete of the control sections. It can be seen from Figure 4.2 that after a 25% substitution of RCA, the mechanical properties drop into the lower 80% when compared to a 100% VA concrete mix. Therefore, care should be taken when exceeding 25% RCA.

Theoretical Analysis

the KENSLABS program was used to estimate the insitu moduli of the base, subbase, and subgrade courses by back calculating the deflection basins produced with the Falling Weight Defelectometer (FWD) test. These values are considered to be reasonable, specially when compared to those obtained through literature

The KENSLABS computer program was then re-run to perform a theoretical analysis on the rigid pavement sections. Its purpose was to help identify what and where the maximum flexural stress in the slab was when a dual-tire load of 48.9 kN (11 kips) was being applied. Simulation determined that the maximum flexural stress occurred at the edge of the concrete slab in the center of the wheel path as seen in Edge Loading 1 of Figure 11.26. This maximum flexural stress was used to carry out a failure analysis on the PCC pavement. Since the σ/S_c ratio is less than 0.45 for all test sections, none of the slabs should fail under fatigue cracking. In the absence of cracks, water intrusion that can eventually lead to the pumping of base materials and the breaking off of portions of the slab, would not take place.

The KENLAYER program was utilized to analyze the flexible pavement test sections. The program calculated the tensile and compressive strains at the bottom of the asphalt layer and on the top of the subgrade soil, respectively. These two strains from Table 11.4 were used in a failure analysis that tried to identify the number of repetitions required for fatigue and permanent deformation failures to occur. This theoretical analysis suggested that the HMA would fail under fatigue cracking well before permanent deformation is visible.

Accelerated Testing Using the UCF-CATT

After 133,634 load repetitions of 49 kN (11,000 lbs) wheel load applied at this testing facility (299,340 ESAL), no signs of failure have been found in either the PCC or HMA pavement sections. The test segments were visually monitored for cracks after every 5 hours of test loading, and the elevation of each section checked with a transit to identify any pavement deformations. This amount of repetitions represent a simulated life expectancy of 9.11 years out of a design of 20 years (assuming an ADT of 7,500 with an average percent of heavy trucks of 4%) for asphalt sections, and 2.39 years of a design of 20 years (assuming an ADT of 20,000 with an average percent of heavy trucks of 6.5%) for concrete sections. .

Upon completion of the performance test on asphalt sections, neither the pavement sections containing RCA base courses, nor the control section containing a limerock base course, showed any signs of distress due to fatigue or permanent deformation. This shows that after approximately 300,000 ESAL an eight-inch RCA base course is capable of performing at least equally to an eight-inch limerock base course. Trenching of the pavement test sections and observation of the cross sections supported these findings.

Guidelines for Use of RCA as Base Course

The findings of this project are supportive of the hypothesis that recycled concrete aggregate can be used effectively as a base course when quality control techniques are utilized. Use of recycled concrete as a base course aggregate helps to reduce the necessity for quarrying natural aggregates and offers an alternative to the costly landfill disposal of old concrete.

From the literature search, it was determined that laboratory tests on recycled concrete aggregate are consistent in their results. The published works have concluded that different source concrete strengths have little or no effect on the particle breakdown of RCA under compaction. The cement paste in the RCA causes it to possess a lower dry density and higher optimum moisture content and L.A. abrasion than natural aggregate. Although different, the values obtained from these tests fall within the allowable material limits for aggregate bases and are therefore acceptable.

A survey of the State of Florida revealed that both fixed and mobile crushing plants are already producing recycled concrete aggregate. The cost of RCA is less expensive or competitive to that of natural aggregates in all of Florida, with the exception of South Florida, where most natural aggregate quarries are located. Ten plants alone have a total recycling production of

10,000 tons/day. The plants in Florida are capable of producing recycled concrete aggregate, which satisfies FDOT's gradation requirements for graded aggregate base. It is imperative, however, that these plants adopt strict regulations concerning their sources of material and efficient quality control plans when producing RCA for public projects. Currently construction and demolition debris, curbs, slabs, old roads, highways, bridges, and sidewalks are all accepted by the plants for recycling. If the recycled concrete aggregate is to be used as a base course, the source concrete should be of a known, reliable uniform quality to ensure structural integrity when used as a base course.

Tables demonstrating the type of material produced by these plants are included in this study (Chapter 6, Table 6.7) and can be used as a means of selecting a plant which produces RCA with the desired material characteristics. From these tables it was also noted that RCA produced in Florida possesses a maximum dry density in the range of 16.3-18.5 kN/m^3 (104-118 lb/ft^3), an optimum moisture content in the range of 10-20 percent and a Limerock Bearing Ratio in the range of 139-242 percent. Several Florida counties and cities have accepted the use of RCA and developed guidelines for its use.

RCA's conformance to the necessary base course aggregate properties of stability, particle size distribution, permeability, plasticity index, limerock bearing ratio, particle shape, soundness, LA abrasion and compaction was evaluated in detail and was found to be either satisfactory or excellent in all instances except that of soundness. Soundness is tested by means of the sodium sulfate test, which is chemically unsuited to test RCA. Therefore, this method should not be used to evaluate the soundness of RCA.

Laboratory tests for gradation, limerock bearing ratio, Los Angeles abrasion, soundness and sand equivalence were performed on the RCA, which further support the results of past findings and the fact that RCA is capable of satisfying the specified requirements for graded aggregate base.

Based on the information examined in this project, preliminary recommendations for the use of recycled concrete aggregate as a base course in flexible pavements were developed (see Chapter 13).

Several countries and many U.S. states were found to have been using RCA in base courses for a considerable amount of time. It is of special importance to note that European countries are completely satisfied with the results obtained from their years of using RCA base courses. The standards and specifications for RCA base courses used in the surveyed foreign countries and U.S. State DOT are included in this report (Chapters 8 and 9) and can be used by other agencies as models for the development of their own standards and guidelines. Thirty U.S. State DOT's have adopted the use of RCA, out of which seventeen have already developed their own standards and specifications for its use.

It is anticipated that with the passage of time and as more data is published on the subject and as more professionals become convinced of RCA's performance, that even more regulating agencies will adopt the use of RCA and include standards and specifications for its use in their manuals. It is also noteworthy that thousands of tests on natural aggregates have been performed over the years, while the testing of RCA has only begun. Recycling old concrete not only alleviates the environmental problems related to the quarrying of natural aggregates and the disposal of old concrete, but it also offers the possibility of further recycling the RCA base course as fill aggregate.

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LIST OF SYMBOLS AND ABBREVIATIONS

AASHTO - American Association of State Highways Transportation Organization

ADT - Average Daily Traffic

AHTT - Annual Heavy Truck Traffic

AI – Asphalt Institute

ASTM - American Society of Testing Materials

CATT - Circular Accelerated Test Track

$CATT_{REPS}$ - Total Repetitions Applied at UCF-CATT

E_1 - Modulus of Elasticity of the Asphalt

EALF - Equivalent Axle Load Factor

E_c - Modulus of Elasticity of Concrete

ESAL - Equivalent Single Axle Load

$ESAL_{18}$ - Number of 18 kip Load Repetitions Corresponding to N_{22}

FDOT - Florida Department of Transportation

FWD – Falling Weight Deflectometer

h - Slab Thickness

HMA- Hot Mix Asphalt

JRCP - Jointed Reinforced Concrete Pavements

KDOT – Kansas Department of Transportation

k - Modulus of Subgrade Reaction

L - Lane Distribution Factor

LBR - Limerock Bearing Ratio

l_r - Radius of Relative Stiffness

l_s - Slab Length

L_x - Load of the Applied Single Axle Load

MDD - Maximum Dry Density

N_{22} - Number of 22 kip Axle Load Repetitions During the Design Period

N - Number of Test Track Repetitions Required per Year

NA - Natural Aggregate

NDT - Non-Destructive Testing

N_d - Number of Allowable Repetitions to Limit Permanent Deformation

N_f - Number of Allowable Load Repetitions to Prevent Fatigue Failure

OC – Original Concrete

OMC - Optimum Moisture Content

P - Probability of Occurrence

PCC - Portland Cement Concrete

PCCP - Portland Cement Concrete Pavement

RCA - Recycled Concrete Aggregate

S_c - Modulus of Rupture of Concrete

SLE - Simulated Life Expectancy

SSD - Surface Saturated Dry

T - Percentage of Trucks in ADT

UCF - University of Central Florida

UCF-CATT - University of Central Florida Circular Accelerated Test Track

UF- University of Florida

VA - Virgin Aggregate

W/C - Water to Cement Ratio

ε_c - Compressive Strain On the Top of the Subgrade

ε_t - Tensile Strain At the Bottom of the Asphalt Layer

ν - Poisson's Ratio

σ - Flexural Stress

PART I: USE OF RECYCLED CONCRETE AGGREGATE IN RIGID PAVEMENT

CHAPTER 1

INTRODUCTION

Since the time before recorded history, human beings have been building structures by which they can be remembered. Whether these structures were buildings or roads, they both required an essential ingredient for their undertaking, aggregates. This is why the generation of aggregates in the United States exceeded $7.7 billion in 1991, which was the largest non-mineral commodity produced in the nation (Poulin et al, 1994).

As concern and awareness for the environment increases in the nineties, political and ecological entities are rightly protesting against the methods used to extract the sand and gravel from the earth. Both dredging and mining scar the earth's surface for life, and even though the vast pits and craters that are generated are sometimes transformed into green areas for society, this is no excuse to destroy what was never ours to begin with. Earth's natural resources have been exploited to a point where the availability of gravel is now scarce if not unrealizable in some states, requiring the material to be hauled for lengthy distances, and elevating the projects expenses.

Furthermore, with the ever increasing population, more and more land is being set aside for the construction of urban zones. This, in turn, is limiting the availability of sectors that can be put to use for landfill sites. Therefore, disposal problems have risen, evolving into a drastic escalation of tipping fees for dumping refuse at a site, specially that originated from waste building and pavement rubble. To avoid exhaustion of the standing dump sites and to help constraint pollution of the environment, there is a need to curtail the production of construction waste materials. There is an acceptable solution to these problems that can keep politicians, environmentalists, and ecologists content. It can effortlessly be summed up into two words: recycled aggregates! If old demolished concrete was crushed to acceptable sizes, removing impurities such as steel ties, PVC pipes, and rebar along the way, it could easily be utilized for road base material or in Portland Cement Concrete (PCC) pavement. Numerous other possibilities exist for the use of reclaimed PCC such as for pipe bedding, drain fields, parking lots, highway shoulders, etc. Regardless of its use, by not throwing away demolished concrete at a landfill location, the amount of natural raw materials produced yearly could decline vastly.

To this date reclaimed PCC aggregate is not being used in pavements to the extent that it could. Why? Because there are no national specifications that control the quality of recycled concrete aggregate in pavement construction. The same standards that classify virgin aggregates are being used on reclaimed material, making it exceedingly incompatible since they are two distinct products. In a world governed by lawsuits, the engineer must feel confident of the durability, consistency, and performance of the recycled aggregate before employing it for any real life application. Researchers and engineers must now focus their attention in dissipating any hesitation users might have concerning the product by conducting extensive tests to prove the quality of the material. As an end result to these studies, a guide should be compiled so that both users and producers of recycled aggregates can guarantee the performance of the material without wavering.

The FDOT as one of the most progressive agencies in recycling efforts sponsored this research project in fiscal year 1996-1997 to develop guidelines and specifications for the use of RCA in new pavement construction.

The objective of this research study was to evaluate the performance of nine RCA design sections through both theoretical and experimental analyses. Five of these sections were 254 mm (10 in) thick slabs of concrete pavement with varying percentages of recycled and virgin aggregates. The remaining four sections were composed of an 88.9 mm (3.5 in) layer of HMA with a 12.7 mm (0.5 in) friction wear course, over different thickness of RCA base material. Both types of pavements had control sections to which the test data could be compared and contrasted.

For the analytical approach, the KENSLABS and KENLAYER computer programs (Huang, 1993) were utilized to determine the stresses in the concrete slabs along with the tensile and compressive strains in the HMA sections. These parameters were then used to estimate the theoretical number of allowable repetitions for failure to occur in the individual sections. As part of the experimental work, samples were collected at the UCF testing facility site and laboratory tested at the FDOT Materials Lab in Gainesville, Florida to characterize the material properties of RCA. The remaining experimental phase was the full-scale accelerated test at UCF. The facility was used to simulate actual traffic loads applied to all sections, which was a dual wheel loading of 48.9 kN (11,000 lbs). During the testing, every section is monitored closely to detect if any signs of distress occurred, and the sum of repetitions endured on the pavements were used to equate the simulated life expectancy (SLE) of the cross-sections.

CHAPTER 2
LITERATURE REVIEW

2.1. Introduction

This chapter presents a review of literature on various aspects of recycling old concrete and reusing it as aggregate for Portland Cement Concrete Pavements (PCCP). The information that is most relevant to this research has been covered in greater details. Some other information is presented briefly, and some literature is just noted. Topics presented deal with properties of aggregate made from crushed concrete and properties of concrete made with recycled aggregates. Also presented is review of guidelines and specifications developed for use of recycled concrete aggregates (RCA). The information covered includes both laboratory and field studies.

2.2. Properties of Aggregates from Laboratory-made Concrete

Aggregate for concrete must meet a number of requirements. It must be strong enough for the concrete grade required, possess good dimensional stability, must not react with either cement or reinforcement, should not contain any potentially harmful impurities, and should have suitable shape and grading to produce concrete of acceptable workability. Major barriers to the use of RCA in concrete production has been the uncertain properties of RCA and concrete made with RCA (RCA concrete), as well as the stringent requirements of the existing standards. As such, properties of RCA and RCA concrete have been intensively investigated in various studies. The majority of the studies used aggregates produced by crushing laboratory-made concrete. In some studies, aggregates were obtained from crushed old concrete.

Kobashi and Kawano (1988) studied the properties of RCA produced at different degrees of crushing refinement. Concrete samples of different strengths were made and then crushed to produce aggregates. Different degrees of mechanical treatment (refinement) were used to remove cement paste adhering to RCA. The RCA were tested for specific gravity, absorption, soundness, abrasion loss, bulk density, solid volume percentage, and fineness modulus. Overall properties of RCA were inferior to those of virgin aggregates (VA) due to cement paste attached to stone aggregate. The study showed that higher amount of adhering cement paste resulted in poor quality. The investigation also showed that further refinements improved properties of RCA, and that at a high degree of refinement, properties of RCA from weak concrete were superior to those from high strength concrete. They concluded that this happened because it was easy to remove the weak cement paste from aggregates. The study also reported that strength of RCA concrete is lower than that of VA concrete for the same water/cement ratio.

Kashino and Takahashi (1988) reported that recycled aggregate concrete can be designed, manufactured, placed, and cured by the same methods as for natural aggregate concrete. In their study they found out that: a) the strength characteristics of RCA concrete obtained in the laboratory are reflected in the actual structure, b) up to 30% of RCA in concrete had little effect on compressive strength, c) larger particles of RCA had less percentage of adhering cement paste compared to smaller particles, and d) RCA concrete required slightly more air-entraining agent to maintain a particular air content requirement.

Kakizaki, et.al. (1988) conducted a study on compressive strength, elastic modulus and bonding strength to steel bars of recycled aggregate concrete. Mix proportion for RCA concrete was determined through a number of trial mixing to check workability. The results showed:

a) compressive strength increased linearly with the inverse of water-cement ratio. However, the compressive strength of RCA concrete showed less increase as compared with VA concrete, b) compressive strength of RCA concrete was about 14% lower compared with VA concrete at 28 days, c) strength development characteristics of RCA concrete were similar to those of VA concrete, d) compressive strength increases if wet curing is used over a long period, e) elastic modulus for RCA concrete is lower than that of VA concrete by about 25 to 40%, and f) the bonding strength for RCA concrete is lower than that of VA concrete by about 25%. The study considered that the lower strength of RCA concrete was due to faults and micro cracks in mortar adhering to the RCA.

Sri Ravindrarajah and Tam (1988) investigated the properties of RCA and RCA concrete. They observed that volume content of mortar attached to aggregate increased with decreased size of aggregates, ranging from 20% for 16-32 mm (0.63-1.25 in) size to 60% for 4-8 mm (0.16-0.31 in) size. They also observed that the water absorption of RCA increased with the decrease in the aggregate size. Tests on mechanical properties showed that RCA particles are more angular than VA, have higher abrasion value, and their mechanical resistance decreases with reduction in the maximum aggregate size. Tests on concrete showed that RCA concrete required about 10% more water than VA concrete for the same workability, had about 25% less compressive strength, and a 30% reduction in modulus of elasticity. The study concluded that qualities of RCA concrete can be improved by reducing water-cement ratio, reducing water content by using admixtures, addition of pozzolan, and blending of RCA with VA. Prolonged initial moist-curing period was found to reduce drying shrinkage. The study also concluded that the quality of original concrete

(OC) had little influence on the absorption capacity of RCA.

Ikeda, Yamane and Sakamoto (1988) conducted laboratory studies on properties of RCA concrete. Tests for fresh concrete included slump, air content and unit weight. Measured properties of hardened concrete were compressive strength, splitting tensile test, bending and shear strength, elastic modulus and unit weight. RCA was made by crushing laboratory-made concrete. An air entraining agent was used to reduce water content of RCA concrete mixes. Reported results showed decrease in strengths of RCA concrete in the order of 8% for compression, 6% for tension, 0% for bending and 20% for shear strength as compared to VA concrete. The elastic modulus was lower by 30 to 50% and unit weight was smaller by 10% compared to VA concrete. However, it was observed that characteristics of strength changes of RCA concrete with respect to age or water-cement ratio were the same as those of VA concrete.

Kikuchi, Mukai and Koizumi (1988) have been studying the application of RCA for new concrete since 1974. They observed that deterioration of RCA concrete properties were proportional to the replacement ratio of VA by RCA. They also observed that replacement of VA with up to 30% RCA do not have practical consequences on concrete qualities. In their investigations, they found out that the mix for RCA concrete needed more water content, cement content and fine aggregate as compared to VA concrete. They also reported that particle size of RCA have direct influence on properties of concrete. They recommended adjusting the grading by blending RCA with natural.

Hansen and Marga (1988) studied properties of RCA and RCA concrete using laboratory-made original concrete which was then crushed to produce RCA. The RCA sizes were mixed to produce same gradation as the aggregates of the OC. Coarse aggregates were defined for range between 25 mm (1 in) and 5 mm (0.20 in). To obtain variations in strength, mixes were proportioned with varying amount of cement but same quantity of water, which resulted in different effective water-cement ratios. The weight proportions of RCA were also adjusted in mix design to compensate for their low density. They found out that for equal slump, concrete with both coarse and fine aggregates recycled required 14% more mixing water than VA concrete. However, if only coarse aggregate is recycled only 6% of additional water is required. For equal water-cement ratio, compressive strength of concrete with recycled coarse and fine aggregates is approximately 30% lower than the control. Strength loss was much smaller for concrete with recycled coarse and natural fine aggregates. Based on their study they concluded that use of recycled fine aggregate cannot produce quality concrete. In an earlier study by Hansen and Narud (1983), where similar concretes were made with only coarse RCA and virgin sand, strength properties of RCA concrete were comparable to those of VA concrete. It was noticed, however, that when RCA from low strength OC was used to make high strength RCA concrete, there was a substantial reduction in compressive strength (Hansen and Marga, 1988). For example, if RCA made from OC of strength 14 MPa (2000 psi) is used to make RCA concrete with target strength of 57 MPa (8300 psi), the resulting strength would be about 62% of the target strength. This phenomenon is illustrated in Figure 2.1. The study designated OC strengths as follows: 14 MPa-low strength (OC-L), 34 MPa-medium strength (OC-M), and 57 MPa-high strength (OC-H).

Kasai, Hisaka and Yanngi (1988) studied the durability of RCA concrete as a function of varying aggregate replacement ratio by testing compressive strength, drying shrinkage, carbonation depth, and freezing and thawing. They used factory-produced RCA of sizes between 20 mm (0.80 in) and 5 mm (0.20 in). From the results of their experiment they concluded that

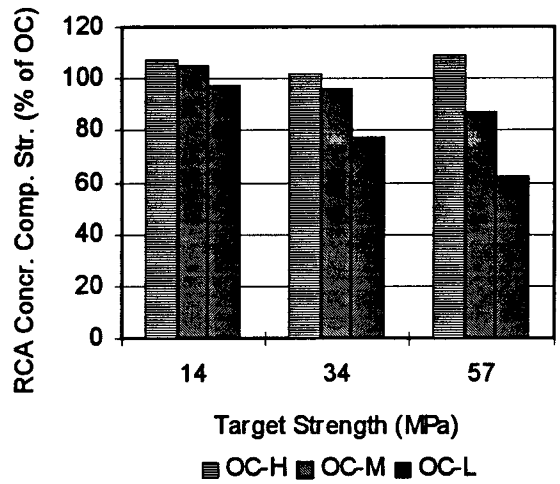


Fig. 2.1. Effects of original concrete on RCA concrete strength
(Source: Hansen and Marga, 1988)

a) compressive strength decreased linearly with increase of ratio of RCA, and that the rate of decrease is lower for lower water-cement ratios, b) for replacements of up to 50% RCA drying shrinkage was practically the same as the control concrete, but increased substantially with higher ratios, c) the depth of accelerated carbonation was independent of the replacement ratio, d) resistance to repeated freezing and thawing decreased with increase of replacement ratio of RCA, and e) absorption of RCA was 2 to 4 times that of VA. Based on the above results they recommended that RCA concrete should contain a blend of RCA and VA, and should be applied to sites where freeze-thaw is not severe.

Durability of RCA and RCA concrete has also been investigated by Mulheron and O'Mahony (1988). They used coarse aggregates of sizes between 20 mm (0.80 in) to 5 mm (0.20 in), and water cement ratios ranging from 0.4 to 0.6. Tests on aggregates were performed to determine particle size distribution, particle shape, apparent relative density and water absorption. Tests on concrete compared the workability, compressive strength, modulus of elasticity, and resistance to freeze/thaw conditions. Tests results agreed with other researchers in that RCA have lower density, higher water absorption and less resistance to freeze/thaw conditions as compared to VA. Results also showed that RCA concrete is more porous, less dense, and has lower modulus of elasticity and strength. However, they also observed that suitably graded RCA could produce concrete of satisfactory qualities.

Kibert (1994) reported that there are no national specifications for use of RCA concrete in road construction in the United States. Properties of RCA are judged by existing specifications for natural aggregate. The report observed that RCA are more irregular in shape and have coarser surface texture, less density, high absorption ranging from 5 to 8%, but have similar durability as VA under freeze-thaw conditions. The paper also noted that RCA concrete has lower compressive strength (64-100%), lower modulus of elasticity (60-100%), and less flexural strength (80-100%) compared to VA concrete.

The German experience with recycled aggregate was presented by Schulz (1994). He pointed out that: a) properties of RCA concrete varied with variation of properties and compositions of RCA, and b) RCA demonstrate low bulk density and high water absorption rate. The report noted that, particle properties of strength, shape, composition, and densities affect mix design and have to be checked at short intervals.

Wainwright, et al. (1994) assessed performance of RCA concrete in terms of its compressive strength, permeability and porosity. They used RCA produced by crushing laboratory-made concrete. Different mix compositions were obtained by varying amount of recycled fine in concrete. Test results showed that strength, porosity and permeability properties of RCA concrete were inferior to those of VA concrete. It was observed that a) when only coarse RCA was used strength was reduced by 11 to 20%, but reduction rose to about 38% when both coarse and fine RCA were used, b) RCA Concrete showed increased porosity and permeability, c) substitution of a percentage of recycled fine with pulverized fuel ash (pfa) improved strength but made porosity and permeability worse, and d) use of superpalsticisers to reduce water quantity improved concrete properties. This study did not find a significant relationship between the strength of RCA concrete and that of OC. However there was a correlation between permeability of RCA concrete and that of OC.

Merlet and Pimienta (1994) reported results of their study on properties of fresh and harden RCA concrete. Different mixes were made by varying the percentage content of recycled fine and ultra-fine aggregate. Properties tested were: compressive and tensile strength, modulus of elasticity, drying shrinkage, moisture movement, freeze-thaw resistance, carbonation rate, influence of pre-moistening of RCA and use of superplasticizers. Mixes had constant slump but varying water-cement ratio. The study concluded that: a) for the same slump, RCA concrete mixes required more water (w/c=0.59-0.98) than VA concrete (w/c=0.4-0.6); b) mechanical properties of RCA concrete are lower than those of VA concrete; c) RCA concrete has a higher rate of drying shrinkage, moisture movement and carbonation; d) reduction of recycled fines improve properties of RCA concrete; e) pre-moistening RCA improves qualities of RCA concrete; and f) when superplasticizers are used mechanical properties and drying shrinkage of

RCA concrete are comparable to those of VA concrete.

Kikuchi, Yasunga and Ehara (1994) evaluated RCA and RCA concrete using aggregates produced from laboratory-made concrete. Concretes were of different strengths classified as high, medium and low. They produced different mixes by varying water-cement ratio, percentages of RCA, and aggregates from concretes of different strength. Tests on aggregates showed that RCA from high strength concrete had slightly superior values than those from low concrete. Overall, in comparison with VA , RCA showed: a) lower specific gravity (88%), b) higher water absorption (200-400%), and c) higher LA abrasion values (150%). Comparison of properties of RCA and VA concretes showed that RCA concrete had a lower unit weight and a higher air content. In addition, drying shrinkage of RCA concrete increased with the decrease in strength of the OC. The researchers also observed that if the OC had a higher strength than the control concrete, then RCA concrete can have comparable or higher compressive, tensile and flexural strength than the control concrete.

Effects of multiple crushing of RCA have been investigated by Yagishita, Sano and Yamanda (1994). In their study three grades of RCA were produced. Low grade was produced by impact-crushing of concrete, medium grade by roll-crushing the low grade, and high grade by roll-crushing the medium grade. Tests on aggregates revealed that multiple crushing improved aggregate qualities of density and water absorption. They concluded that repeated crushing reduced the amount of mortar adhering to aggregate particles.

Other studies dealing with the properties of RCA and performance of RCA concrete as compared to that of VA concrete include: Yamoto et.al (1988), Nishibayashi and Yamura (1988), Fujii (1988), Kaga et.al (1988), Buck (1977), Richardson and Jordan (1991), Hansen and Narud (1983), Yannas (1977), Topcu and Guncan (1995), Bairagi, Ravande and Pareek (1993) and Vries (1993). Though numerical values may vary, results from these studies are consistent and in line with the other studies described in detail above.

2.3. Properties of Aggregates from Demolished PCCP

When Portland cement concrete pavement (PCCP) deteriorates beyond repair, it has to be removed. The question then is whether the demolished materials can be recycled into aggregates for the production of new pavement. Some researchers have investigated the properties of RCA produced by crushing demolished old pavement and other concrete structures.

Jakobsen et.al. (1988) investigated the gradation quality of aggregate obtained by crushing concrete obtained from a demolished old factory building. The results showed that RCA grading curve had qualities of too high content of medium and coarse gravel. They attributed this to the gradation of aggregate in the original concrete.

Puckman and Henrichsen (1988) examined the potential of using deteriorated concrete pavements as aggregates for new pavements. Their investigation included the following:

a) Description and analysis of the pavements before removing.

b) Determination of the properties of RCA from the old PCCP.

c) Preparation of laboratory mixes using RCA and control mix using VA. All mixes had identical cement content, sand, water and additives.

d) Test of the properties of fresh and hardened RCA concrete.

Demolished concrete was crushed and sieved to produce aggregates of 32 mm (1.25 in) maximum particle size. The RCA were tested for gradation, particle shape, mortar content attached to crushed concrete particles, chloride content, water absorption and alkali-silica reaction. Concrete mixes were prepared with water-cement ratio of 0.38 and superplasticizer and air entraining admixtures . RCA concretes were tested for compressive strength, tensile strength, elastic modulus, drying shrinkage, and freeze and thaw. They concluded that: a) recycled material from demolished concrete pavements can produce high quality concrete, provided the OC was made of normal quality concrete for pavement, b) crushed materials from deteriorated pavement due to alkali-silica reaction should not be recycled, c) frost resistance of RCA concrete is impaired if paste from OC was not frost resistant, d) drying shrinkage for RCA concrete is 50-100% higher than for VA concrete, e) due to its high water absorption rate, RCA should be in water saturated condition during the mixing process, and f) it is not advisable to use RCA of size less than 4 mm (0.16 in).

Sommer (1994) reported on the reconstruction of concrete pavement using 100% RCA from the demolished pavement. The old pavement was 30 years old and had 20-30 mm (0.8-1.2 in) thick bituminous surfacing to fill the ruts produced by the studded tires. Thus the crushed material contained about 90% concrete and 10% asphaltic material. The effects of asphalt on RCA and RCA concrete were investigated. Concrete mixes were prepared using RCA and different types of VA aggregates for comparison. All the mixes had identical cement quantity, air content, maximum aggregate size of 32 mm (1.25 in), continuous grading, and water-cement ratio of 0.40. Concrete specimen were tested for strength (compressive and flexural), modulus of elasticity, shrinkage, and frost-salt resistance. Results showed that: a) aggregates from crushed concrete pavement were as good as VA, b) compressive strengths were the same, c) flexural strength were better than for some types of VA concrete, d) asphalt content of up to 20% of volume had no significant effect on flexural strength, and e) use of recycled sand reduced resistance against frost and deicing chemicals. The new pavement was a two layer system 250 mm (9.9 in) thick, unreinforced but with doweled joints. The bottom 210 mm (8.3 in) was constructed of RCA concrete, and the top 40 mm (1.6 in) was constructed of high grade VA concrete. Lessons learned from the project are: a) RCA should be used in a wet state, b) a net mixing time of 60 seconds recommended in order to obtain a good air-void system, c) flexural strength was as high as with the best of VA, and d) asphalt particles from bituminous overlays not exceeding 10% of coarse aggregate had no practical harmful effects on pavement qualities.

Tavakoli and Soroushian (1996) investigated the effects of RCA on the properties of RCA concrete. Parameters whose effects in RCA and RCA concrete were investigated are: aggregate source, size, dry mixing of RCA in a rotary drum mixer, and water cement ratio. RCA were obtained from two different freeways in Michigan. Two maximum sizes of 19 mm (0.75 in) and 25 mm (1 in) were used. Water-cement ratios considered were 0.3 and 0.4. Dry mixing was performed by running RCA in the mixer for 30 min. before adding other materials. Test results showed that: a) compressive strength of RCA concrete can be higher than that of control concrete if the crushed concrete had higher strength than the control one [This trend was also observed by Kikuchi, Yasunga and Ehara (1994), and Hansen and Marga (1988)];

b) increased LA abrasion loss and water absorption lead to reduction in compressive strength of

RCA concrete; c) splitting tensile and flexural strengths of RCA concrete depend on water-cement ratio and dry mixing period; d) the qualities of RCA concrete seem to be influenced by the qualities of the crushed concrete; and e) in this particular study, strength characteristics of field-demolished concrete aggregates were similar to those of laboratory-made crushed concrete aggregates.

2.4. Performance of RCA PCC Pavement

Kansas. In 1985 the Kansas Department of Transportation (KDOT) began a research study on recycling of old PCCP as aggregates for new concrete pavement (Wojakowski and Fager 1995). A twenty-five year old PCCP was demolished and then crushed to produce RCA, which was used as aggregates for new PCCP or for Portland cement treated base (PCTB).

The study included both laboratory and field tests. Laboratory tests included: sieve analysis, specific gravity, and freeze-thaw resistance. Results showed that RCA grading was within the standard limit and had durability of Class I aggregate of KDOT's specifications.

Field studies involved the construction and monitoring performance of four test sections. One section utilized RCA for the PCTB and VA for PCCP. The other section was constructed using RCA both for PCTB and PCCP. The remaining two sections were constructed using VA for both PCTB and PCCP and were used as control sections. Performance parameters monitored in the field included: load transfer efficiency, overall strength, spreadability, joint faulting, rideability, and surface friction. The field studies were progressive and spanned from 1985 to 1995 though the actual period varied for different parameters observed.

Field investigations on all four sections showed that: a) of the two sections constructed using RCA, the VA-PCCP with RCA-PCTB section had the higher strength values, b) the RCA-PCCP with RCA-PCTB had the best performance in spreadability, surface friction and rideability, and less faulting, c) sections utilizing RCA had strength values slightly lower than those of the control sections. The study concluded that it is technically feasible to recycle old PCCP as aggregates for new PCCP or for PCTB.

Michigan. The Michigan Department of Transportation (MDOT) studied the performance of its PCCP highways which had been reconstructed in 1980 using RCA (MDOT 1996). Field investigations revealed that the reconstructed RCA PCCP developed transverse cracks sooner than expected. The cracks were straight, vertical and showed very little roughness or meander. The cause of cracks was therefore attributed to the lack of aggregate interlock.

Laboratory investigations were then conducted to study in more details the effects of RCA on load transfer performance across joints. Results showed that VA PCCP had better performance compared to RCA PCCP. However the study also showed that performance of RCA PCCP can be greatly improved by executing either of the following mix design modifications:
a) use gradation with large size RCA, b) blend RCA with VA, c) increase base stiffness,
d) construct shorter slabs to reduce tension, e) use high reinforcement ratio, f) use deformed wire mesh, g) induce cracks between joints by using hinge joints, and h) any combination of the above.

Ohio. The Ohio Department of Transportation (ODOT) conducted a research on the utilization of RCA for use in rigid pavements (Saraf and Majidzadeh 1995). The study had two objectives:
a) demonstrate the feasibility of using crushed concrete from old pavements as aggregates in new PCCP and b) develop guidelines and criteria for making cost-effective decisions concerning the recycling of old PCCP. The study consisted of the following activities: a) construction of a PCCP control section using VA and a PCCP section using RCA; b) preparation of concrete trial mixes using RCA from crushed cores of old PCCP; c) demolition and crushing of old PCCP; d) test samples of concrete mixes collected during construction; e) test cores of concrete

obtained from newly constructed PCCP; and f) field study of the performance of the RCA PCCP. Test results and field investigations showed that:

a) RCA concrete mixes lost slump at a much higher rate than VA concrete mixes,

b) tests on laboratory made samples showed that compressive strength of RCA concrete mix was slightly lower than that of VA concrete,

c) tests on cores from new pavement indicated that the strength of RCA PCCP was slightly lower than ODOT specifications of 27.6 MPa (4000 psi), whereas that of VA concrete was higher for the same mix design, and

d) 7.4% of the RCA PCCP section developed transverse cracks at mid slabs after about two months of operation.

Based on the results of the tests it was concluded that: a) use of RCA in new concrete is a feasible alternative, b) use of fine RCA is not practical because of its high water absorption rate, c) initial set time of RCA concrete mix should be studied before construction, and d) pre-pour placements to be conducted in order to become familiar with properties of RCA concrete mix.

Based on the post construction observations of this study the following field tests have been recommended: a) visual pavement condition survey, b) skid resistance tests, c) roughness tests, d) deflection measurements, and e) investigation of cause of transverse cracks.

Minnesota. The University of Minnesota (Wade, et al. 1997) investigated the field performance of nine concrete pavement projects were constructed using RCA. These projects were located in Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming. The main objective of the study was to determine the causes of concrete pavement distresses that are related to the use of RCA in jointed pavements. The field tests consisted of, pavement condition survey, falling weight deflectometer (FWD) testing, coring, and serviceability assessment.

The in-service performance of RCA pavements was comparable to that of the control sections. Only the project in Minnesota displayed significantly more transverse cracking in the RCA concrete section than in the control section. Little or no cracking was observed in the RCA or control sections in all the other projects. Laboratory tests revealed that in each case where there was a difference in the observed cracking, the section which cracked the most had lower compressive strength and lower back-calculated modulus of subgrade support.

2.5. Guidelines and Specifications

Literature cited above show that RCA can be used to produce quality concrete. However, in most cases, RCA fail to meet the aggregate requirements of the existing codes and therefore, their use has been limited. To promote use of RCA research studies have been conducted to develop guidelines and specifications for the use of RCA in concrete.

Collins (1994) reports that UK's Specification for Highways Works (Department 1991) allows use of RCA as aggregate in concrete pavement provided it complies with quality and grading requirements of BS882, the UK's main specification for aggregate in concrete (BSI: 1992). The recommended quality checks are: a) strength and flakiness; b) chloride content (due to deicing salts); c) sulphate content (SO_3); d) alkali-silica reaction; e) cleanliness, hardness and durability; and f) magnesium sulphate soundness mass loss. It is to be noted that all these quality requirements are for natural aggregates, and therefore, provide no special provision for

RCA. Limiting values for some properties are presented in Table 2.1.

Table 2.1 Quality requirements of concrete aggregate
(Source: Collins, 1988)

Aggregate Property	Limiting Value (%)
Flacky particles	40
Sulphate, SO^3	4*
Drying shrinkage	0.075
Soundness test (Magnesium sulphate)	25
Water absorption	2

* % with respect to cement.

A study in Belgium screened the existing specification to eliminate barriers for use of RCA (Vyncke and Rousseau 1994). Modifications to the specifications contained acceptable limits of RCA qualities, applications of RCA concrete, design values for RCA concrete, and acceptable aggregate gradation. Two types of RCA (GBSB-I and GBSB-II) are distinguished and allowed to be used in RCA concrete. RCA requirements are presented in Table 2.2, applications in Table 2.3, and design values in Table 2.4. RCA grading is the same as that of VA.

Morel, et.al (1994) conducted a two-year study of recycling practices in France and Spain. RCA from two recycling plants were studied. Results showed consistency in aggregate properties over time (only slight variations in physical, chemical and mechanical). When examined under existing standards, only four properties were outside the limits. These were, coefficient of absorption (higher), sulphate content (higher), density (lower), and organic matter (higher). To develop specifications for use of RCA in concrete, several concrete compositions were prepared using RCA. Properties monitored were: a) workability of fresh concrete, b) mechanical properties of hardened concrete, c) dimensional variations (moisture related), and d) durability. Results showed that RCA can be used in producing concrete subject to modifications to counteract

Table 2.2 Acceptable qualities of RCA
(Source: Vyncke and Rousseau, 1994)

Property	GBSB-I	GBSB-II
Dry density (kg/m^3)*	> 1600	> 2100
Water absorption (%)	< 18	< 9
Content of material with a density < 2100 kg/m^3 (%)	-	< 10
Content of material with a density < 1600 kg/m^3 (%)	< 10	< 1
Content of material with a density < 1000 kg/m^3 (%)	< 1	< 0.5
Foreign materials (%)	1	
Organic material (%)	< 0.5	
Chloride content (%)	< 0.06	
Sulphate content (%)	< 1	

* 1 kg/m^3 = 1.685 56 lb/yd^3

Table 2.3 Field of application of RCA concrete
(Source: Vyncke and Rousseau, 1994)

RCA Type	Strength Class	Allowed Exposure Class
GBSB-I	C16/20	a) interior of building with dry environment (Class 1) b) components in non-aggressive soil and/or water not exposed to frost (Class 2a)
GBSB-II	C30/37	a) interior of building with dry environment (Class 1) b) components in non-aggressive soil and/or water (Class 2)

deficiencies specific to RCA. Tests also showed that a) the level of sulphate content and organic matter contained in the RCA had no effects on durability, b) lower elastic modulus was advantageous in high strain conditions, and c) RCA concrete had good frost resistance but showed general cracking due to major shrinkage. A guideline was developed with following recommendations: a) cement with high content of C_3A is not suitable for use with RCA,

Table 2.4 Acceptable design values
(Source: Vyncke and Rousseau, 1994)

	Coefficients to be applied to standard values	
RCA Concrete Properties	GBSB-I	GBSB-II
Tensile strength	1	1
Modulus of elasticity	0.65	0.8
Creep	1	1
Shrinkage	2	1.5

b) use of recycled fines is not recommended, c) RCA to be pre-moistened before mixing to avoid absorption of mixing water by aggregates, which might result to premature stiffening, d) use of superplasticizers and water reducing agents (to reduce surplus water) is strongly recommended, and e) since RCA concrete is sensitive to evaporation, early protection and curing is highly recommended to reduce drying shrinkage.

Japan has developed six guidelines so far for recycling concrete (Kasai 1994). Research studies regarding the use of demolished concrete as aggregate was initiated in 1973. Properties of

RCA studied were: means of production, water absorption, specific gravity, grading and existence of deleterious matter. Properties of RCA concrete observed included strength, durability, water tightness, and workability. Regarding production, the study found out that the quality of RCA depends on the production method, that is, type of crusher and number of crushing cycles. It was observed that:

a) multiple crushing of aggregates reduced amount of mortar adhering to particles, resulting in improved water absorption and stability properties of RCA,

b) high strength OC may not always produce high quality RCA. Where the aggregates are refined by multiple crushing, mortar adhering to aggregates from weak OC easily falls off, resulting in better quality RCA, that is, low water absorption and high density,

c) mortar attached to stone particles increased trapped air, thus entrained air content of RCA concrete is higher than for VA concrete, and

d) water absorption, stability (chemical and physical), and harmful compositions (residual soils, residue powder from crushing process and excessive chloride), are reduced by avoiding recycled fine aggregates.

Guidelines developed have the following recommendations: a) RCA to be pre-watered before mixing (24 hr. spray); b) water per unit volume of concrete should be as small as possible to attain strength, durability, water tightness and workability; and c) concrete should be air entrained with air content about 4-6% by volume depending on the maximum size of aggregates.

2.6. Summary

2.6.1. General

Extensive literature coverage on recycling of concrete has been done in this study. Major topics covered in most of the researches are: properties of RCA and RCA concrete, application and performance of PCCP containing RCA, and recommendations on the use of RCA. The information contained in the literature, which is relevant to this study is summarized as follows:

2.6.1.1. Properties of RCA

When compared to VA, RCA have: lower density, higher water absorption, higher LA abrasion value, higher soundness mass loss, and higher content of foreign matters. However, in most cases gradation of RCA is within limits of the specifications for concrete aggregates. Fig. 2.2 shows the comparisons of specific gravity (SG), water absorption (WA) and LA abrasion

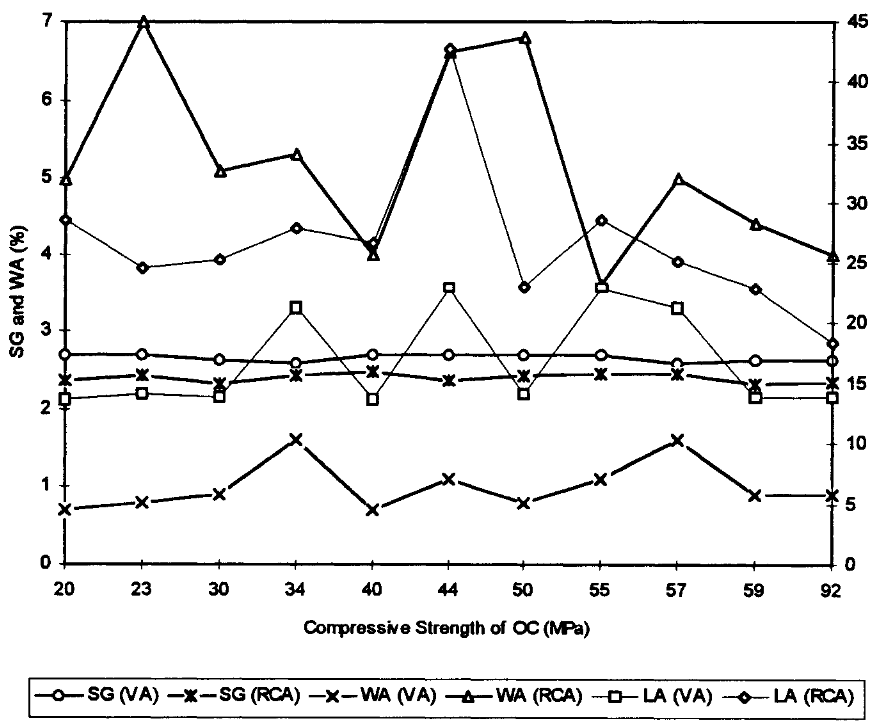


Fig. 2.2 Properties of VA and RCA as function of strength of original concrete
(Source: Compiled from various studies)

(LA) properties of RCA and VA as functions of the compressive strengths of the OC. The data used is a collection from various studies covered in this chapter. As the graphs show there is no clear correlation between properties of RCA and the strength of OC. However, properties of RCA are of lower quality when compared with those of VA.

2.6.1.2. RCA concrete

Relative to VA concrete, the RCA concrete requires more water for the same slump; has a lower compressive strength, modulus of elasticity, tensile and flexural strengths; has a higher drying shrinkage and coefficient of thermal expansion. Some properties of RCA concrete as percentage of VA concrete are illustrated in Fig. 2.3. Again there is no solid relationship between strength of OC and the demonstrated properties of RCA concrete.

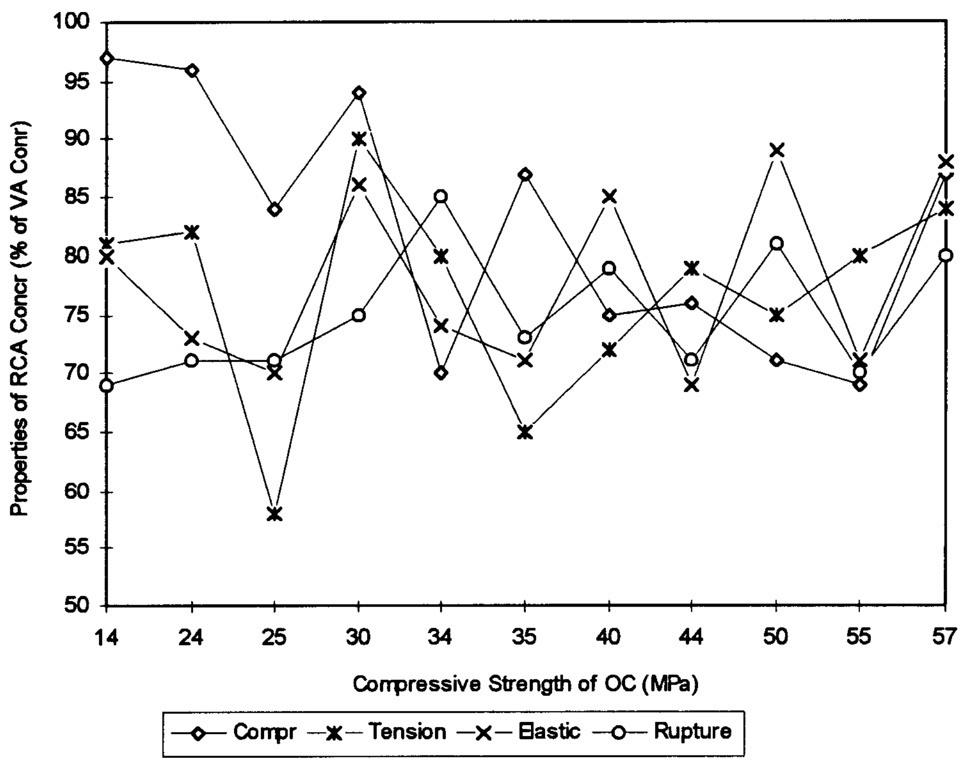


Fig. 2.3 Properties of RCA concrete as functions of strength of original concrete (Source: Compiled from various studies)

2.6.1.3. Application of RCA and development of guideline

Major applications of RCA in USA have been in road base and subbase constructions. A limited application has been in the construction of new PCCP. The performance of PCCP containing RCA has been satisfactory except for isolated incidences of occurrence of transverse cracks.

Most developed guidelines contain the following recommendations for the use of RCA in concrete: a) aggregates should be kept moist before mixing, b) water reducing agents should be used, and c) early protection against drying shrinkage is required.

2.6.2. Specific Observations.

Based on the information reviewed in the literature search, following specific observations are noted:

2.6.2.1. Utilization of RCA

RCA are seldom utilized as aggregates for new concrete because: a) they cannot meet most of the quality standards specified for concrete aggregates, and b) adequate guidelines for utilization of RCA are not available.

2.6.2.2. Quality of RCA

Various variables affect the quality of RCA. Some of these variables are: mortar adhering to aggregates, foreign materials, method of aggregate production, and size of aggregate particles.

Adhering Mortar. The main cause of the inferior quality of RCA is the amount of cement paste attached to the stone particles. This paste is responsible for higher water absorption, lower specific gravity, higher soundness mass loss, and higher LA abrasion value.

Foreign Materials. Foreign materials also have negative effects on the properties of RCA and RCA concrete. The degree of influence depends on the type and quantity of impurities in RCA. The quantity of foreign matter is dependent on the method used to demolish old concrete.

Method of Production. The type of crusher used and method of crushing are other variables, which influence the quality of RCA. Multiple crushing of demolished concrete improves quality of RCA because more mortar is displaced from stone particles. However, the degree of quality improvement is not sufficient to justify the additional cost of multiple crushing.

Size of Aggregate Particles. Large-size particles have better qualities than small-size particles because the larger the particle size, the lesser is the amount of adhering mortar. This improves properties such as specific gravity, water absorption and LA abrasion. Figs. 2.4 to 2.6 illustrate this phenomenon. The types OCs crushed to produce RCA are: 14 MPa-low strength (L), 34 MPa-medium strength (M), and 57 MPa-high strength (H). Thus, RCA (M) denotes recycled aggregates produced by crushing medium strength (M) concrete. The figures also show that:

a) except for LA abrasion (Fig. 2.6), quality of OC has little influence on the resulting properties of RCA,

b) quality of RCA deteriorates at a faster rate for sizes bellow 8 mm (0.31 in). Thus RCA sizes below 8 mm should not be used as concrete aggregates whenever possible, and

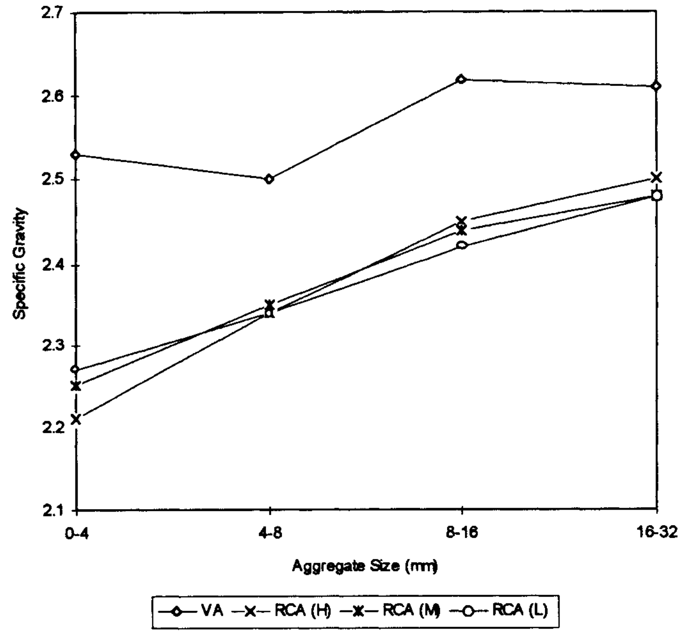


Fig. 2.4 Specific gravity of VA and RCA as function of aggregate size
(Source: Hansen and Narud, 1983)

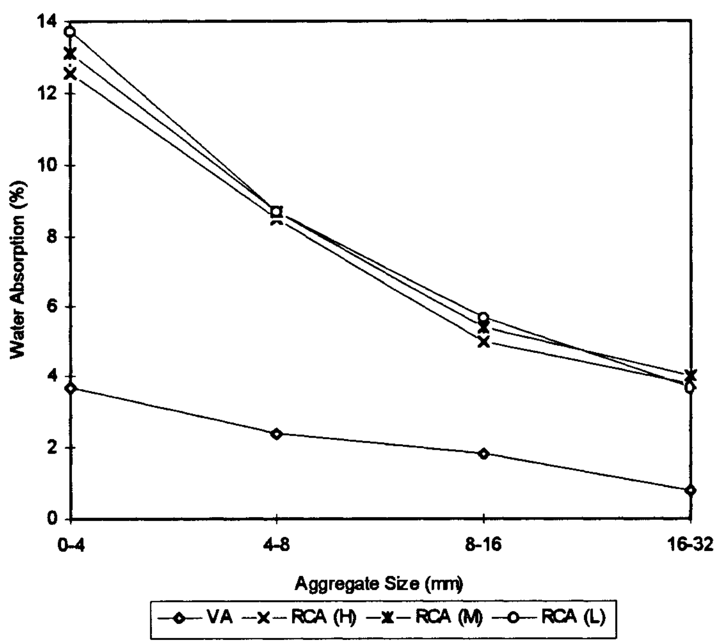


Fig. 2.5 Water absorption of VA and RCA as function of aggregate size
(Source: Hansen and Narud, 1983)

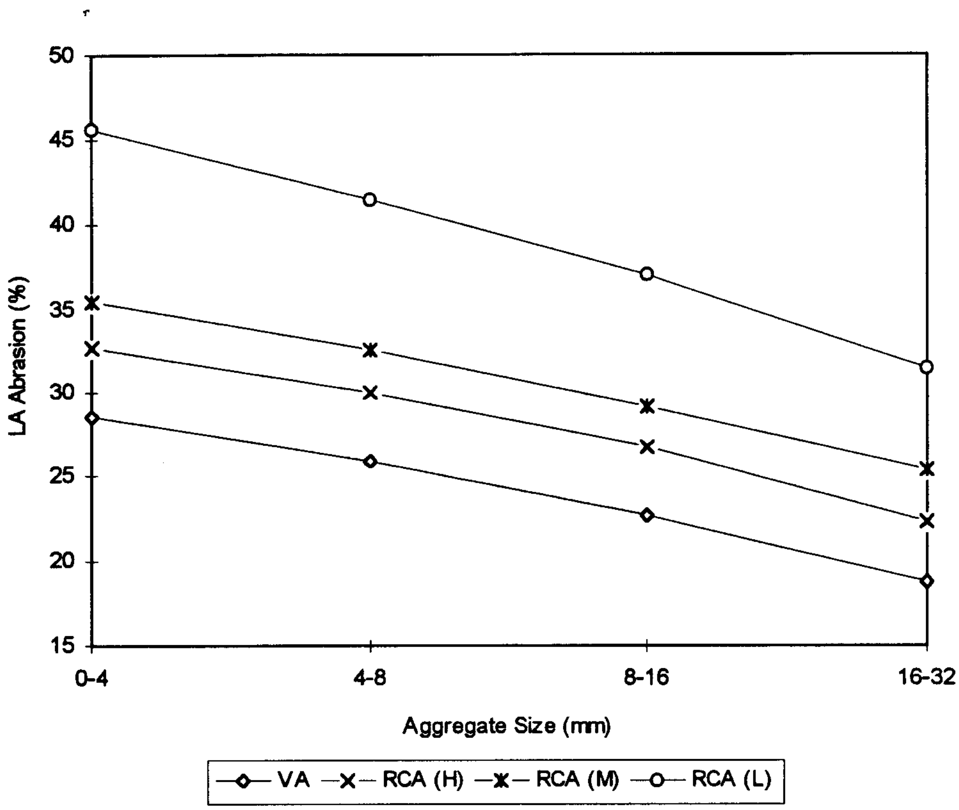


Fig. 2.6 LA abrasion of VA and RCA as function of aggregate size
(Source: Hansen and Narud, 1983)

c) in all the properties presented, RCA show inferior qualities as compared to VA.

2.6.2.3. Quality of original concrete (OC)

The composition and properties of OC have influence in the properties of RCA. An OC of higher quality produces RCA of better qualities than those from a low quality OC. However the level of influence is not very significant and may be neglected. The advantage of this is that the OC can be recycled without special considerations of its original composition.

CHAPTER 3
USE OF RECYCLED CONCRETE AGGREGATE IN THE UNITED STATES

3.1. Introduction

When concrete pavement deteriorates, it could be rehabilitated by either overlaying it with a thin layer to cover the deteriorated surface, or removing the old concrete and reconstruct the pavement. The removed concrete materials can either be disposed of in the land fill, or be reclaimed by crashing it and then using the aggregates in the new concrete. The quantity of demolished concrete that is discarded as waste in USA every year, is over 1 billion metric tones (Bairagi, Ravande and Pareek 1992). There are several private operators who crush the demolished concrete into aggregates. However, the biggest problem faced by these recyclers is the lack of acceptance on the part of public officials, who control the demand, to use recycled concrete aggregate (RCA) in most of their major projects (Broughton 1993).

This chapter presents results of a survey which was developed by Timothy Sergenian (Sergenian 1996) to determine where, and in what applications, RCA are currently being used throughout the USA; and reasons for reluctance of public agencies to using RCA. In addition, design provisions and specifications associated with the use of RCA in pavement construction are reviewed. The information provided in this chapter, covers mainly the use of RCA as aggregates for the construction of new Portland Cement Concrete Pavement (PCCP). The survey is focussed on the State Highway Agencies.

3.2. Use of RCA in Pavement Construction

A survey was developed to determine the current use of RCA in pavement construction in USA. The questionnaire designed for the survey was distributed to the Department of Transportation's Materials Engineer for each state and Puerto Rico (51 total). A total of 46 replies were received (90%). 35 respondents indicated that use of RCA was allowed by their state agency. The profile of the responses is shown if Fig. 3.1.

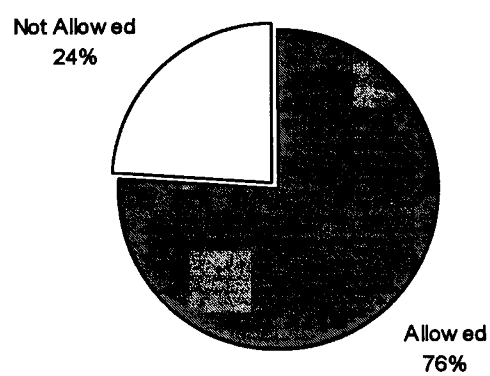


Fig. 3.1 Acceptability of RCA by State DOT Agencies

The applications of RCA in pavement construction, as provided by the 35 state agencies that allow its use, are presented in Table 3.1. The results show that RCA is currently being utilized primarily in non-structural areas. This includes such applications as base course, sub-base, backfill and rip-rap. In order to increase the reuse of waste materials in the U.S., additional areas of application must be utilized. This is where the concerns for not allowing the use of RCA as listed in Table 3.3 are significant. As studies are developed to address these issues, the state agencies will feel more confident in using RCA in a greater array of applications.

Table 3.1 Current applications of PCC aggregates by State Highway Agencies

Application	Number of Responses*
Base course	21
PCC pavement	11
Bituminous/Asphaltic concrete pavement	10
Backfill	8
Sub-base	7
Rip-rap	4
Miscellaneous concrete (shoulders, sidewalks, curbs and gutters)	3
Mechanical soil stabilization	2
Concrete rehabilitation	1

* Total number is more than 35 because of multiple responses.

Table 3.2 presents main reasons why the 11 state agencies do not allow the use of RCA in any area of pavement construction. Virgin aggregates (VA) and landfill space are not infinite in quantity. Japan and Europe discovered this several years ago. Japan has a very high population density and a limited amount of land available for landfill sites. As a result, 48% of concrete rubble associated with demolishing work was reused in 1990 (Kasai 1994). This compares to 40% in the United Kingdom (Collins, 1994). Due to a growing shortage of VA, the Dutch

Government published the Law on Waste Materials in 1988. It is the Government□s policy that, by the year 2000, 90% of demolition waste must be reused (de Vries, 1993). Parts of the U.S. are discovering that it is economically beneficial to use RCA in pavement construction. In the New York City metro area, where landfill space and RCA are both in short supply, RCA is almost exclusively the material of choice (Snyder, 1996). In Maine, the availability of VA may be in jeopardy. It is believed that many of the state's sources for gravel are highly radioactive (Redmond, 1996). The lack of existing PCCP to recycle will change as the nation's highway system and aging bridges require replacement and reconstruction.

Table 3.2 Reasons why RCA is not allowed in any application

Reason	Number of Responses
Limited supply of existing PCC pavement	8
Plentiful supply of high quality virgin aggregates	8
Abundant landfill space	1

The respondents also listed specific technical reasons for not allowing the use of RCA as aggregate in new PCCP. These reasons are presented in Table 3.3. The resistance due to these technical issues, that is, quality, chloride content, shear capacity, durability, and water demand of RCA, will be eliminated as research makes more information available. Numerous studies have been performed and are underway on RCA that address the areas of water absorption, impurities, mechanical properties, durability, strength, and quality improvement methods. The continuous flow of information produced by these studies will help in heightening the level of confidence in the use of RCA by the state departments of transportation.

Table 3.3 Technical reasons for not allowing RCA in PCCP

Reason	Number of Responses
'D' cracking of old PCCP	2
VA in old PCCP is highly radioactive	1
Results in unpredictable quality	3
Unpredictable water demand during mixing	2
High chloride content	1
Low shear capacity	1
Long term durability is unknown	1
Quality of VA in old PCCP is poor	1

The agencies were also queried as to whether they have any design provisions and specifications for the use of RCA. Out of the eleven agencies that allow RCA as aggregates in PCCP, nine had specifications specifically tailored for RCA, and two applied same specifications for both RCA and VA. The specifications covered processing of PCCP (removal, crushing and stockpiling), mix design, physical properties of RCA and conditions of the old PCCP. Specific items covered by various specifications are given in Table 3.4.

3.3 Discussions on the Specifications for RCA in PCCP

As mentioned above, two of the state agencies that allow use of RCA in PCCP apply the same design standards and specifications to RCA as they do to VA. As a result, these states exclude the use of RCA when properties such as particle size, density, and water absorption are design concerns. The continuing research being performed on RCA and RCA concrete should result in an increasing number of states developing design provisions and specifications for

Table 3.4 Design provision and specifications of use of RCA in PCCP

Area	Item Covered	Number of
Old PCCP	"D"- cracking	1
	Alkali-silica reactivity	1
Processing	Removal and crushing	5
	Crushing, sizing and stockpiling	5
Physical properties	Freeze-thaw	3
	Sulfate soundness loss	3
	Gradation	3
	LA abrasion	5
	Asphalt content	3
Mix design	Admixture	1
	Cement content	2
	w/c ratio	1
	Air content	1

the use of RCA as aggregates in new PCCP. Important elements included in some of the specifications for RCA and RCA concrete are discussed below.

3.3.1 Indiana DOT

Though infrequently used, the Indiana specification has a special provision entitled "Recycling Existing Concrete Pavement as Coarse Aggregate in New Concrete Pavement." This provision gives the contractor the option of either recycling existing concrete pavement as coarse aggregate in the new pavement, or using VA. According to the provision, the RCA concrete shall conform to Sect. 501 of IDOT Specification in addition to the following requirements:

- All asphaltic overlay patching materials to be removed from existing pavement surface before concrete removal operations takes place.
- The concrete pavement to be removed without disturbing the subgrade or subbase material to the maximum extent practical.
- All existing reinforcing steel must be removed from the existing concrete either before or during crushing.
- No. 4 screen to be included in the processing equipment for the removal of fine material.
- The cementitious content of the new concrete to be 350 kg/m^3 (586 lb/yd^3) instead of the usual requirement of 330 kg/m^3 (564 lb/yd^3).
- Fly ash to be incorporated into the new concrete with a 10% minimum and 20% maximum cement replacement.
- Gradations of RCA to be in accordance with grading size number 8. The RCA to be stockpiled in such a manner that it shall not be contaminated with foreign materials.
- The RCA concrete shall contain 100% natural (river) sand.

- A water-reducing or water-reducing and retarding chemical admixture may be used in the new concrete mix
- The air content of fresh RCA concrete to be determined by means of volumetric method by both the IDOT and the contractor.
- If the quantity of RCA is not sufficient for the job, VA shall be used as needed.

3.3.2 New York Department of Transportation (NYDOT)

In the ITEM 18203.0249: "Pavement Removal and Disposal or Recycling" of NYDOT's Specifications, the contractor is given an option of either removing the PCCP and dispose it or remove the PCCP, crush, size and stockpile it as aggregate for new PCCP. The new PCCP is covered in ITEM 18502.5: "Portland Cement Concrete Pavement (Reinforced) including Virgin or Recycled Coarse Aggregate Option".

When RCA is used as aggregate for new PCCP, it shall conform to Materials Specifications covered in Section 502. In addition, the following requirements must be met:

- The concrete to be recycled must be from the existing pavement of the project.
- RCA must conform to required gradation. If this gradation is not achievable, VA may be proportioned with RCA at the time of batching to provide the specified gradation in the mix.
- All metallic materials in PCCP must be removed either before or during the crushing operation.
- The RCA shall be stockpiled separately from other materials, and must meet the stockpile requirements of Section 501-3.03.
- The stockpile has to be prewatered to uniform moisture content before concrete mixing.

- The concrete proportioning must be determined from trial mixes prepared using project RCA. The concrete will be designed to have minimum cement content of 360 kg/m^3 (605 lb/yd^3), a w/c ratio of 0.44, and an air content of 4.0-8.0%.

In 1980, a contractor was given this option of using RCA but chose to use VA in the construction of the new PCCP, and landfilled the removed concrete from the old PCCP for economic reasons. So far this provision is known to have been used only once.

3.3.3 Louisiana Department of Transportation (LDOT)

LDOT allows use of RCA as coarse aggregate in concrete mixtures for minor structures and PCCP. The RCA must meet requirements stipulated in Subsection 1003.02(c)(3) of LDOT Specifications in addition to the following:

- The coarse aggregate for concrete mixtures used in minor structures or pavement may consist of 100% RCA or any combination of RCA and VA.

- The combined coarse aggregates are required to conform to the gradation requirements in Subsection 1003.02(c): Grades B or D for pavements and Grades A or B for minor structures. Grades A, B and D are given in Table 3.5. The exception to this requirement is that the percentage of material finer than size 0.075 mm (No 200) shall be 0-3 instead of 0-1 as shown in the table.

3.3.4 West Virginia Department of Transportation (WVDOT)

The WVDOT's Specification, Section 501.2.1-"Recycled Pavement for use as Coarse Aggregate for Concrete" outlines the processing and grading requirements as follows:

- Any asphaltic concrete resurfacing must be removed before the Portland cement concrete is crushed.

- Any existing reinforcing steel shall be removed from the existing PCCP prior to or during crushing operations.

Table 3.5 LDOT Gradation requirements for uncrushed coarse aggregate

	PERCENT PASSING		
Sieve Size (mm)	Grade A	Grade B	Grade D
63	---	---	100
50	---	100	90-100
37.5	100	85-100	---
25	90-100	---	35-80
19	---	35-85	---
12.5	25-60	---	---
4.75	0-10	0-6	0-6
2.36	0-5	---	---
1.18	---	---	---
0.075	0-1	0-1	0-1

- The PCCP to be removed in a manner which excludes subgrade and base material to the maximum extent practical.
- The PCCP material shall be crushed to pass the 37.5-mm sieve, and must exclude materials finer than 4.75-mm size.

Other aggregate requirements are the same for RCA and VA.

3.3.5 Oklahoma Department of Transportation (ODOT)

As related to using RCA in PCCP, the ODOT's Specification has the following provisions:

- The coarse RCA must pass the Freeze-Thaw test as described in ASTM C-666 Method "A" with the following exceptions: number of cycles shall be 350, and a minimum durability factor (DF) of 50.

- The existing PCCP shall have no signs of "D" cracking, and the crushed RCA shall be free of alkali-silica reactivity.

ODOT allow the use of RCA in concrete rehabilitation of existing PCCP only.

3.3.6 North Dakota Department of Transportation (NDDOT)

Section 560: "Recycled Portland Cement Concrete Pavement" of the NDDOT's Standard Specifications covers the following items: preparation of sites to stockpile crushed material (RCA), stockpiling, removing concrete pavement, existing reinforcing steel, processing salvaged concrete, mixing, and placing. Requirements for these items are almost similar to the ones discussed in other specifications above. However, the following are exceptions:

- The removed concrete shall be crushed to the gradation such that when combined with VA, the total coarse aggregate meets the gradation requirements of Size 4, including material passing 0.075-mm (No. 200) sieve.
- Crushing operation to be adjusted so as to maximize the amount of crushed material retained on 2.36 mm (No. 8) sieve, while still maintaining the Size 4 grading.
- A spray bar shall be installed at the end of the crushing operation to prewet the salvaged coarse aggregate before it is stockpiled. All RCA stockpiles to be prewatered to the extent that it is above surface dry condition (SSD) at the time of incorporating into the mix.
- The RCA shall be mixed according to Section 802 of the Standard Specifications. Both RCA and VA shall be blended in the plant.
- The RCA concrete mixture shall be placed according to Section 550. The pavement surface riding quality must be as specified in Section 550.04 of the Specifications.

3.3.7 Illinois Department of Transportation (IDOT)

Section 704 of IDOT's "Standard Specification for Road and Bridge Construction" includes "crushed concrete" as an acceptable source of aggregate material. The IDOT has two criteria for accepting RCA: a) project-by-project basis (concrete from IDOT existing pavement), and b) stockpiled RCA at a central recycling plant (CRP). For project acceptance, the followings are required:

- Freeze-thaw tests must be performed if RCA is to be used in PCCP.
- Preliminary samples of existing PCCP from a number of locations (minimum 3) shall be submitted to the IDOT Laboratory for quality testing. A period of three months is required for freeze-thaw testing.
- Gradation of RCA shall conform to the "Manual for Aggregate Inspection."
- RCA to be stockpiled in a well-prepared stockpile pads to avoid contamination.

Acceptance of RCA from CRP is on stockpile-by-stockpile basis. However, since RCA produced at the CRP may include non-IDOT specified concrete, it is not accepted by IDOT for use in concrete.

3.3.8 Minnesota Department of Transportation (MDOT)

MDOT permits the use of RCA as coarse aggregate in PCCP on a project-by-project basis. Approval is dependent on the performance of the VA in the existing PCCP (no evidence of 'D' cracking), and on freeze-thaw test. If approved, the only size of RCA accepted is the fraction between 19 mm (0.75 in) and 4.75 mm (No. 4) sieve sizes.

3.3.9 Connecticut Department of Transportation (CDOT)

The Standard Specifications for Roads, Bridges and Incidental Construction of the CDOT, Section M.03.01, describes coarse aggregate as broken stone, gravel, or reclaimed concrete. It defines reclaimed concrete aggregate (RCA) as mortar-coated rock, consisting of clean durable fragments of uniform quality throughout. The specification requirements for RCA are: it shall be free from soft, disintegrated pieces, mud, dirt, organic or other injurious material; and shall not contain more than one percent of dust by weight. The specification also states that RCA shall not be used in prestressed concrete members.

3.4 Summary

There is great potential for use of reclaimed PCCP as coarse aggregate in new pavement construction. Many state highway agencies recognize this potential but still continue to use specifications, which contain requirements that cannot be attained by RCA, thus restricting its use. Thus, before reclaimed PCCP can be fully utilized, two events need to occur.

First, research into the various uses of RCA must build-up to a level in which users feel confident in the level of quality, durability, and consistency of RCA and its products.

Second, and most important, the economic environment for recycling construction waste must improve. The use of RCA will approach economic feasibility as the following events occur:

- The availability of VA is depleted.
- Landfill space becomes scarce, resulting in an increase in tipping charges and taxes.
- The cost of transporting concrete waste increases.

Most of the specifications address the issues of removal and crushing of old concrete, stockpiling the crushed material (RCA), and gradation. However, the essential parameters presented in Table 3.3 are hardly covered by the states' specifications. These issues have to be investigated further to determine their effects on RCA concrete. With more reliable information, state DOT agencies will include them in the specifications, thus promoting the use of RCA.

CHAPTER 4
LABORATORY TEST RESULTS

4.1 Introduction

One approach for maximizing the use of concrete from demolished pavements is to use it as aggregates in the reconstruction of the new pavement. This can be achieved by characterizing the properties of recycled concrete aggregate (RCA), and those of concrete containing RCA (RCA concrete). This chapter presents results of experimental studies on the properties of concrete materials and concrete mixtures. Concrete materials include RCA, virgin aggregate (VA) and natural sand. Concrete mixtures are differentiated by the type of coarse aggregate used, RCA, VA or a combination of the two in various proportions.

4.2 Materials

4.2.1 Sources of Material

The source of RCA was a demolished concrete pavement section of I-10 in Santa Rosa County, Florida. The crushed material was provided by the Anderson Columbia Co., Inc., from its stock of crushed concrete in Baghdad, Florida. About 3.8 m^3 (5 yd^3) of RCA was collected, of which 0.76 m^3 (1 yd^3) was separated for use in testing the properties of the aggregate, and the remaining amount was used for casting test-track concrete in Orlando. Samples of VA and sand used for control purposes, were provided by CSR Rinker Materials of Orlando.

4.2.2 Material Properties-Tests and Results

Laboratory tests were conducted at Laboratories of FDOT's State Material Office in Gainesville. The RCA samples were tested for: gradation, unit weight, bulk specific gravity, water absorption, resistance to degradation by abrasion and impact in the LA Machine (LA abrasion), and void ratio. All the tests were conducted according to the appropriate FDOT Testing Methods as shown in Table 4.1. The results of these tests, including some properties of VA and sand are given in Table 4.2. Both the physical and mechanical properties of RCA are in

Table 4.1 Aggregate test methods

TEST METHOD	FDOT (ASTM) DESIGNATION
Sieve Analysis of Fine and Coarse Aggregate	FM 1-T 027 (C-136)
Specific Gravity and Absorption of Coarse Aggregate	FM 1-T 085 (C-127)
Unit Mass and Voids in Aggregate	FM 1-T 019 (C-29)
LA Abrasion (Small-sized Coarse Aggregate)	FM 1-T 096 (C-131)

agreement with results from other studies. For example, typical values of some of RCA properties are (Hanks and Magni, 1989; ACPA, 1993): specific gravity (2.2 to 2.5), water absorption (2 to 6), and LA abrasion (20 to 45). When compared to VA, properties of RCA are as good, and some, like specific gravity and unit weight, are even better. The high quality of RCA is an indication that the aggregates used in the demolished concrete were of good quality because properties of RCA depend, to a great extent, on the properties of aggregates in the original

Table 4.2 Properties of RCA, VA and sand

PARAMETER	AGGREGATE TYPE		
	RCA	VA (RP # 1041)	Sand (RP # 3156)
Specific Gravity (SSD)	2.43	2.42	2.64
Water Absorption (SSD), %	4.36	4.1	0.6
Unit Weight, lb/ft^3	88.2	84.2	---
LA Abrasion, %	33.9	32.6	---
Void Ratio, %	41.9	---	---

RP = Rinker Pit (mine)

Table 4.3 Gradation of RCA, VA and sand (% passing)

Sieve Size, mm	SAND		COARSE AGGREGATE, #57		
	Sample	Limits	RCA	VA	Limits
37.5	---	---	100	100	100
25	---	---	97.6	100	95-100
12.5	---	---	46.4	42	25-60
4.75	100	95-100	4.8	3	0-10
2.36	100	80-100	4.2	1	0-5
1.18	95	50-85	---	---	---
0.6	62	25-60	---	---	---
0.3	18	5-30	---	---	---
0.15	1	0-10	---	---	---
0.075	0	0-4	---	---	---

concrete. In this particular case, the demolished concrete contained river gravel as coarse aggregate, which has better qualities compared to limerock.

Results of sieve analysis are presented in Table 4.3 and are plotted in Fig. 4.1. Both RCA and VA are well within the acceptable gradation range for Grade Size 57. In comparison, however, RCA has more small sized particles than VA.

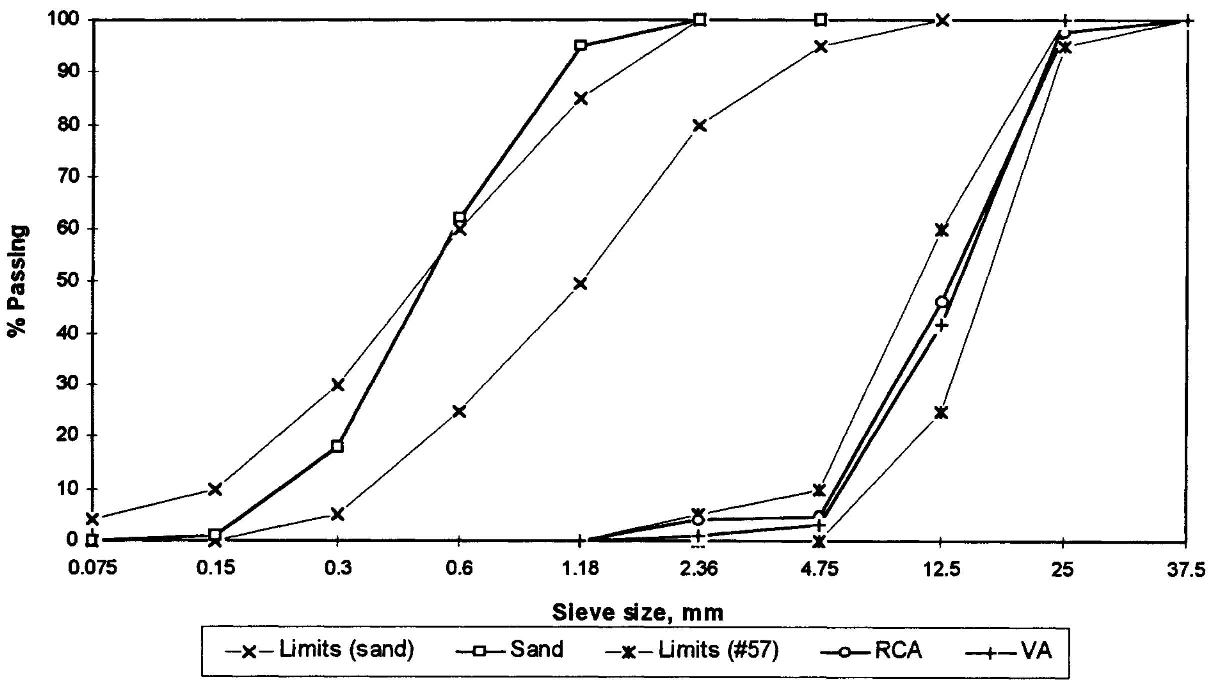


Fig. 4.1 Gradation of aggregates (RCA, VA and sand)

4.3 Concrete

4.3.1 Trial Concrete Mix

A concrete trial mix using RCA was prepared at the FDOT's State Material Office to determine the characteristics of RCA concrete. The trial mix was designed to satisfy the FDOT's Class II concrete using No. 57 size aggregate and virgin sand. The Class II concrete has a target compressive strength of 25 MPa (3630 psi) at the age of 28 days. According to FDOT concrete design procedures two parameters are given for 1 m^3 of concrete: the cement content (335 kg/m^3 for Class II concrete), and volume of coarse aggregate (0.41 m^3/m^3). After deciding on the air content and water/cement ratio (w/c), other parameters of the mix design are determined on the basis of the specific gravities of the components. The trial mix contained w/c ratio of 0.45, air entraining (for 4% air) and high range water reducing admixtures. The material proportions used in the trial mix are summarized in Table 4.4. Weights of RCA and sand are based on their individual specific gravities at SSD state.

Table 4.4 Material proportions of the trial mix

COMPONENT	SPECIFIC GRAVITY	WEIGHT (kg)	VOLUME (m3)
Cement Type I (AASHTO M 85)	3.15	335	0.11
Water (1000 kg/m^3)	1	151	0.15
Coarse Aggregate (RCA)	2.43	990	0.41
Fine Aggregate (Virgin Sand)	2.6	754	0.29
Air, 4%			0.04
Theoretical Volume			1.0
Admixture: Master Builders (ml/100 kg cement)	MBVR air entraining = 32.6		
	Rheobuild High Range Water Reducer = 978		

1 kg=2.204 lb, 1 ml=0.033 oz, 1 m^3=35.315 ft^3, 1 kg/m^3=1.686 lb/yd^3

Four cylinders of standard size 150 mm ϕ by 300 mm length (6 X 12 in) were prepared for compression test. The properties of fresh concrete of the trial mix are summarized in Table 4.5, and the results of cylinder compressive strength are presented in Table 4.6.

Table 4.5 Results of fresh trial mix concrete

PARAMETER	VALUE
Slump, mm (in)	178 (7)
Air, %	4
Unit Weight, kg/m^3 (lb/ft^3)	2360 (147)
Temperature, °C (°F)	28.9 (84)

Table 4.6 Results of compressive strength test of trial mix concrete

SAMPLE	AGE, days	STRENGTH, MPa (psi)	AVERAGE, MPa (psi)	TARGET MPa (psi)
1	3	15.9 (2310)	15.8 (2290)	-----
2	3	15.6 (2260)		
3	28	26.5 (3840)	25.7 (3730)	25 (3630)
4	28	24.9 (3610)		

4.3.2 Field Concrete

4.3.2.1 Mix design. The results of trial mix were used to develop mix design for concrete to be used in the circular accelerated test track (CATT) at the University of Central Florida (UCF) in Orlando. Due to high slump of the trial concrete, it was decided to reduce the w/c ratio from 0.45 to 0.42. Four alternative types of concrete mixes were developed based on the type and content of RCA coarse aggregate: a) 100% RCA; b) 75% RCA + 25% VA; c) 25% RCA + 75% VA; and d) 100% VA, which was the control mix. Virgin sand was used in all the mix types and design was the same for all the mixes. The aggregates conformed to the properties presented in Tables 4.2 and 4.3. The mix proportions for 100% RCA and VA Class II concretes are summarized in Table 4.7.

Table 4.7 Mix design for test track concrete

COMPONENT	SPECIFIC GRAVITY	WEIGHT (kg)	VOLUME (m3)
Cement Type I (AASHTO M 85)	3.15	335	0.11
Water (1000 kg/m^3)	1	141	0.14
Coarse Aggregate, RCA (VA)	2.43 (2.42)	990 (992)	0.41
Fine Aggregate (Virgin Sand)	2.6	780	0.30
Air, 4%			0.04
Theoretical Volume			1.0
Admixture: Master Builders (ml/100 kg cement)	MBVR air entraining = 32.6		
	Rheobuild High Range Water Reducer = 978		

1 kg=2.204 lb, 1 ml=0.033 oz, 1 m^3=35.315 ft^3, 1 kg/m^3=1.686 lb/yd^3

4.3.2.2 Concrete mixing

Concrete mixes with RCA were made at the job site using two, 0.26 m^3 (9 ft^3) mixers, while the control mix (VA concrete) was ready-mix concrete. Mix proportions for coarse aggregates (CA), fine aggregate (FA) and water were adjusted based on the actual moisture contents of the aggregates with respect to SSD weights. The adjustments were based on the following relationship

$$W_{FA} = \frac{W_{SSD}^{FA}}{1-(MC_{FA}-WA_{FA})}$$

$$W_{CA} = \frac{W_{SSD}^{CA}}{1-(MC_{CA}-WA_{CA})}$$

$$FW = (W_{FA} - W_{SSD}^{FA}) + (W_{CA} - W_{SSD}^{CA})$$

$$BW = DW - FW$$

where W = weight of aggregate, WA = water absorption, MC = moisture content, FW = free water, BW = batch water (adjusted), DW = design (batch) water. The moisture content and water absorption values for sand and coarse aggregates (RCA and VA) are shown in Table 4.8.

Table 4.8 MC and water absorption of sand and coarse aggregate

	SAND	RCA	VA
Water Absorption (SSD) %	0.6	4.36	3.5
MC (%)	2.31	3.58	5.76

4.3.2.3 Concrete specimen tests and results

During concrete placing, two concrete samples were collected from each of the four concrete types. From the samples, 9 cylinders (6 by 12-inches) and 2 beams (6 by 6 by 30-inches) were prepared and molded from each mix type containing RCA; and 5 cylinders and 2 beams for the control mix, making a total of 32 concrete cylinders and 8 beams. The specimens were removed from the molds after 24 hours, and then immersed in lime-saturated water. At age of 27 days the samples were removed from the lime-water, and transported from Orlando to Gainesville, where they were tested at the age of 28 days. The procedures for sampling, making specimens and testing were in accordance with the standard methods summarized in Table 4.9. The placed concrete was cured by spraying the finished surface with a styrene-arcyclic resin-based curing compound known as Crystal Seal, supplied by the Lambert Corporation.

Table 4.9 Test methods for concrete

TEST METHOD	FDOT (ASTM) DESIGNATION
Sampling Fresh Cement Concrete	FM 1-T 097 (C-78)
Making and Curing Concrete Test Specimen in the Field	(C-31)
Slump of Portland Cement Concrete	FM 1-T 119 (C-143)
Air Content of Freshly Mixed Concrete by Volumetric Method	FM 1-T 196 (C-173)
Compressive Strength of Cylindrical Concrete Specimens	FM 1-T 022 (C-39)
Flexural Strength of Concrete (using simple beam with 3-point loading)	FM 1-T 097 (C-78)
Splitting Tensile Strength of Cylindrical Concrete Specimens	(C-496)

Table 4.10 Properties of fresh concrete

CONCRETE TYPE	SAMPLE	PARAMETER		
		Slump, mm (in)	Temp., °C (°F)	Air, %
100% VA	1	152 (6)	---	2.2
75% VA + 25% RCA	1	114 (4.5)	25.3 (77.5)	3.2
	2	70 (2.8)	26.1 (79.0)	3.0
25% VA + 75% RCA	1	83 (3.3)	26.0 (78.8)	2
	2	178 (7)	23.0 (73.4)	2.5
100% RCA	1	76 (3)	29.2 (84.6)	1.4
	2	191 (7.5)	29.1 (84.3)	2.8

Fresh concrete. The properties of fresh concrete measured were: temperature, air content and slump. Results of the tests for different types of concrete are presented in Table 4.10.

Hardened Concrete. The following properties of hardened concrete were measured: compressive strength, elastic modulus, splitting tensile strength, and flexural strength (3rd point loading) The test program was designed as follows:

Per each RCA mix type:

a) 5 cylinders for compression test
b) 1 cylinder for elastic modulus test, then used for compression test
c) 1 cylinder for elastic modulus test only
d) 2 cylinders for tensile split test
e) 2 beams for modulus of rupture test

Thus the resulting number of specimens were 6 cylinders for compression test, 2 for elastic modulus, 2 for split test and 2 beams for modulus of rupture for each mix with RCA.

Control mix:

3 cylinders for compression test
1 cylinder for elastic modulus test, then used for tensile split test
1 cylinder for tensile split test only
2 beams for modulus of rupture test

The set up resulted in 2 cylinders for tensile split test. In the elastic modulus test, each sample was loaded to 40 percent of its ultimate compressive strength. Results of the above tests are summarized in Table 4.11, and plotted in Fig.4.2. The extreme values for each category are shown in Figs. 4.3 to 4.6. Results for individual specimens are presented in the Appendix.

Table 4.11 Mechanical properties (averages) of concrete used at the test track

MIX TYPE (% of RCA)	CONCRETE PROPERTIES, MPa (psi)			
	Compression	Tensile	Flexural	Modulus of Elasticity (10^3)
0	42.9 (6220)	2.58 (374)	5.16 (748)	35.6 (5170)
25	39.5 (5730)	2.57 (373)	4.99 (724)	33.4 (4850)
75	38.1 (5520)	2.52 (365)	4.50 (653)	32.0 (4640)
100	35.0 (5070)	2.47 (358)	4.16 (604)	30.5 (4420)

The values of the ratio of 100% RCA to VA concrete are within the range observed by other researchers (Fig. 2.3). Overall, however, the results of this study are above the average of the typical values. Also the trend of quality changes of RCA concrete with the increase of RCA ratio in the mix is consistent with observations in other studies (Kashino and Takahashi, 1988; Kikuchi, Mukai and Koizumi, 1988; and Kasai, Hisaka and Yanngi, 1988). In addition, results in Fig. 4.2

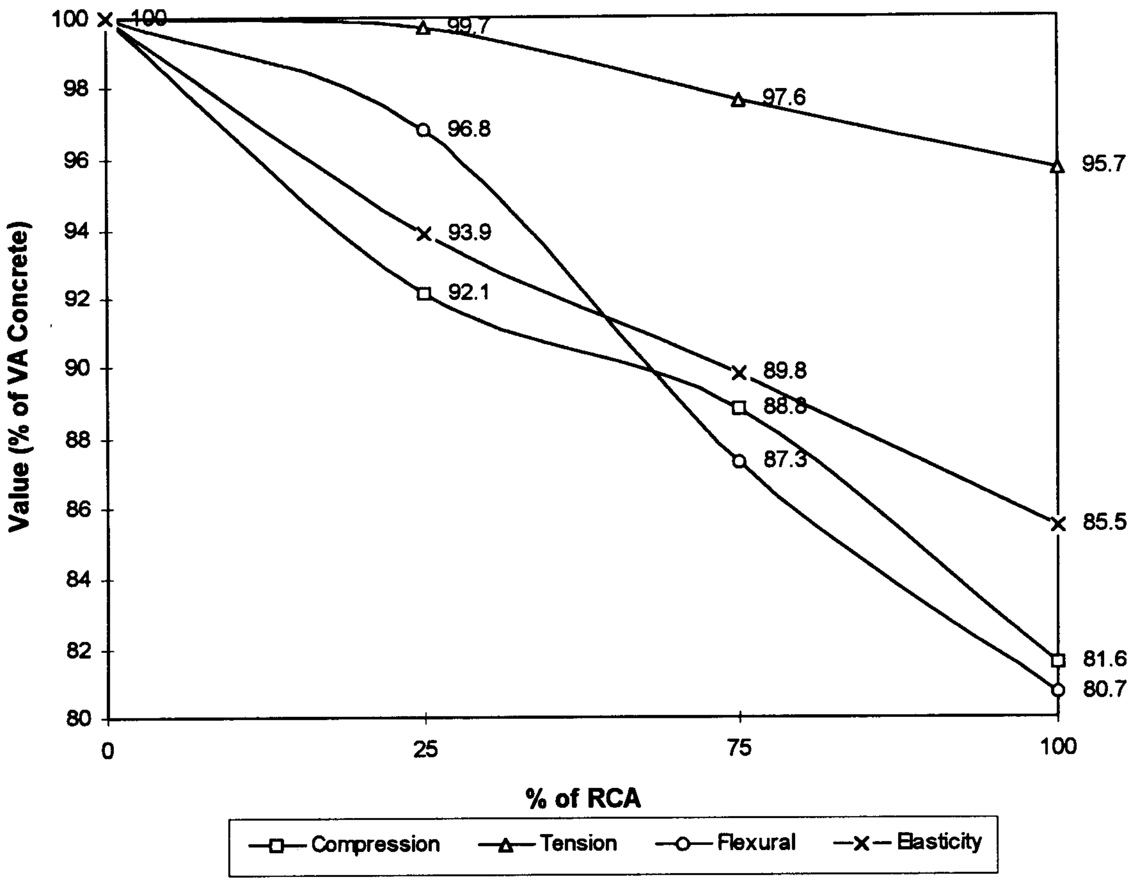


Fig. 4.2 Influence of RCA in concrete properties

show that inclusion of RCA of up to 30% of coarse aggregate have only slight effect on the resulting properties of concrete. Kashino and Takahashi (1988); and Kikuchi, Mukai and Koizumi (1988) reported similar observations.

It is interesting, however, to note that though properties of RCA were comparable to, or better than, those of VA, the properties of RCA concrete are lower than those of VA concrete. The strength of concrete is not only dependent on the strength of aggregates, but is also dependent on the strength of the cement paste and the bond with the aggregates. Thus this phenomenon indicates that bond between cement paste and aggregates is stronger for VA than for RCA, mainly due to old mortar.

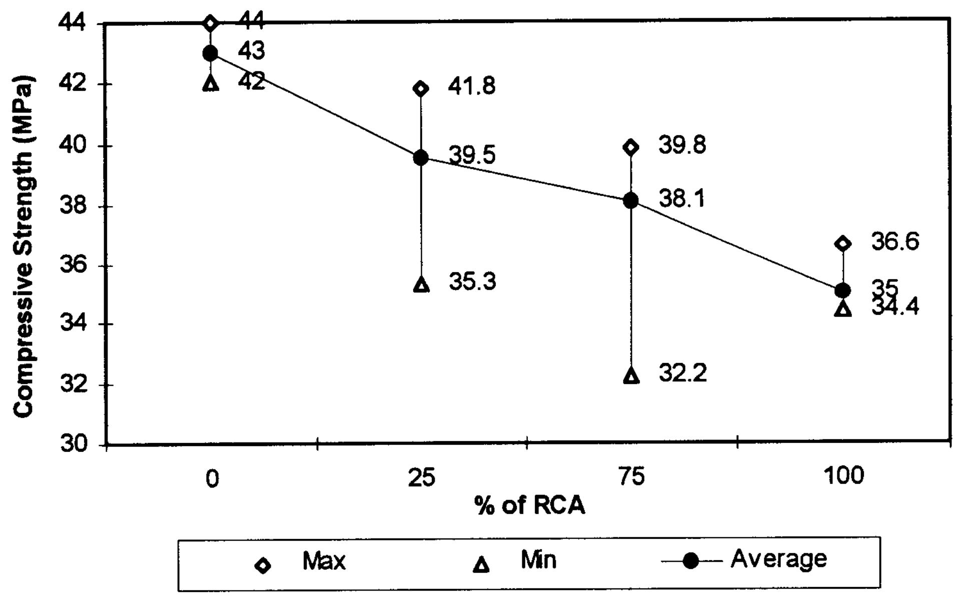


Fig. 4.3 Spread of compressive strength test results

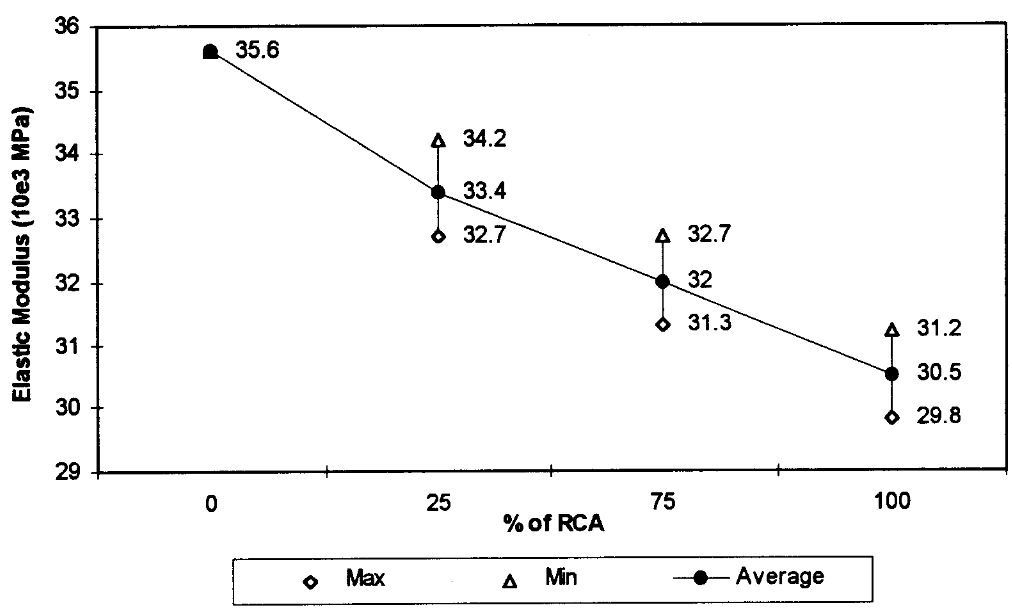


Fig. 4.4. Spread of test results for elastic modulus

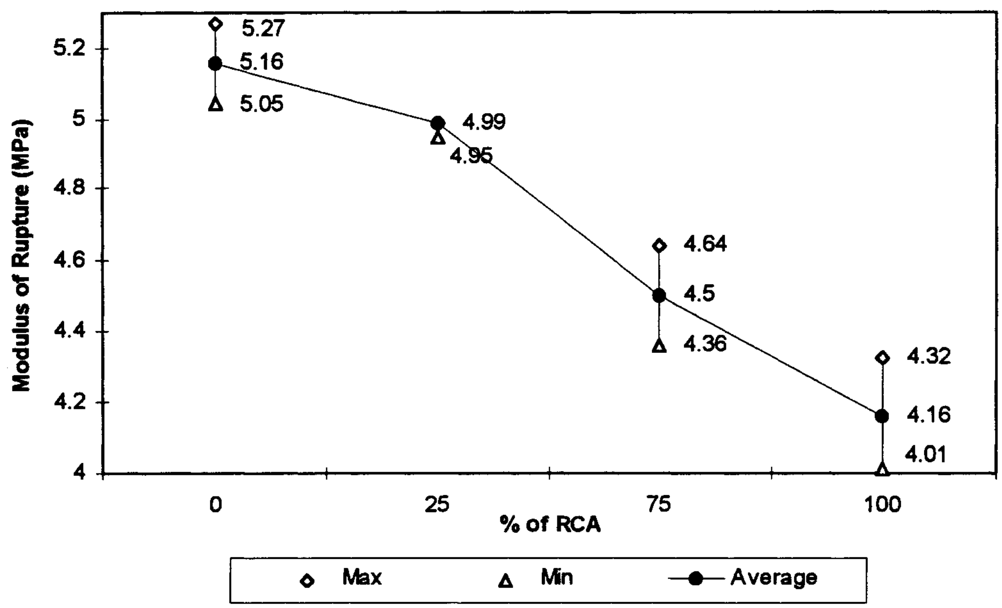


Fig. 4.5 Spread of modulus of rupture test results

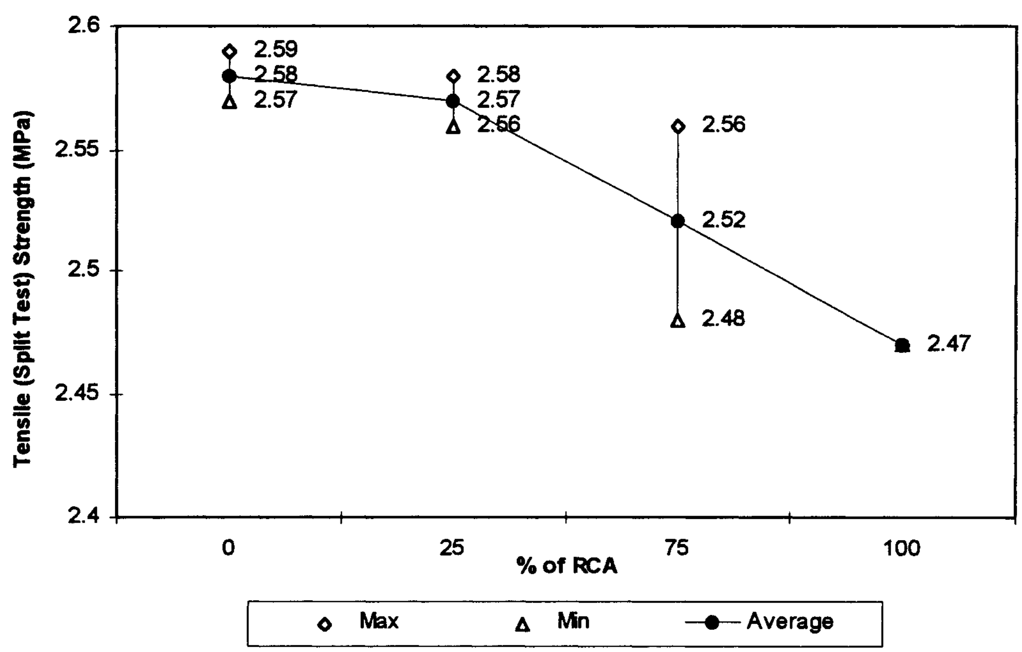


Fig. 4.6 Spread of test results for split tensile test

4.3.3 Improving Strength of RCA Concrete

It has been demonstrated in this study that for the same mix design, compressive strength of RCA concrete is lower than that of VA concrete. However, it is possible to improve the strength of RCA concrete to match that of VA concrete by making following modifications to RCA concrete mix proportions:

1. increase the amount cement per unit volume of concrete,
2. use more superplasticiser to enable reduction of w/c ratio, or
3. the combination of the above strategies.

Whatever method is used, it will be necessary to evaluate the benefits of strength improvement of RCA concrete versus the additional cost required to achieve it.

PART II: USE OF RECYCLED CONCRETE AGGREGATE AS A BASE COURSE IN FLEXIBLE PAVEMENT

CHAPTER 5

LITERATURE REVIEW

Background

The development of recycling technology began 1900 years ago by Romans who built walls, roads and aqueducts with concrete using rock and crushed burnt-clay brick as aggregate (Richardson, 1994). Recycling of concrete in Europe had its inception after World War II, generating a productive form of utilization for debris resulting from the war. The recycling of concrete in Europe has continued and proliferated in the applications of road base and fill. Japan was also compelled to recycling concrete due to its limitations in land area and its high population index. The first concrete recycling plant in Japan had its inauguration in 1975, producing road base aggregate (Richardson, 1994).

In the United States of America, concrete recycling was first investigated in 1942 by the Portland Cement Association, but recycling on a large scale did not commence until the 1970s, with work performed by the Army on runway construction (Richardson, 1994). Over the years, research on recycled concrete aggregate has continued, and a few states recognizing the potential advantages of recycling have adopted specifications for its use in their Department of Transportation manuals.

Literature Search

Richardson and Jordan, 1994

Richardson and Jordan sampled recycled concrete aggregates taken from the stockpile of a commercial producer in Australia at monthly intervals for six months and tested them for grading, plasticity, compaction, and Los Angeles abrasion loss. All samples were found to satisfy the grading requirements of Australian VicRoads specification 820Q (Crushed Concrete for Subbase Pavement).

All aggregate samples were found to be non-plastic. Recycled concrete fines contain approximately 4% calcium hydroxide $Ca(OH)_2$, ie hydrated lime. The exact percentage depends on the amount of cement used to produce the original concrete. Hydrated lime has long been used to improve the workability and strength of clayey soils. The presence of $Ca(OH)_2$ within the crusher fines would reduce the influence of any clayey material on the plasticity of recycled concrete aggregate.

The results of compaction tests indicate that recycled concrete aggregates compacted at either Standard or Modified energy have a density lower than quarried aggregates due to the attachment of low density cement paste. Basalts typically have a maximum dry density (M.D.D.) of 2.35 t/m^3 with an optimum moisture content (O.M.C.) of 7-8% using modified compaction. RCA has a maximum dry density approximately 15% lower than the basalt and an optimum moisture content of up to 33% higher, because the cement paste absorbs greater amounts of moisture. Los Angeles abrasion results of the samples were consistently 29%.

Table 5.1 Results of RCA Tests

Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Plasticity	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.
L.A. Abrasion	29	29	30	29	29	29
Modified Compaction Details						
O.M.C.	10.9	11.5	12.0	11.8	12.1	12.5
M.D.D. (t/m^3)	2.02	2.05	2.01	2.05	2.07	2.02
Marginal and Unsuitable Material Contents (% by mass)						
Brick	2.3	0.5	1.8	1.7	2.6	1.3
Asphalt	1.2	0.8	0	1.1	0	0
Timber	0	0	0.1	0.1	0	0
Glass	0	0	0	0.3	0	0
Plastic	0	Negligible	0	0	Negligible	0
Other	0	0	0	0	0	0

In addition, Richardson and Jordan also performed tests on RCA to determine what effects the strength of the original concrete has on the properties of recycled concrete aggregates. To do so, recycled aggregates from concretes of 32 MPa and 80 MPa, were tested for gradation, Los Angeles abrasion loss, and particle breakdown under compaction. Of the two concretes, the 32 MPa concrete was found to produce a greater amount of fines. This was expected, as the 32 MPa cement paste is more readily broken down than the 80 MPa material.

The 80 MPa sample had a LA abrasion loss of 26% and the 32 MPa of 27%. The difference of only 1% was smaller than expected considering the large difference in the strength of the concretes. The basalt aggregate used to produce the concretes had a LA abrasion loss of 17%. This indicates that the cement paste attached to the original stone causes a significant rise in the LA abrasion loss. The paste is relatively soft when compared with the original stone and was more readily broken down during the test.

Table 5.2 Particle Breakdown Under Modified Compaction and RTL

		80 MPa Sample		32 MPa Sample	
Particle Size (mm)	Pre Compaction Grading (% Passing)	After Comp. & RTL Grading (% Passing)	Change in Grading (% Passing)	After Comp. & RTL Grading (% Passing)	Change in Grading (% Passing)
26.5	100	100	0	100	0
19.0	96	98	2	99	3
13.2	79	87	7	86	7
9.5	66	76	10	72	6
4.75	49	58	8	78	9
2.36	40	47	7	47	7
0.425	20	25	4	25	5
0.075	7	8	1	9	2

To evaluate particle breakdown under compaction, the grading of the samples was adjusted to that shown in Table 2.2, and the material was compacted using modified compaction energy (2,703 kJ/m^3) on ten layers in a mold of 100mm (4 in.) inside diameter and 207mm (8 in.). The specimens were then subjected to 3,000 cycles of Repeated Triaxial Loading (RTL), after which the material was crumbled, dried and re-sieved. This is obviously a more severe condition than determining the grading after compaction alone. Even so, both samples still fell within the Australian grading requirements of VicRoads specification 820Q before and after compaction. Both materials broke down by a similar amount, indicating that different source concrete strengths have little or no effect on the particle breakdown under compaction.

Orlando International Airport

Originally developed as a major U.S. Air Force bomber base, the Orlando International Airport has grown to become one of the major air carrier airports in the United States. In 1989, the Orlando International Airport underwent construction to reconstruct a runway (18R-36L), and construct a number of new asphalt taxiways. The rehabilitation process required the removal of over 60,000 square yards of airfield pavement, approximately 40,000 square yards of which was Portland cement concrete. With the intent of recycling as much of the available on-site materials as possible, it was decided to allow use of the crushed concrete pavement as a coarse aggregate base course (conforming to FAA specification P-209) for the shoulder of the taxiways.

The existing concrete pavements were removed and crushed on site into 3/4" maximum size aggregate. Testing was performed in order to determine the suitability of the recycled concrete aggregate for this application. The sodium sulfate soundness loss was tested in accordance with ASTM C88 and found to be below the 12% allowable limit. The following tests were performed on the recycled concrete aggregate:

Test Method	Description
ASTM C-131	Resistance to degradation of small sized coarse aggregate by abrasion and impact in the Los Angeles machine
ASTM C-88	Soundness of aggregate by use of sulfate solution
ASTM C-117	Material finer than No. 200 in mineral aggregate by washing
CRD-C119	Flat and elongated particles in coarse aggregate

The recycled concrete aggregate met all the required specifications of FAA P-209 for coarse aggregate bases, but was considered a departure from the limerock material called for in the project's contract documents. It was therefore, allowed for use in the shoulder pavement area only.

Mulheron and O'Mahony, 1990

Mulheron and O'Mahony conducted a research study in 1990 to examine the physical and mechanical properties of crushed concrete in the United Kingdom and assess the suitability of crushed concrete aggregate for use as Type 1 or Type 2 granular subbase materials. Mulheron reported that crushed concrete had lower compacted densities than limestone, but the density of the crushed concrete proved to be more consistent. He explains in his report that as the compacted density of the material is dependent on the particle grading, this shows that recycling plants can produce material of consistent particle grading.

Mulheron also tested the recycled concrete aggregate for plasticity and strength. The recycled aggregate was found to be nonplastic, a result which indicates that the recycled concrete tested by Mulheron did not contain any impurities such as demolished brick. The 10% fines test was conducted to measure the resistance of the recycled aggregate to crushing. The test consisted of applying an incremental load to the aggregate and measuring the percentage fines for each increment. One sample of crushed concrete aggregate underwent degradation to the point of producing 10% fines by mass at a load of 80 kN and a second sample did so at a load of 110 kN. In both instances the degradation of the sample occurred at a load higher than 50 kN, which is the minimum specified for Type 1 and Type 2 material. Mulheron concluded from his research that recycled concrete aggregate met all Type 1 specifications and should be considered as a suitable granular subbase material.

Recycled Concrete and Glass

A study was performed in Canada by Senior in 1992 to investigate the possibility of combining recycled glass and recycled concrete as granular base aggregates. Clear glass is recycled by container manufacturers, while all colored glass is regarded as waste and requires disposal in ever diminishing landfill sites (Senior, 1992). If glass is found to improve the properties of recycled concrete base courses, two environmental waste products will be utilized to humanity's advantage.

The glass tests included gradation and physical properties. Durability testing included the Los Angeles abrasion loss and the British aggregate impact value (AIV) to measure impact resistance. Samples of recycled concrete aggregate were tested for compliance with the current granular base specifications. Mixtures of crushed concrete with 0%, 10%, 25% and 50% glass (by mass) along with one sample of 100% glass were tested for strength in the California Bearing Ratio (CBR) test.

The physical test results of this study found that both recycled glass and concrete aggregates met Granular A specifications. California Bearing Ratio test results indicated that the use of glass as an aggregate in granular base composed of reclaimed crushed Portland cement concrete increases potential strength and compaction properties if the amount does not exceed 15% glass by mass (Senior, 1992). It is suggested by Senior that the glass acts somewhat like an inter-particle lubricant because of its smooth surface texture improving compacted density. In addition, the glass replaces concrete fragments reducing the amount of water absorbed, thus higher densities are achieved which increases the CBR values. It was found that beyond the optimum blend of 15% glass, strength of the mixture rapidly falls off.

Table 5.3 Glass and Crushed Concrete Gradations (% Passing)

Sieve Size (mm)	Glass	Concrete
26.5		100
19.0	100	94.8
16.0	99.8	84.1
13.2	96.7	68.7
9.5	68.3	49.8
6.7	40.6	36.5
4.75	26.1	28.4
2.36	12.2	20.8
1.18	6.3	16.5
0.600	3.6	13.7
0.300	2.1	11.3
0.150	1.2	9.0
0.075	0.6	7.3

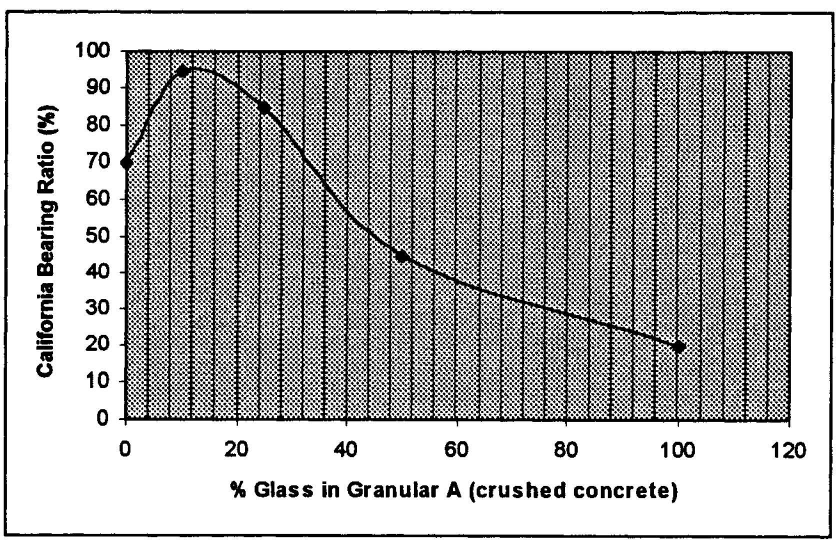


Fig. 5.1 CBR vs % Glass in Granular A (crushed concrete)

Stabilized Base made from Recyclables

Unbound road bases are predominant in the industry because they are more economical than stabilized bases. Portland cement is used in stabilized bases to bind the aggregate and thus provide more support to the overlying pavements than an unstabilized base. The Portland cement used is not only the factor contributing to the strength of stabilized bases, but it is also the factor that makes them expensive.

Research has been done by Hausen suggests that it is possible to produce concrete entirely from waste products such as recycled concrete aggregate and fly ash without the use of Portland cement. When concrete is crushed to be recycled as aggregate, unhydrated cement in the old concrete fines is exposed. The new concrete gains strength from the hardening of the remaining unhydrated cement in the old concrete fines (Hausen, 1990).

Fly ash which is an industrial waste product contributes to the hardening of the binder due to the pozzolanic reaction between calcium hydroxide from the old cement paste and the ground slag (Hausen, 1990). Tests indicate that the concrete made from waste products (recycled concrete aggregate and fly ash) will only have half the compressive strength of a conventional stabilized base. This process may be refined in order to upgrade the quality of demolished crushed concrete for road base purposes from an ordinary granular material to a stabilized product (Hausen, 1990). The recycled stabilized base would present superior performance over the performance of an unstabilized recycled base. Of course, the recycled stabilized base would be weaker than a conventional stabilized base, but it would be less expensive and would contribute to solving two important industrial waste disposal problems.

CHAPTER 6

STATE OF CONCRETE RECYCLING IN FLORIDA

Florida is the nation's fourth largest state in terms of population, home to more than 14 million people, and this figure is projected to grow to nearly 18 million by the year 2010 (US Department of Commerce). To ensure the Florida way of life, the State of Florida has been working hard to maintain the balance between Florida's environmental and natural resources and the needs of Florida businesses. Florida does not seek to lower its high environmental standards, rather it works to effectively manage the process of permitting and environmental planning. The State of Florida prides itself on its careful management of resources and encouragement for recycling.

Florida's production of natural aggregates consists mainly of limestone, which has unique properties when compared to aggregates in the northern United States. There are greater variations in the strengths of limestone obtained from different quarries. As a result Florida generally has to import high quality aggregates from other states.

Independent of the benefits of utilizing recycled concrete aggregates, most professionals are unsure of using a relatively untested material which has no developed guidelines and specifications for its use.

The Florida Department of Transportation (FDOT) is one of the primary standard setters in the nation for soil construction applications. It is looked to by professionals and other government transportation agencies for information and guidance. Several recycled concrete aggregate research projects funded by FDOT encompass a continuing effort to gather scientific data on this material. Furthermore, FDOT has allowed the use of recycled concrete aggregates as a base course on the shoulders of State Road 10, which is located in Florida's Santa Rosa County in the proximity of Pensacola.

As data on recycled concrete aggregates continues to expand, it is likely that FDOT will incorporate recycled concrete aggregate base course standards and specifications in its manual. The development of practical standards and specifications for recycled concrete aggregates by FDOT will encourage its use by professionals and local governments, who can use them as a guide in establishing their own specifications.

Survey of Concrete Recycling Plants in Florida

A survey was developed and sent to recycling concrete plants in Florida to determine each plant's daily production, the supply sources of the plant's production, the type of material produced and common use. To know which companies recycle concrete in Florida, a list of all recycling companies was obtained from the Florida Department of Environmental Protection. All the companies on this list (approximately 200) were called by telephone and asked if they recycle Portland Cement Concrete (PCC). Out of the 200 companies contacted, eighteen were found to recycle in the state of Florida. The fact that many recycling operations are of a mobile and temporary nature, and that concrete recycling companies are not required to possess a recycling license, supports the hypotheses that there may be more than eighteen concrete recycling companies in Florida. A complete list of all concrete recycling companies in Florida would facilitate the obtainment of data on this industry.

A total of 10 responses were obtained from the list of 18 companies, which were found to recycle concrete in Florida. This results in a 55% response rate, which is acceptable for mailed surveys. Following are the results of the responses received.

Question 1a: Is your operation fixed or mobile?

The companies were queried as to whether their operations have a mobile or fixed location. Five companies stated that their operations are mobile, meaning that they can move and operate their crushing equipment where it is most advantageous. One company reported that they possess one mobile crusher and two fixed location crushers. Table 6.1 summarizes the results of this question.

Table 6.1 Is your Operation Fixed or Mobile?

Fixed Location Operation	4
Mobile Operation	5
Both Fixed and Mobile	1

Question 1b: What is your daily (or monthly) production of recycled concrete aggregate?

It can be noted from table 6.2 that the survey population included both large and small recycling companies. It is estimated that the ten companies, which responded to the survey, recycle 10,000 tons/day of concrete in Florida.

Table 6.2 What is your daily Production of Recycled Concrete Aggregate ?

Anderson Columbia Co.	1,000 tons/day
Continental Waste Industries	2,975 tons/day
Dade Recycling Center	300 tons/day
Dixie Septic Tank	600 tons/day
D.S. Eakins Construction	2,025 tons/day
Frontier Recycling	1,200 tons/day
Glasbrenner Sonny Inc.	800 tons/day
Homestead Landfill & Recycling	40 tons/day
Kimmins Contracting Corp.	500 tons/day
Realco Recycling	500 tons/day

Question 1c: What type of crusher do you use?

The use of impact crushers is predominant in the ten companies in Florida, which responded to this question.

Table 6.3 What type of Crusher do you use?

Jaw Crusher	3
Impact Crusher	6
No Response	1

Question 2a: What are your sources of material?

Sources of Material:

- Construction & Demolition Debris
- Curbs
- Slabs
- Old Roads, Highways & Bridges
- Sidewalks
- Concrete Yards

Question 2b: What type of material do you produce?

Type of Material Produced:

- No. 4 FDOT (37.5 to 19mm)
- No. 5 FDOT (75.0 to 12.5mm)
- Base Material
  - 3/8" Minus
  - 1 1/2" Minus
  - 3" Minus
- #57 (25.0 to 4.75mm)
- #89 (9.5 to 1.18mm)
- Fill Dirt
- Screening 1/2" Minus

Question 2c: What are your most common clients and for what applications is your product being used?

The companies surveyed listed contractors and private entities as their most common clients for recycled concrete aggregate. Of those responding, seven stated that the PCC processed by them is used as recycled concrete aggregate (RCA) in road bases. A list of the applications follows.

- Base and Subbase Courses
- Pipe Bedding
- Private Driveways and Parking Lots
- Erosion Control
- Fill
- Septic Tanks and Drainfields
- Building Blocks
- Asphalt
- Widening of Roads and Shoulders

Question 2d: Are you aware of the use of your product in producing fresh concrete? If yes, in what applications?

One company sells premixed concrete in carts to private home owners. Two companies responded that they use their products in the precasting of septic tanks and drainage structures. In addition, one company replied that their #89 recycled aggregate is used with their screenings to make concrete blocks. The data regarding how many companies are aware of the use of RCA in concrete is summarized in table 6.4.

Table 6.4 Are you aware of the use of your product in producing fresh concrete?

Aware	4
Not Aware	5
No Response	1

Question 3a: How does the cost of recycled concrete compare to the cost of natural aggregate in your area?

Two companies reported that recycled concrete aggregate (RCA) is competitive in cost because natural aggregates are not readily available in their area. Two companies stated that RCA is cost effective because of the large freight costs for virgin aggregates. Figure 6.1 shows the geographical distribution of the responding companies according to their replies to this survey question. The white ovals indicate the areas in which RCA is less expensive than virgin aggregates. The black squares depict the areas in which RCA is either equal or competitive to the cost of natural aggregates. The areas where RCA is more expensive than virgin aggregate are marked in the form of red circles.

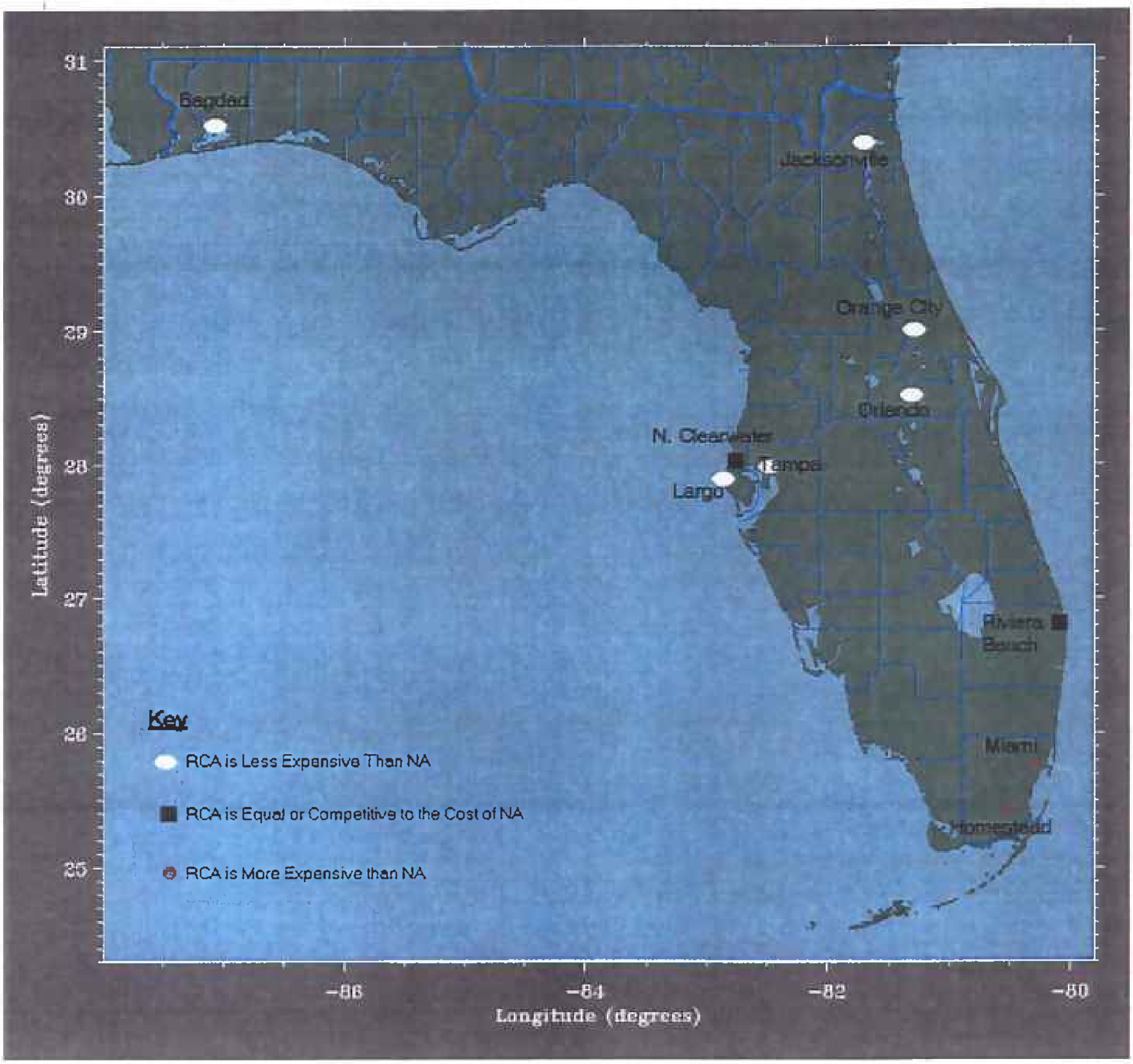


Fig 6.1 RCA Cost Map of Florida

Table 6.5 How does the cost of recycled concrete compare to the cost of natural aggregate in your area?

RCA is Less Expensive	Costs are the Same	RCA is More Expensive
6	2	2

Question 3b: Does your product meet any agencies' (city, county, state) specifications?

Detailed Responses:

- "We are using our coarse aggregate in septic tank drainfields approved by Florida State Health Dept. under Chapter 10-D-6. We have used our base material under many parking lots, driveways, airport runways, subbase and soil cement."
- "Palm Beach County has approved it as an equal to shell rock."
- "Both Hillsborough and Pinellas Counties and all the towns in each permit the use of our products. Our road base meets FDOT specifications for base material."
- Our product meets city (Jacksonville) and county specifications.
- "Orange County is allowing 3/8" minus (fines) to be used as parking lot base, a substitute for limestone."

Table 6.6 Does your product meet any agencies' specifications?

Yes	8
No	1
Not Sure	1

Questions 3c and 3d: Has your product been tested by independent materials testing laboratories? If yes, is it possible to please include a copy of the test results?

Table 6.7 Has your product been tested by independent materials testing laboratories?

Yes	7
No	2
No Response	1

Continental Waste Industries:

Material	Use	Max. Dry Density (lb/ft^3)	Opt. Moisture Content (%)	LBR (%)	LA Abrasion	Additional
RCA Fines	Base	109.7	13.8	175		Layer Coeff.=0.18
RCA (50/50) Blend by Volume	Base	117.9	12.0	200		

Dixie Septic Tank:

Material	Use	Max. Dry Density (lb/ft^3)	Opt. Moisture Content (%)	LBR (%)	L.A. Abrasion (%)	Additional
Screenings	Pipe rock				42.8	gravelly sand (SW)
RCA & lime					37.3	
RCA					38.3	
RCA	Drainfield filter material	78.1				n=0.49 e=0.96 G=2.45
RCA	Base	117.2	13.9			
RCA	Base	117.2	12.6	139		

D.S. Eakins Construction Co.:

Material	Use	Max. Dry Density (lb/ft^3)	Opt. Moisture Content (%)	LBR (%)	L.A. Abrasion (%)	Additional
Screenings	Road Base	109.5	13.8	220		LL=non-plastic PL=non-plastic %Carbonate=62.8
RCA	Road Base	108.1	16.6	195		LL=non-plastic PL=non-plastic %Carbonate=64.6
RCA	Road Base	104.2	20.0	200		LL=non-plastic PL=non-plastic %Carbonate=68.1
RCA	Road Base	107.9	16.2	231		LL=non-plastic PL=non-plastic %Carbonate=73.4

Frontier Recycling:

Material	Use	Max. Dry Density (lb/ft^3)	Opt. Moisture Content (%)	LBR (%)	L.A. Abrasion (%)	Additional
RCA #57						Bulk Specific Gravity (SSD)=2.280
RCA #89						SSD=2.288
Screenings						SSD=2.357
RCA	Road Base	118.8	11.5	242		FDOT Road Base= $7.00 per Ton
RCA & screenings	Base	116.4	10.0	170		

Glasbrenner Sonny Inc.:

Material	Use	Max. Dry Density (%)	Opt. Moisture Content (%)	LBR (%)	L.A. Abrasion (%)	Additional
1.5" RCA Prescreened	Road Base	120.0	10.9	204		$7.00 per Ton at crusher
3/8" RCA	Base	116.0	11.3	175		$4.50 per Ton at crusher

Realco Recycling:

Material	Use	Max. Dry Density (%)	Opt. Moisture Content (%)	LBR (%)	L.A. Abrasion (%)	Additional
RCA		113.5	11.5	187		Organic Content=1.8 %

Question 4: Do you have any additional comments?

1. "I welcome this survey wholeheartedly. We produce a great material that definitely has a place in D.O.T. Standards."

"We have been manufacturing recycled concrete for app. ten years."

2. "We have about 12 years experience in recycled concrete. We believe as base rock, it should be equal to lime rock."

3. "Because recycled concrete base has a higher LBR and has less fines, it can be worked through a rain storm, that would shut down work with a limerock base. The more water the better. Because of freight cost for natural aggregate in this area, we not only reduce dumping in our landfills, but provide the aggregate user with a lower cost material

that in some uses is better than the higher cost natural aggregate. I offer my customers the free service of making them a mix design using my aggregates for their fresh concrete use."

4. "LBR test results indicate that the materials tested should provide adequate results when placed as roadway base material. LBR values obtained on samples from the subject sites are generally equal to or greater than values obtained on limerock samples that we have encountered in the past. Visual inspection also indicates that the material should be less vulnerable to water influences than limerock, which will tend to lead to a more durable product."

CHAPTER 7

AGGREGATE PROPERTIES IMPORTANT FOR BASE COURSES

A base course is defined as the layer of material that lies immediately below the wearing surface of a pavement. In the case of asphalt pavements, the base course lies close to the surface; hence, it must possess high resistance to deformation in order to withstand the high pressures imposed upon it by traffic. The principal function of base courses and subbases used under flexible pavements, is to increase the load supporting capacity of the pavement by providing added stiffness and resistance to fatigue as well as building up relatively thick layers to distribute the load through a finite thickness of pavement (Witczak, 1975). Base courses in a flexible pavement provide a stress distributing medium which spreads the load applied to the surface, so that shear and consolidation deformations will not take place in the subgrade. Consequently, in a satisfactory design, the thickness of base plus subbase should be sufficient to prevent over stressing of the subgrade. This is the prime requirement of the base course, although it may also provide drainage and give added protection against frost action when necessary.

To succesfully evaluate recycled concrete aggregate base courses it is important to analyse the functions of a base course and the factors which influence its function. This chapter examines the critical functions and properties of base courses and analyses the suitability of recycled concrete aggregates for this purpose.

Stability

The term stability is used to describe a base course's steadiness, firmness and resistance to deformation. Base courses possessing stability have the strength to stand and endure traffic loads, without alteration of layer position and material change. The stability of a base course is derived and evaluated by the aggregate's particle size distribution, particle shape, relative density, internal friction and cohesion. Deformations in base courses result from shear failures, which in turn are caused by the compressive action of traffic. A soil's shear strength is derived from its cohesion and angle of internal friction, and can be calculated with Coulomb's equation:

$$s = c + \sigma \tan \phi$$

where,

s = Shear Strength

c = Cohesion

σ = Effective Intergranular Normal Pressure

ϕ = Angle of Internal Friction

$\tan \phi$ = Coefficient of Friction

Recycled concrete aggregates are non-plastic and therefore do not possess cohesion. The shear strength of recycled concrete aggregate bases therefore depends on angle of internal friction, which in turn depends on grain size distribution, particle shape and relative density. The particle-size distribution for RCA bases should be such that the grain interlock of coarse particles develops their shear strength. The fine material fills the voids between the coarse particles, lending them added shear resistance.

Particle Size Distribution

Particle size distribution, particularly the proportion of very fine (diam. < 75 μm) to coarse fraction, is considered the most significant contributor to a base course's internal friction and therefore shear strength. A soil's particle size distribution is evaluated by means of sieve analysis test. In a sieve analysis test, a weighed sample of dry aggregate is separated through a series of sieves of progressively smaller openings.

Figure 7.1 shows the three physical states of soil aggregate mixtures. Fig. 7.1a exemplifies a gradation with a low content of fines and Fig. 7.1c shows a gradation with a low content of coarse particles. Fig. 7.1b depicts a gradation that gains its strength from the grain interlock of coarse particles, but has sufficient fines to fill all the voids between the coarse aggregate particles, which results in added shear resistance. To ensure this type of gradation, 6-8% fines (diam. < 75 μm) are typically specified.

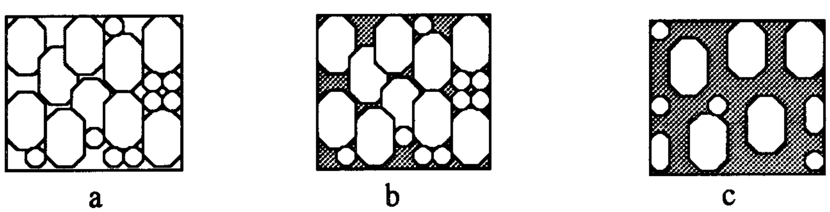


Figure 7.1, Physical Soil States

Recycled concrete is similar to conventional quarry products in respect to the amount of particle reduction during the crushing process, grading characteristics and aggregate shape. Any desired grading could be produced by making appropriate adjustments to crushing plants. It has been observed that the lower the strength of the original concrete, the greater the amount of fines produced during crushing. The particle size distribution, however, is not significantly affected by the strength of the concrete being crushed.

Permeability

There is a tradeoff in base course properties between the ideal gradation for maximum stability and the ideal gradation for permeability, the flow of water through soils. The inclusion of fines in a gradation provides added support to the large soil particles in a base course, therefore providing superior load supporting strength. Gradation that only possesses a small percentage of fines, on the other hand, permits water to readily flow out of base courses and therefore minimizes the risk of premature pavement failures. Ideally, for good performance, the permeabilities of granular base aggregates should be 10^{-4} cm/s or greater (Senior, 1992).

For Natural Aggregates (NA), maximum density gradation is nearly impervious. RCA, however, possesses a greater amount of void space in its mortar. This is also the reason why RCA exemplifies a higher water absorption than NA. Because of the volume of void spaces, RCA when graded for maximum stability, exemplifies a lower relative density than natural aggregates when compacted, and a higher permeability coefficient.

Plasticity Index

The plasticity index of a soil is the range in water content, expressed as a percentage of the mass of the oven dried soil, within which the material is in a plastic state. Numerically, it is the difference between the liquid limit and the plastic limit of the soil. Plasticity becomes a significant factor in base course properties when the amount of fines in a gradation is increased to the amount required for maximum density, which usually coincides with the amount required for optimum stability. Past research indicates that the lower the plasticity index, the higher the strength obtained from the fine material will be. For this purpose, base course specifications typically limit the plasticity index of an aggregate to less than 6%. All RCA samples have been found to be nonplastic, therefore satisfying this base course property.

Limerock Bearing Ratio

The limerock bearing ratio test is the single most indicative test of a base course's stability because it evaluates an aggregate's overall bearing and shear strength as compared to the standard strength of limerock, 5.516 Mpa (800 psi).

The test consists of drawing a sample of soil and grading it so that the maximum particle diameter is 19 mm. Water is added to four or five soil samples, so as to bracket the optimum moisture content. The soil is then compacted with a 4.54 kg (10 lb) rammer dropped from a height of 457 mm (18 in) into cylindrical molds. A perforated plate is then placed over the molds and the molds are flipped upside down, so that the perforated base plate remains on the bottom. The molds are placed in a soak tank for 48 ±4 hrs and then drained of water for 15 ±2min. A penetration piston, then proceeds to load the soil, and load readings are recorded for each 0.25mm (0.01 in) of penetration. A curve showing the unit load on the piston vs. penetration is then plotted. Finally, the unit load at 2.54 mm (0.1 in) is obtained from the plotted curve and is presented as a percentage of the standard bearing strength of limerock.

The limerock bearing ratio of base courses is typically specified to be at least 100%. Recycled concrete aggregates consistently exemplify very high LBR values (200% range), meaning that RCA not only meets the required bearing capacity for base courses, but exceeds it offering a superior stability.

Particle Shape

The use of crushed particles provides bases with a superior amount of grain interlock, which in turn provides stability. RCA has this advantage due to the manner in which it is obtained. There is a tendency, however, that the higher the strength of the original concrete, the more angular and flat particles are produced during crushing. Flat and elongated particles are more easily broken, and thus their use affords less stability and strength from grain interlock. Typically aggregates are required to possess less than 8% flat or elongated particles. RCA has been tested according to ASTM D4791 for content of such particles, and has generally been found not to produce excessive amounts of flat and elongated particles (less than 5%).

Soundness

Soundness, as regards base and subbase materials, is defined as the ability of the aggregate to withstand abrasion and/or crushing. This is important from the standpoint of generation of fines under the action of rollers and traffic. Soundness of aggregates can be tested by means of the sodium sulfate test, the Los Angeles abrasion test and a combination of compaction and sieve tests. RCA generally has a higher loss of soundness due to its mortar content. When the mortar is crushed, less grain interlock results, and more fines are created. An Australian study showed that the soundness loss of RCA is not excessive (Richardson, 1994).

Sodium Sulfate Test

The sodium sulfate test is performed to determine an aggregate's resistance to disintegration by saturated solution of sodium sulfate. It is accomplished by repeated immersion of the aggregate in saturated solutions of sodium sulfate, followed by oven drying to partially or completely dehydrate the salt precipitated in permeable pore spaces. The internal expansive force, derived from the rehydration of the salt upon re-immersion, simulates the expansion of water on freezing. After completion of the immersion cycle, the aggregate sample is washed clean of all sodium sulfate, dried and weighed. The difference between the sample's original weight, and the weight after immersion in the sulfate solution is the loss in the test and is expressed as a percentage of the initial mass.

This test method furnishes information helpful in judging the soundness of aggregates subject to weathering action. Acceptable limits of 15% are established by FDOT for graded aggregate bases. Many countries and U.S. state DOT's have decided to waive the sodium sulfate test for recycled concrete aggregates. According to materials engineers the sulfate test is inappropriate for use on RCA because of the nature of the chemical attacks that take place on concrete materials.

Coarse Aggregate Degradation Resistance by Abrasional Impact

As described in ASTM C131-89, the Los Angeles (LA) abrasion test is a measure of degradation of mineral aggregates of standard gradings resulting from a combination actions including abrasion, impact, and grinding in a rotating steel drum containing a number of steel spheres. As the drum rotates, a shelf plate picks up the sample and the steel spheres, carrying them around until they are dropped to the opposite side of the drum, creating an impact-crushing effect. The contents then roll within the drum with an abrading and grinding action until the shelf plate impacts and the cycle is repeated. After the prescribed number of revolutions, the contents are removed from the drum and the aggregate portion is sieved to measure the degradation as percent loss.

RCA has a higher abrasion loss than natural aggregates due to the fact that it is composed of natural stone coated with hydrated cement paste. The cement paste is weaker and more prone to degradation than the natural stone it is attached to. It has also been determined that the strength of the original concrete does not greatly affect LA loss. Natural aggregates for base courses are typically specified to possess a Los Angeles abrasion loss of less than 40-50%. Average values of LA loss for RCA are in the range of 26-37%, proving that although RCA exemplifies a higher abrasion loss, it is still within the acceptable limits specified for base course aggregates.

Compaction

RCA has been able to maintain the same grading before and after undergoing compaction. Past studies indicate that different source concrete strengths have little effect on the particle breakdown under compaction. Compaction tests can be performed on RCA to determine its optimum compaction, optimum moisture content and the compaction effort necessary to achieve this. Compacted RCA have a lower density than quarried aggregates due to the presence of low density cement paste (mortar).

CHAPTER 8

REVIEW OF INTERNATIONAL STANDARDS

Australia

According to Richardson, in Australia well located, high quality natural aggregates exist in a reasonably plentiful supply (Richardson, 1994). Suitable landfill sites close to major cities, however, are expensive and becoming scarce. It is estimated that between 1.5 to 3 million tons of demolition rubble is produced each year, most of which is concrete. Tipping fees range from $20 to $50 per ton, and when transportation costs are considered, an estimated unproductive cost of at least $50 million per year is absorbed by the Australian community.

As a direct consequence, the use of recycled concrete aggregates has been expanding and specifications have been developed covering its use. In 1991, 132,000 tons of concrete were recycled by Australian municipalities. It is further estimated that in the future, 600,000 tons per year of recycled concrete aggregate will be needed for road bases.

Richardson surveyed 156 metropolitan councils in Australia and found that currently, recycled concrete aggregates are being used in the following applications: road bases and subbases (29%), trench bases (19%), pathways (16%), fill (13%), and concrete aggregate (8%). 68 % of the respondents believed that the lack of technical data has limited the use of RCA, but 87% would use the material if uncertainties or objections to its use could be overcome. The major areas of concern for those contemplating using RCA were pavement cracking, ensuring adequate quality control, and design guidelines.

In addition, many respondents believed that an evaluation of the material by means of test pavement would be useful.

Tables 8.1 and 8.2 show the percentage of municipalities in Australia engaged in concrete recycling. The high participation from Melbourne and Sydney is primarily due to the substantial increases in landfill disposal costs, which reflect the higher cost of replacement facilities and the relatively short lifespan of existing sites. Present landfill sites in Melbourne have a lifespan of approximately five years. Table 682 also shows the methods of disposal of waste concrete.

Table 8.1 Municipalities Engaged in Concrete Recycling

Region	Responses	Yes (%)	No (%)
Melbourne	44	60	40
Sydney	26	65	35
Brisbane	5	0	100
Perth	18	12	88
Adelaide	15	7	93
Overall	**108**	**43**	**57**

Table 8.2 Methods of Waste Concrete Disposal

Region	Responses	Recycled (%)	Landfill (%)	Stockpiled (%)
Melbourne	44	60	38	2
Sydney	26	63	33	4
Brisbane	5	0	80	20
Perth	18	12	88	0
Adelaide	16	6	94	0
Overall	**109**	**41**	**56**	**3**

The Australian VicRoads specification 820Q delineates standards for the use of crushed concrete in pavement subbases. These specifications detail requirements for grading, plasticity, abrasion, and content of high density materials, as follows:

- Upper subbases shall have a maximum plasticity index of 10, and lower subbases shall have a maximum plasticity index of 20.
- Abrasive loss as measured by the Los Angeles test shall be less than 35% for upper subbases and 40% for lower subbases.
- The amount of high density materials present such as brick and asphalt, shall be less than 3% for upper subbases and 5% for the lower subbases.

<u>Belgium- CRAB (Concrete Recycled Aggregate Bases)</u>

In Belgium, according to Vyncke, approximately forty recycling installations are currently in use (Vyncke, 1994). It is estimated that actually about 2 million tons of demolition waste are being recycled each year . Concrete aggregate in the range of 0-80mm are the type of recycled aggregate presently produced by recycling plants for use as road subbase material. These aggregates with a continuous particle size distribution are the bulk of the Belgian production of recycled aggregate. In 1994 the price of recycled aggregate was 220 to 240 Belgian francs per ton which is 100 Belgian francs per ton less than the price of natural aggregates. Technical specifications were established in 1991 and 1992 by the Ministry of the Environment and Infrastructure covering the use of recycled concrete for the construction of road subbases. It is a strict requirement of these specifications that the recycled product should be supplied by recycling plants under control of a certification bureau.

Canada

Ontario has an estimated annual consumption of 40 million tonnes of granular base and sub-base aggregates, out of which less than 15% is used by Canada's Ministry of Transportation (Senior, 1992). Canada recognizes the importance and the advantages of recycling waste materials in construction. Such being the case, many studies have been conducted to evaluate recycling opportunities.

In 1992 the Canadian Geotechnical Society published the results of a survey of how many U.S. states and Canadian provinces were recycling concrete in transportation construction (Senior, 1992). Responses to this survey reported that 4 provinces and 29 states were recycling concrete in transportation construction applications. The survey also examined how many states and provinces possessed specifications for the use of recycled concrete. Eight states and one province were found to have standards for the use of recycled concrete in transportation construction.

Recycled concrete is primarily used in Canada as a granular base material and is frequently used on Ministry of Transportation contracts (Emery, 1992). Research done in Canada on recycled concrete aggregate base courses has not found any economic, environmental, or technical impediments for its use (Emery, 1992). The current Ministry of Transportation specifications allow for the use of up to 100% recycled concrete in granular A (Senior, 1992). Granular A are gradation and physical requirements set by the Ontario Provincial Standards for base aggregates. The specifications in Granular A are Canada's most stringent requirements for base aggregates and must be met by both natural aggregates and recycled concrete aggregates. The gradation and physical specifications in Granular A are meant to ensure well graded bases, which are strong and durable enough to withstand traffic loads and construction handling. Tables 8.3 and 8.4 depict the Ontario Provincial Standard (OPS) requirements for Granular A.

Table 8.3 Granular A Gradations

Sieve (mm)	Percent Passing
26.5	100
19.0	90-100
16.0	
13.2	65-90
9.5	50-73
4.75	35-55
2.36	
1.18	15-40
0.300	5-22
0.075	2-8

Table 8.4 Physical Requirements for Granular A

Ministry of Transportation Test[1]	Test Number	Requirement
LA Abrasion (max)	LS-603	60 %
% Crushed (min)	LS-607	50 %
Petrographic Number, (gran, max)	LS-609	200
Plasticity Index[2]	LS-704	0

1. Ministry of Transportation, 1989.
2. Material passing the 0.075 mm sieve (fines) shall be non-plastic; ie, have a plasticity index of 0.

There is a tradeoff in base course properties between the ideal gradation for maximum stability (load support) and the ideal gradation for permeability, the flow of water through soils. The inclusion of fines in a gradation provides added support to the large soil particles in a base course, therefore providing superior load supporting strength. The gradation of Granular A requires a minimum of 2% fines to reduce the amount of voids for maximum stability (Senior, 1992). Gradations that only possess a small percentage of fines, on the other hand, permit water to readily flow out of base courses and therefore minimize the risk of premature pavement failures. Ideally, for good performance, the permeabilities of granular base aggregates should be 10^{-4} cm/s or greater (Senior, 1992). There is concern among Canadian professionals that the gradation specified in Granular A does not provide sufficient permeability and alternatives are currently being studied in Canada.

France

According to Morel, France is trying to achieve the goal of 50% recycling of demolition materials by the year 2000 (Morel, 1994). France's demolition sector is currently producing about 25 million tons of waste materials. Of these waste materials 20-30% are currently being recycled. The producers of recycled aggregates have adopted a very stringent selection policy for demolition materials. More than 90% of materials processed are actually clean materials, with 60% of clean concrete, 33% of other clean materials and the remaining 7% being diverse substances. The use of recycled materials in France is limited to roadworks and land filling (90% as aggregates, 10% with binders).

Morel monitored the production of a recycling concrete plant in France (SDVM Paris) to evaluate the sources of material and the type of aggregates produced. The materials accepted for recycling at the plant are obtained from the following operations:

- earthworks
- demolition of roads including natural unbound aggregates, gravel-cement,

gravel-slag mixtures, bitumen coated aggregates, etc.

- demolition of concrete or reinforced concrete construction works.

After initial screening to 40 mm, the materials are crushed and screened into these aggregate sizes:

- sand 0/6 mm
- gravel 6/25 mm
- stones 25/40 mm

The French selection criteria excludes materials obtained from building demolition and construction site waste due to the presence of gypsum. The presence of gypsum in aggregates has been blamed for certain defects in road bases or foundation courses where recycled aggregates were treated with cement (Morel, 1994). This is because gypsum reacts with the cement to form hydrated calcium sulphoaluminates (ettringite) which, in certain cases, can cause damage due to expansion and cracking of the concrete (Morel, 1994).

Japan

In Japan demolished concrete is not considered a burdening industrial waste, but rather it is considered an important resource. In the fiscal year of 1990, 48% of the 25.4 million tons of concrete rubbles were reused, mostly in road bases (Nasa, 1994).

Utilization of demolished concrete for road bases began in 1978. Consequently, the technical guideline for plants recycling demolished pavement materials was issued by The Japan Road Association in December of 1992 (Nasa, 1994). This guideline covers the recycling of demolished asphalt concrete and of demolished cement concrete from buildings on public works. This guideline defines the recycled road base material as a composite made by blending recycled aggregates from demolished asphalt and cement concretes. The material must meet specified quality requirements and may be supplemented with other materials such as crushed stone, blast furnace slag, and sand.

The Japanese quality requirements for recycled concrete bases provide acceptable limits for abrasion, bearing strength and plasticity. The percentage weight loss of recycled concrete aggregate tested by the Los Angeles abrasion test should be less than 50%. Other specified quality requirements are shown in Table 8.5.

Table 8.5 Quality of recycled crusher-run used for road base.

	Materials	Corrected CBR %	Plasticity Index
Simple Pavement	Recycled Crusher-Run	10 over	9 under
Asphalt Pavement	Recycled Crusher-Run	20 over	6 under
Cement Concrete Pavement	Recycled Crusher-Run	20 over	6 under

Note: The maximum grain diameter for road base materials must be smaller than 50 mm.

Netherlands

Holland's building industry requires 45 million tons of raw materials per year (DeVries, 1993), of which 20 million tons is gravel. The Netherlands are capable of producing 10 million tons per year of gravel, which are mainly obtained from river dredging, and the remaining 10 million tons needed are imported. Holland's gravel production of 10 million tons a year is concentrated in Limburg, but the Dutch government intends to limit the national production of gravel to 2.5 million tons a year by the year 2010 because of its adverse effect on the landscape (DeVries, 1993). This policy will cause a shortage of raw materials for the Dutch building industry, which is forced to look for alternative aggregates.

It is also government policy in Holland that the re-use of construction and demolition waste must be increased to 90% by the year 2000. Presently, there are about

14 million tons a year of construction and demolition waste available in Holland and this quantity is expected to increase in the future (DeVries, 1993). At the present time, with 55 fixed location crushing plants and over 100 mobile crushing plants, the Netherlands have a total crushing capacity of 9.3 million tons per year (DeVries, 1993). In 1991, one million tons of concrete were processed for re-use.

Table 8.6 Gravel Demand and Supply

Demand for Gravel		**Supply of Gravel**	
Concrete	14 million tons	Dutch Production	10 million tons
Asphalt	4 million tons	Import Gravel	10 million tons
Other	2 million tons	Import Porphyrite	1 million tons
		Import Limestone/Granite	1.5 million tons
		Export Gravel	-2.5 million tons
Total Demand	**20 million tons**	**Total Supply**	**20 million tons**

Holland's government developed a regulation in 1984, the CUR-VB Recommendation 4, which covers the control and acceptance testing of crushed concrete. The CUR-VB Recommendation 4 states (DeVries, 1993):

> "The principal constituent, the crushed concrete aggregate, must be at least 95% of the total. Not more than 5% may consist of secondary materials such as clay-bricks, sand-lime building bricks, light-weight concrete, foamed concrete, ceramic materials and masonry-mortar, with the definite exclusion of gypsum and gypsum containing materials. Not more than 1% of the crushed concrete aggregate may consist of nonstone-like constituents such as wood, paper, glass, textiles, bituminous materials, etc."

Spain

The production of demolition wastes in the large urban centers of Spain is estimated at 800 tons/days in the Madrid area, 500 tons/day for Barcelona, and 100 tons/day for medium-sized cities like Valencia and Bilbao (Morel, 1994). It seems, however, that the recycling of demolition materials has only attained a significant level for the construction of Olympic site facilities at Barcelona, where it has been extensively exploited (Morel, 1994).

Only inert materials (concrete, ceramic, stone, brick) obtained from the demolition of structures, enclosures, and foundations are accepted. Mixed materials or those containing impurities (wool, plastic, plaster, textiles, iron, etc.) are rejected (Morel, 1994). To enable the greatest proportion of materials to be recycled, special attention has been directed toward the organization of demolition work sites (selective demolition, on site pre cleaning) (Morel, 1994).

Recycled materials have been used to build the Olympic city's streets and highway system, the base and sub base, as well as the protective rockfill structures of the encircling coastline (Morel, 1994).

United Kingdom

The United Kingdom is concerned with the loss of mature countryside that results from the quarrying of virgin aggregates. The latest estimate of the total amount of derelict land due to pits and waste dumps is more than 40,000 ha (155 mi^2), which is roughly the area of the Isle of Wight (Sherwood, 1995). Presently, waste and recycled materials account for about 10% of the aggregates used in the UK and 40% of demolition waste is recycled (Collins, 1994). Twenty-four million tons of construction and demolition wastes were produced in the United Kingdom in 1990 (Sherwood, 1995). In 1991, the annual reuse of demolition waste in the UK was approximately 11 million tons, being the highest in Europe (Collins, 1994).

The British Specifications for Highway Works allows the use of crushed concrete as a substitute for natural aggregates for most purposes (Sherwood, 1995). An increasing amount of crushed concrete is being used as an unbound subbase for road construction to the Type 1 specification in the UK national Specifications for Highway Works (Collins, 1994). Type 1 has a fairly low strength requirement of 50 kN (as measured by the wet 10% fines test in BS812: Part 111: 1990), moderately wide grading limits, and a requirement that material finer than 425 μm is non-plastic (Collins, 1994). All of these requirements can easily be satisfied by recycled aggregate.

CHAPTER 9

U.S.A. DEPARTMENT OF TRANSPORTATION SPECIFICATIONS

California

According to Connel, in 1989 the California state legislation passed a package of waste-management laws which require the state transportation department to use recycled concrete (Connel, 1990). A second act in the integrated waste-management plan, Assembly Bill 1306, requires the California Department of Transportation (Caltrans) to review and modify all bid specifications for paving materials, base, subbase and backfill materials, to encourage the maximum use of recycled materials. The law directs the state procurement officer to contract recycled material whenever it meets specifications and is priced to compete with new materials. In addition, the California Integrated Waste Management Board has published and posted on the internet a recycled aggregate fact sheet to help concrete recyclers expand their markets for aggregate and to help local governments promote recycled aggregate.

Local governments are also providing support for the use of recycled concrete aggregates. In March of 1995, the City of Los Angeles passed a motion requiring that road base in all city projects include Crushed Miscellaneous Base (CMB) with 100% recycled asphalt, concrete and other inert solid wastes, except when site conditions or standards require otherwise. The City of Modesto has a purchasing practice for on-site street recycling that includes recycled aggregate. The City of Palo Alto also requires that concrete and asphalt in city projects be recycled.

Construction and demolition materials make up about 28% of California's waste stream of approximately 11 million tons per year. Presently, there are approximately 100 producers of recycled aggregate in California and their primary market is that of aggregate base and subbase on road projects.

The Standard Specifications for Public Works Construction allows recycled concrete to be used as crushed miscellaneous base, processed miscellaneous base and as aggregate subbase. Caltrans Standard Specifications and the Standard Specifications for Public Works Construction have adopted regulations covering the use of recycled concrete aggregate. Caltrans has a Standard Special Provision which allows reclaimed portland cement concrete in class 2 and 3 aggregate bases and also in class 1,2 and 3 aggregate subbases. The Standard Special Provision states:

> Aggregate may include or consist of material processed from reclaimed asphalt concrete, portland cement concrete, lean concrete base, cement treated base, glass or a combination of any of these materials. Untreated reclaimed asphalt concrete and portland cement concrete will not be considered to be treated with lime, cement or other chemical material for purposes of performing the Durability Index test.

Furthermore, the Standard Special Provision for Class 3 aggregate base, permits the contractor to choose between the following 38mm (1.5 in) or 19mm (3/4 in) maximum gradations.

Table 9.1 California Class 3 Base Aggregate Gradations

	Percentage Passing			
	38mm (1.5 in) Maximum		19mm (3/4 in) Maximum	
Sieve Sizes	Operating Range	Contract Compliance	Operating Range	Contract Compliance
2"	100	100		
1.5"	90 - 100	87 - 100		
1"			100	100
3/4"	50 - 90	45 - 95	90 - 100	87 - 100
No. 4	25 - 60	20 - 65	35 - 60	30 - 65
No. 30	10 - 35	6 - 39	10 - 30	5 - 35
No. 200	3 - 15	0 - 19	2 - 9	0 - 12

Survey of State Departments of Transportation

A survey was developed to determine the current use of recycled aggregates in pavement construction. It was distributed to the Department of Transportation's Materials Engineer for each state and Puerto Rico (51 total). A total of 45 replies were received (88% response rate). Of those responding, 26 indicated that the use of reclaimed Portland cement concrete (PCC) as a base course aggregate was allowed by their state agency. Four states replied that recycled concrete aggregate was allowed as a subbase aggregate (Table 9.2).

Table 9.2 Use of Recycled PCC in surveyed state DOTs:

Used in Base Course	*26*
Used Solely on Subbase Course	*4*
Not Used as Base or Subbase	*15*
Total	*45*

The agencies were then queried as to whether they have any standards for the use of reclaimed PCC as a base or subbase course aggregate. Only 15 of the 28 state agencies that allow use of recycled concrete aggregates in bases and subbases, have standards specifically for recycled aggregates. Two states replied that recycled concrete aggregates are subject to the same specifications as natural aggregates and three states evaluate the material on a project by project basis. Table 9.3 summarizes these results.

Table 9.3 Standards for recycled PCC in surveyed state DOTs:

Specific Standards	17
Same Standards as for Natural Aggregate	2
Project-by-Project Standards	3
No Standards	8
Total	*30*

In addition to returning the surveys, the states were asked to send a copy of their specifications concerning the use of recycled concrete aggregate. These specifications were carefully analyzed and the results are summarized as follows:

Key:
(N)- indicates specifications for natural aggregates.
(S)- indicates specifications for RCA.
(P)- indicates project by project specifications.

Alabama Specifications (N):

- Must be free from adherent coatings.
- Limits on deleterious substances.
- Physical tests: Percent Wear Los Angeles abrasion Test,
  Percent Sound, Soundness loss Test.
- Coarse Aggregate Gradation Table Specification.
- Separate Stockpiles.
- Must be protected from rain.

Arkansas Specifications (S):

- Free of: reinforcing steel,
  excess of thin or elongated particles,
  clay lumps,
  vegetation,
  asphalt pavement,
  deleterious substances.

- Los Angeles abrasion Test is waived.
- Sodium Sulfate Soundness loss Test is waived.

Connecticut Specifications (S):

- Free of: mud, dirt, and organic material.
- Must have < 1% dust by weight
- Soundness Loss < 10% @ 5 cycles
- Los Angeles abrasion test < 40%
- "Coarse aggregate of a size retained on a $1^{1/8}$ inch square opening sieve shall not contain more than 8% of flat or elongated pieces, whose longest dimension exceeds five times their maximum thickness."

Florida Specifications (S):

- Recycled concrete aggregate is currently being evaluated.
- Los Angeles abrasion < 50%

Georgia Specifications (S):

- No washout material
- Free of: asphaltic concrete
  steel,
  clay balls,
  soils,
  epoxy expansion material,
  miscellaneous paving materials.

Illinois Specifications (P):

- "Higher quality uses are allowed in project-by-project recycling while the recycled concrete from a central recycler is limited to lower quality uses."
- Removal and stockpiling performed in a manner to avoid contamination with dirt and foreign matter.
- Quality testing of at least 3 locations of recycled concrete.
- Freeze-thaw testing.
- Quality testing: one sample for each 5000 tons in each stockpile.

Kansas Specifications (S):

- Los Angeles abrasion test waived.

Louisiana Specifications (S):

- Max. 100% recycled Portland cement concrete by weight is to be combined with natural aggregates.
- Gradation requirement.

Maryland Specifications (S):

- Gradation table.
- Max. % Sodium Sulfate Soundness = 18
- Max. % Flat or Elongated = 15
- Max % Los Angeles abrasion = 50

Michigan Specifications (S):

- Use is only allowed on roads with ADT < 250 (concrete pavement).

Minnesota Specifications (P):

- Project-by-Project requirement basis.
- Performance of original concrete is evaluated.
- Freeze-thaw tests.
- Not to be used near perforated drainage pipes.
- Los Angeles Rattler Loss 40% max.
- Gradation table.

Nebraska Specifications (S):

- Modulus Elasticity E = 22,000 psi.
- No deleterious materials.

New Jersey Specifications (S):

- Can be combined with broken stone, crushed gravel or crushed vitreous china to meet the minimum requirements.

New York Specifications (S):

- Same gradation as natural aggregates.
- Allows 5% non-PCC material.
- "Alternative A- at least 95%, by weight, of Recycled Portland Cement Concrete Aggregate (RPCCA), and free from organic or other deleterious material."
- "Alternative B- at least 95%, by weight, of a homogeneous, thoroughly-blended mixture of RPCCA, free from organic organic or other deleterious material, with

stone, sand, gravel or blast furnace slag, whichever is allowed in the material type chosen."

- Free of asphalt pavement and other contaminating materials.

North Carolina Specifications (N):

- Same design specifications as for natural aggregate.
- Same material specifications to be met as for natural aggregate.
- Sodium Sulfate Soundness test is waived.

Oklahoma Specifications (S):

- Freeze-thaw tests (350 cycles, min DF=50).
- Must be free of Alkali-silica reactivity.

Pensylvania Specifications (S):

- Gradation chart.
- Max. % Abrasion = 40.
- Max. % Thin and elongated pieces = 15.
- Max. % Material finer than no. 200 sieve = 10.
- Min. % Crushed fragments = 55.
- Min. lb/cuft Compacted unit weight = 70.
- Max. % Deleterious shale = 2.
- Max. % Clay lumps = 0.25.
- Max. Friable particles (excluding shale) = 1.0
- Max. % Coal or coke = 1.
- Max. % Total of: deleterious shale, clay lumps, frable particles, coal or coke = 2.
- Los Angeles abrasion loss < 55% by weight.

South Carolina Specifications (S):

- Gradation table.
- Los Angeles Abrasion test < 65%
- Has details on base making procedure.

Washington Specifications (S):

- 10% asphalt allowed.
- Same LA wear and Degradation Factor is used as that of natural aggregates.

Wyoming Specifications (P):

- Project-by-Project basis.

CHAPTER 10

TEST FACILITY AND TEST SECTION PREPARATION

The objective of this project was to test the performance of recycled concrete aggregate (RCA) as a substitute for coarse aggregate in Portland cement concrete pavements (PCCP) and as a base material for hot mix asphalt (HMA) pavements. The following chapter describes the process of preparing the sections for testing at the University of Central Florida Circular Accelerated Test Track (UCF-CATT).

UCF-CATT

The UCF-CATT was funded by the Florida Department of Transportation in 1989 with the purpose of testing bridge expansion joints. As seen in Figure 10.1 (Bergeson, 1990), the testing machine is 15.2 meters (50 ft) in diameter to the centerline of a 1.2 meter (4 ft) wide concrete pavement slab that was designed to accommodate a dual wheel assembly consisting of half an axle. The slab, which was designed based on the AASHTO Design Guide to carry 288 million load repetitions of an 80.1 kN (18 kips) equivalent single axle load (ESAL), was on the average 38.1 cm (15 in) thick. The track is divided into two halves which are separated by two bridge sections that span a length of 3.7 meters (12 ft). The bridges, which are diametrically opposed and have been denoted as "near bridge" and "far bridge" in Figure 10.1, are 1.8 meters wide (6 ft) and 20.3 cm (8 in) thick. Each bridge is supported by 8 columns which are 929 cm^2 (1 ft^2) by 61 cm (2 ft) long.

The testing apparatus is powered by a 164 kilowatt (220 horsepower) engine. The engine is connected to a variable displacement hydraulic pump which carries hydraulic fluid to a swivel joint mounted on top of the machines central support. This swivel joint then distributes the fluid to three 44.7 kilowatt (60 horsepower) hydraulic motors which deliver power through a planetary gear speed reducer to the dual-wheel assemblies mounted on tractor drive axles with a capacity to handle loads up to 133.5 kN (30,000 lbs). The hydraulic transmission provides up to 43.3 kilometers per hour (30 mi/hr) of rotational speed in either clockwise or counter-clockwise direction.

The test track has three sets of dual truck wheels which travel around in a circular path guided by radial arms. Each arm is a 7.6 meter (25 ft) W36 x 150 I-beam anchored to the center support pivot at 120 degree intervals. The center support and bearing assembly were designed to hold the entire system in place while allowing the machine vertical flotation and small angular movements. This permits a variance in the tracks surface grade.

The loading on the dual-wheel assemblies is created by a 28.49 m^3 (7,500 gallon) water tank, 3.7 meters (12 ft) in diameter by 2.4 meters (8 ft) high. The tank is placed on top of the center support, supported by the I-beams. Depending on the water level in the tank, the total load of the structural weight and filled water tank can vary between 133.5 kN (30,000 lbs) and 356 kN (80,000 lbs). This load is evenly distributed to the three dual-wheel assemblies. This UCF facility, which can be seen in Photograph 1, has been used to test large-scale bridge expansion joints, patching materials, and experimental pavements since 1990.

In a recent project (Lewis, 1996), a 12.7 cm (5 in) slab of fiber-reinforced concrete was placed over the existing track slab. The axles on the machine were fitted with new structural steel

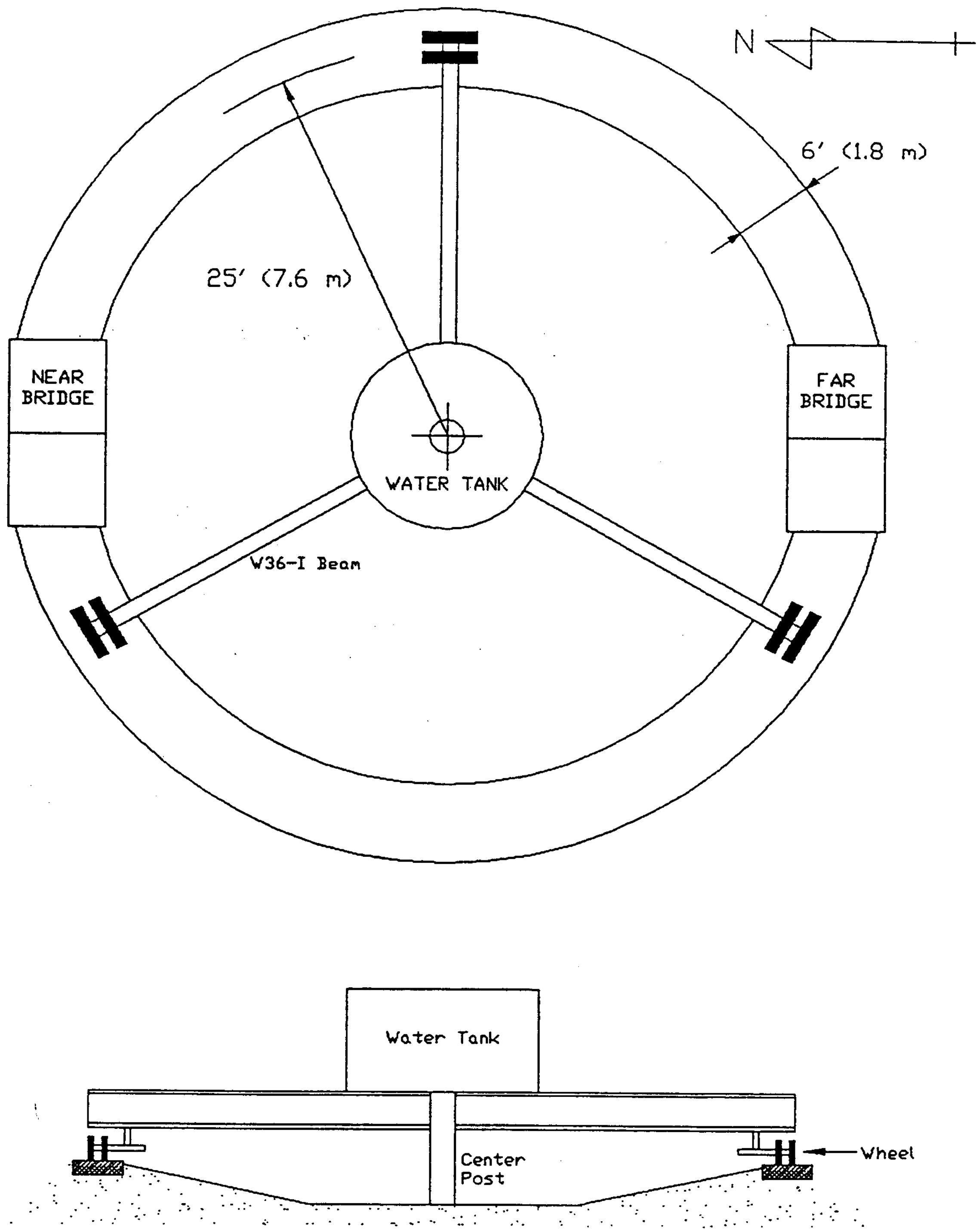


Fig 10.1 UCF Circular Accelerated Test Track

to adjust the elevation change and concrete slabs of the same thickness poured over the bridge slabs to make all surfaces even. The present track slab is 50.8 cm (20 in) thick.

PHOTOGRAPH 1. University of Central Florida Circular Accelerated Test Track

Removal of Track Slab

Before construction of the new test sections began, the test track was stabilized to prevent damage to the machine and the hydraulic system. The individual I-beams were elevated with a standard 12 ton (24,000 lbs) hydraulic jack and steel columns placed under the center of the I-beam flange. Photograph 2 illustrates the stabilized I-beams.

PHOTOGRAPH 2. Stabilized UCF-CATT

With the machine stabilized, focus turned toward the removal of the track. To perform this task, Hunter Concrete was contracted. The contractor excavated the berm that surrounded the inside of the track with a backhoe and exposed the 50.8 cm (20 in) concrete slab. As can be seen in Photograph 3, a jack hammer mounted on a John Deere 310D backhoe was utilized to break up the concrete slab into sections approximately 6 meters (20 ft) long. The sections were tipped over so the 10 cm (4 in) cover of concrete protecting the reinforcing steel in the slab could be chipped off. The four uncovered bars were then cut with a high speed saw and the concrete slab broken in two. The chunks of concrete rubble were deposited in dumpsters with 15 m^3 (20 yd^3) capacity and then hauled away to a local concrete recycling plant.

PHOTOGRAPH 3. Breaking Up of Concrete

In order to protect the existing bridge abutments, it was decided not to remove approximately 91.4 cm (3 ft) of the original 38.1 cm (15 in) slab of concrete that led up to the bridges. As can be seen in Photograph 4, a 30.5 cm (12 in) high speed diamond blade saw cut off the excess concrete leaving a smooth finished face. The entire extraction of the track was achieved in seven days. Photograph 5 shows the UCF-CATT after the 50.8 cm (20 in) track slab had been removed.

PHOTOGRAPH 4. Diamond Blade Cutting of Bridge Abutment

PHOTOGRAPH 5. UCF-CATT Without Original Slab

UCF-CATT Layout

Figure 10.2 illustrates the new track layout. Half of the track was employed to test the performance of RCA as base material for flexible pavements while the other tested RCA as substitute for coarse aggregate in rigid pavements. It was proposed to have four flexible pavement sections (labeled 1 through 4), one control using limerock as a base course (section 2) while the three remaining used RCA (section 1, 3, and 4). Three different base thickness were tested: 203 mm (8 in) (sections 2 and 3), 254 mm (10 in) (section 1), and 305 mm (12 in) (section 4). A HMA layer 88.9 mm (3.5 in) thick with a 12.7 mm (0.5 in) wear course was applied over the base materials. Each section was approximately 4.6 meters (15 ft) long.

Five different rigid pavements 254 mm (10 in) thick were poured (labeled 5 through 9). Section 6 was the control, having 100% NA concrete. Sections 5, 7, and 8 had pavements composed of 25% RCA + 75% NA, 100% RCA, and 75% RCA + 25% NA, respectively. Section 9 also used 100% NA concrete, but with a 254 mm (10 in) RCA base course. Sections 5 through 8 had an AASHTO A3 soil for base. Each section was 3.66 meters (12 ft) long.

Rigid Pavement

Depth of Slab

The depth of slab is the thickness of the concrete pavement that has to be constructed to carry the traffic loads to the subgrade while providing satisfactory serviceability throughout its design period. The American Association of State Highway and Transportation Officials' (AASHTO) model for calculating the required concrete depth relates pavement performance, vehicle loadings, strength of embankment, pavement structure, and several other parameters.

The summation of the vehicle loads over the pavement design period is expressed in the Accumulated 80 kilonewton Equivalent Single Axle Loads ($ESAL_D$). The procedure for computing $ESAL_D$ is given in the FDOT Rigid Pavement Design Manual (*Florida 1996*), and is summarized below

$$ESAL_D = Y * (AADT * T_{24} * D_F * L_F * E_{80} * 365) \tag{1a}$$

where:

Y = The design period, in years (all parameters are assumed constant)

$AADT$ = Average Annual Daily Traffic.

T_{24} = Percent of heavy trucks during a 24 hour period.

D_F = Directional distribution factor (1.0 for one way traffic, 0.5 for two way traffic).

L_F = Lane factor, converting directional trucks to the design lane trucks.

E_{80} = Equivalency factor, which is the damage caused by one average heavy truck measured in 80 kN Equivalent Single Axle Loads.

The Lane Factor (L_F) is defined as

$$L_F = [1.567 - 0.0826 * \mathrm{Ln}\,(One\ Way\ AADT) - 0.12368 * LV] \tag{1b}$$

where:

LV = 0 if number of lanes in one direction is 2. LV = 1 if the number of lanes in one direction is 3 or more.

Ln = Natural logarithm

Assuming that the CATT is designed to represent a medium to high volume, urban, arterial, two way facility, the following input data is used:

Estimated AADT = 20,000, T_{24} = 6.5%, D_F = 0.5 (for two way traffic), E_{80} = 1.95 (from Table C.3 of the FDOT Manual), Y = 20 years (from Table 3.1 of the FDOT Manual), and L_F = 0.81 (from Eq. 1b). Substituting these values in Eq. (1a) the result is $ESAL_D$ = 7,495,000 which rounded up to 8,000,000.

Using $ESAL_D$ = 8,000,000, the modulus of subgrade reaction (K_G) = 50 MPa/m (standard value), and Reliability value (R%) of 90% (from Table 3.2 of FDOT Manual), the required slab thickness D_R = 252 mm (from Table A.4 of FDOT Manual). The figure is rounded to 250 mm, which was used for the construction of the rigid pavement part of the CATT.

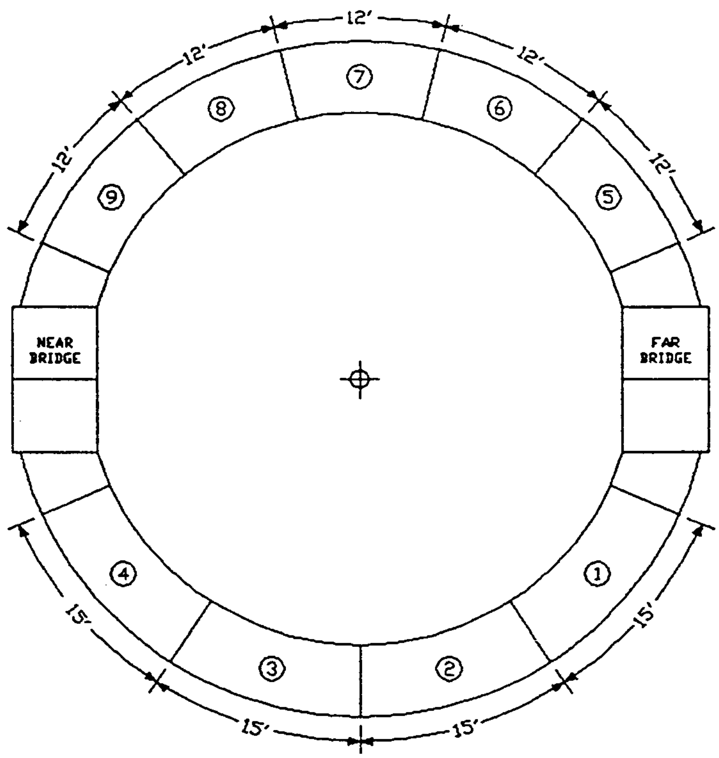
Transverse Joint Spacing

The purpose of transverse joints is to control the cracking of concrete due to drying shrinkage, effects of loads and warping. Joint spacing depends upon the thickness of the pavement, strength of concrete, type of aggregates, climatic conditions, and whether or not distributed steel reinforcement is used.

The slab length of the CATT at UCF was determined based on the principle that maximum length of slab should not be more than 5 times the radius of relative stiffness (Morse and Green, 1996). The computed maximum length for the 250 mm thick slab was 4.7 m (15.4 ft). The computation is based on the following expression

$$l_r = \left[\frac{Eh^3}{12k(1-\nu^2} \right]^{0.25} \tag{1c}$$

where, l_r = radius of relative stiffness, h = slab thickness, k = modulus of subgrade reaction, E = modulus of elasticity, and ν = Poisson's ratio (0.15). Assuming l_s = slab length, then $l_s \leq 5l_r$. FDOT design values to be used in Eq. (1c) for JPCP are: k = 50 MPa/m (184 psi/in), and E = 27,500 MPa (3,987,500 psi). Thus for a pavement thickness of 250 mm (10 in), the expression yields a maximum slab length of 4.7 m (15.4 ft). This results to a length/width ratio of 3.9, which symbolizes a very slender slab. It is desirable to have the transverse joints divide the pavement into panels that are approximately square. Thus, to reduce the length/width ratio, the track width for the rigid pavement segment was increased from 1.2 m to 1.83 m (6 ft), and the panel length set at 3.66 m (12 ft), which resulted in the length/width ratio of 2. The rigid pavement segment then resulted in five panels of 3.66 m (12 ft) length each as shown in Fig. 10.2.



FLEXIBLE PAVEMENT		
Section	Base Course	Pavement
1	RCA	Asphalt
2	Limerock	Asphalt
3	RCA	Asphalt
4	RCA	Asphalt

RIGID PAVEMENT		
Section	Base Course	Pavement
5	AASHTO A3	PC with 25% RCA, 75% NA
6	AASHTO A3	PC with 100% NA
7	AASHTO A3	PC with 100% RCA
8	AASHTO A3	PC with 75% RCA, 25% NA
9	RCA	PC with 100% NA

Figure 10.2 Flexible and Rigid Pavement Sections

Bagging Procedure

It has been well documented that RCA has higher water absorption than virgin coarse aggregate, and for that reason, RCA should be pre-moistened before the actual mixing takes place. Since quality control was crucial throughout this project, it was decided to pre-moisten the coarse (virgin and recycled) aggregate and place them inside impermeable bags. The fine (virgin) sand was also bagged but not pre-moistened.

With the use of a digital scale, 18 kg (40 lb) of aggregate were measured and dumped inside sand bags, which were then enclosed in two trash bags. Before sealing each bag, one small scoop was removed and deposited inside an impermeable sample sack. The sample bags were then taken to the laboratory where the moisture content was determined. The average moisture content was then used to adjust the total batch water for the mix.

As can be seen from Table 10.2, the moisture contents varied. This was a consequence of the extremely slow bagging process and the oscillating daily climate conditions. For the RCA concrete sections (sections 5, 7, and 8), a total of 660 bags (RCA, limerock, and sand) were prepared, and it took 12 days to complete the task. Photographs 6 and 7 demonstrate the bagging process.

SAND SAMPLES					
BAGS	CAN #	CAN WT.	CAN + WET	CAN + DRY	MOISTURE
1-1 to 1-20	L6	58.8	247.8	242.5	2.89
2-1 to 2-20	L25	58.6	263.7	258.0	2.86
3-1 to 3-20	L21	59.1	255.4	250.5	2.56
4-1 to 4-20	L2	59.4	220.6	217.4	2.03
5-1 to 5-20	L20	60.0	244.3	240.0	2.39
6-1 to 6-20	L40	56.0	253.9	249.6	2.22
7-1 to 7-20	L10	58.7	251.5	247.6	2.06
8-1 to 8-20	L11	58.5	251.9	247.9	2.11
9-1 to 9-20	L9	58.9	269.1	264.8	2.09
10-1 to 10-20	L39	57.4	236.8	233.6	1.82
11-1 to 11-20	L30	56.8	229.9	226.0	2.30
12-1 to 12-20	L38	58.3	268.5	263.7	2.34
13-1 to 13-20	L28	56.9	245.2	241.0	2.28
14-1 to 14-20	L12	59.3	236.6	232.8	2.19
15-1 to 15-20	L29	56.8	261.0	256.5	2.25
16-1 to 16-20	L130	59.7	236.0	231.7	2.50
				AVG.	2.31

LIMEROCK SAMPLES					
BAGS	CAN #	CAN WT.	CAN + WET	CAN + DRY	MOISTURE
1-1 to 1-20	L13	59.0	276.2	267.5	4.17
2-1 to 2-20	L16	58.5	279.6	266.1	6.50
3-1 to 3-20	L43	55.8	273.7	259.9	6.76
4-1 to 4-20	L47	56.6	289.6	275.9	6.25
5-1 to 5-20	L35	56.7	286.8	273.5	6.13
6-1 to 6-20	L24	57.6	284.1	273.8	4.76
				AVG.	5.76

RCA SAMPLES					
BAGS	CAN #	CAN WT.	CAN + WET	CAN + DRY	MOISTURE
1-1 to 1-20	L46	56.6	292.0	281.5	4.67
2-1 to 2-20	L34	57.2	277.9	270.4	3.52
3-1 to 3-20	L31	56.9	279.7	271.7	3.72
4-1 to 4-20	L18	58.0	252.1	243.9	4.41
5-1 to 5-20	L22	60.1	283.8	275.8	3.71
6-1 to 6-20	L27	57.7	247.2	240.6	3.61
7-1 to 7-20	L15	59.1	275.4	269.7	2.71
8-1 to 8-20	L5	58.7	263.7	257.9	2.91
9-1 to 9-20	L32	57.4	248.6	241.4	3.91
10-1 to 10-21	L3	57.9	264.9	259.1	2.88
11-1 to 11-21	L26	57.7	264.2	257.6	3.30
				AVG.	3.58

Table 10.2 Moisture Content of the Sample Bags

PHOTOGRAPH 6. Bagging of Fine Aggregate

PHOTOGRAPH 7. Bagging of Recycled Concrete Aggregate

Mix Design Adjustment

With the aggregate moisture contents, it was possible to correct the mix design for each of the three RCA sections (Table 10.3). The following formulas were applied to obtain the corrected values:

$$\text{Weight Needed} = \frac{\text{Aggregate SSD Weight From Design}}{1 - \frac{(\%\ \text{Total Moisture} - \text{Absorption})}{100}} \qquad (2)$$

$$\text{Free } H_20 = \text{Weight Needed} - \text{SSD Weight} \qquad (3)$$

$$\text{Additional Water} = \text{Batch Water} - \text{Free Water} \qquad (4)$$

AGGREGATE	Total Moisture (%)	Absorption (%)
RCA	3.58	4.36
Limerock	5.76	3.50
Sand	2.31	0.60

NOTE: The mix design adjustment only affects the coarse aggregate, fine aggregate, and total batch water quantities. The cement and admixture contents remain the same.

SECTION 5: 25 % RCA + 75 % LIMEROCK					
COMPONENT	SSD Weight kg (lb)	(2) kg (lb)	(3) kg (lb)	(4) kg (lb)	ADJUSTED kg (lb)
Cement	256 (564)	***	***	***	256 (564)
Water	108 (237)	***	***	85 (188)	85 (188)
RCA	188 (415)	187 (412)	-1 (-3)	***	187 (412)
Limerock	565 (1,246)	578 (1,275)	+13 (+29)	***	578 (1,275)
Sand	607 (1,338)	618 (1,361)	+11 (+23)	***	618 (1,361)

SECTION 7: 100 % RCA					
COMPONENT	SSD Weight kg (lb)	(2) kg (lb)	(3) kg (lb)	(4) kg (lb)	ADJUSTED kg (lb)
Cement	256 (564)	***	***	***	256 (564)
Water	108 (237)	***	***	103 (227)	103 (227)
RCA	753 (1,661)	748 (1,648)	-5 (-13)	***	748 (1,648)
Sand	607 (1,338)	618 (1,361)	+11 (+23)	***	618 (1,361)

SECTION 8: 75 % RCA + 25 % LIMEROCK					
COMPONENT	SSD Weight kg (lb)	(2) kg (lb)	(3) kg (lb)	(4) kg (lb)	ADJUSTED kg (lb)
Cement	256 (564)	***	***	***	256 (564)
Water	108 (237)	***	***	97 (214)	97 (214)
RCA	565 (1,246)	561 (1,236)	-4 (-10)	***	561 (1,236)
Limerock	188 (415)	193 (425)	+5 (+10)	***	193 (425)
Sand	607 (1,338)	618 (1,361)	+11 (+23)	***	618 (1,361)

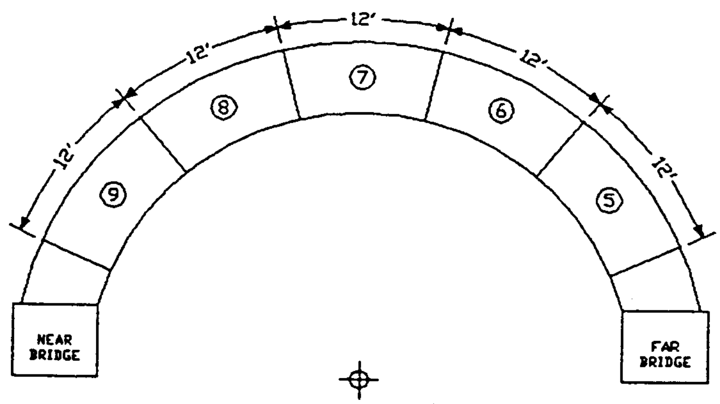
Table 10.3 Adjusted Mix Design

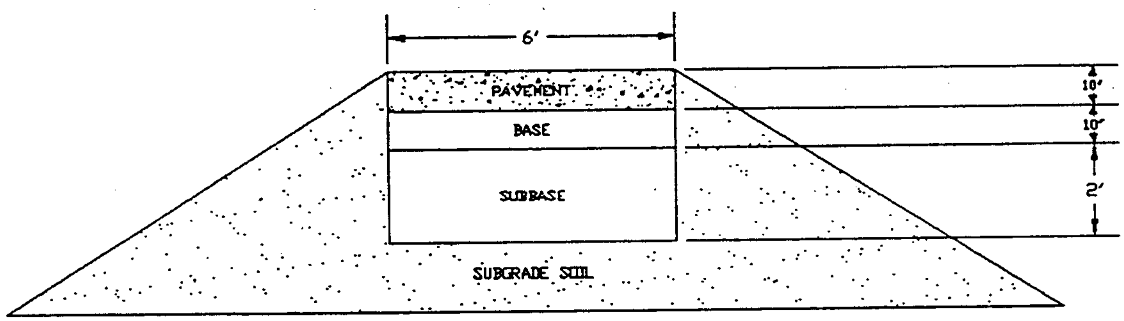
Base Compaction

Before pouring the five rigid pavement sections (Figure 10.3), a 254 mm (10 in) layer of base material had to be placed and compacted. An AASHTO classified A-3 soil (51 % min. passing No. 40 sieve and 10 % max. passing No. 200 sieve) was selected to serve as base for sections 5 through 8 (section 9 used RCA). After performing Sieve Analysis and Modified Proctor Compaction tests on several soils, an appropriate Pit was chosen to supply the sandy soil.

The base material was placed in two 127 mm (5 in) lifts. A jumping jack (Photograph 9), 114 kg (250 lb) compactor (Photograph 10), and a 454 kg (1000 lb) vibrating compactor (Photograph 11) were used to compact each layer. Once completed, a Nuclear Gauge was utilized to obtain the compacted soil densities. None of the tested densities reached 95 % of the Modified Proctor value. For this reason, the borrowed A-3 soil along with an additional 61 cm (2 ft) of existing subgrade soil were removed.

As can be seen on Photograph 8, the 61 cm (2 ft) of soil that was removed was re-compacted with soil from the UCF Campus borrow pit which met A-3 soil classification requirements. Once packed, a local Geotechnical Engineering consulting firm was requested to conduct Nuclear Gauge density tests (Photograph 12).





RIGID PAVEMENT			
Section	Base Course	Subbase Course	Pavement
5	Red Clayey Sandy Soil	UCF Soil	PC with 25% RCA, 75% NA
6	Red Clayey Sandy Soil	UCF Soil	PC with 100% NA
7	Red Clayey Sandy Soil	UCF Soil	PC with 100% RCA
8	Red Clayey Sandy Soil	UCF Soil	PC with 75% RCA, 25% NA
9	RCA	UCF Soil	PC with 100% NA

Figure 10.3 Rigid Pavement Cross Section

The subbase compaction reached 95 % maximum dry density of the Modified Proctor value.

A substitute A-3 base soil was found at a Pit in South Orlando. The soil, which was classified as a red clayey sandy soil, was compacted in two 127 mm (5 in) lifts. Once again, a local Geotechnical Engineering firm tested the stabilized base compaction and results were considered satisfactory. With the proper compaction on all five sections, the form work for the concrete was installed.

NOTE: Sieve Analysis and Modified Proctor test data, along with Nuclear Gauge test results are found in Appendix A.

PHOTOGRAPH 8. UCF Campus Borrow Pit A-3 Soil

PHOTOGRAPH 9. Compaction of RCA Base With Jumping Jack (Section 9)

PHOTOGRAPH 10. Compaction of UCF Borrow Pit Soil

PHOTOGRAPH 11. Compaction of Red Clayey Sandy Soil

PHOTOGRAPH 12. Nuclear Gauge Testing

Placement of Rigid Pavement Sections

The concrete was poured with the help of two 0.25 m^3 (9 ft^3) mixers. Even though a crew of 15 men worked on the placement of the rigid pavement, the mixing was relatively difficult and tedious because only 0.14 m^3 (5 ft^3) of concrete could be prepared in each batch (Table 10.4). On the average, 15 batches had to be mixed in order to finish one section. It took approximately 16 hours to pour sections 5, 7, and 8 while sections 6 and 9 were poured in one hour using concrete delivered by a ready-mixed plant. Because of the changes in temperature during the pours, the quantities of admixture of Table 5 were modified slightly in order to obtain a more workable mix. Between sections, 5 dowel bars 35 mm (1 3/8 in) in diameter, 457 mm (18 in) long, and spaced every 305 mm (12 in) were utilized to help transfer the load from one slab to the other. To protect against shrinkage provoked by excessive evaporation, all the finished concrete surfaces were treated with curing compound. Photographs 13 through 18 summarize the placement process.

On the day of each pour, concrete specimens were collected so that the 28-day compressive strength, elastic modulus, splitting tensile strength, and modulus of rupture could be determined from laboratory tests. Results are found in Table 4.11.

SECTION 5: 25 % RCA + 75 % LIMEROCK		
COMPONENT	ADJUSTED kg (lb)	BATCH PROPORTIONS For 0.14 m^3 (5 ft^3)
Cement	256 (564)	47.4 (104)
Water	85 (188)	15. 75 liters (4.25 gal)
RCA	187 (412)	1 bag + 16.5 kg (1 bag + 36 lbs)
Limerock	578 (1,275)	5 bags + 16.5 kg (5 bags + 36 lbs)
Sand	618 (1,361)	6 bags + 5.5 kg (6 bags + 12 lbs)

SECTION 7: 100 % RCA		
COMPONENT	ADJUSTED kg (lb)	BATCH PROPORTIONS For 0.14 m^3 (5 ft^3)
Cement	256 (564)	47.4 (104)
Water	103 (227)	19.0 liters (5.0 gal)
RCA	748 (1,648)	7 bag + 11.5 kg (7 bag + 25 lbs)
Sand	618 (1,361)	6 bags + 5.5 kg (6 bags + 12 lbs)

SECTION 8: 75 % RCA + 25 % LIMEROCK		
COMPONENT	ADJUSTED kg (lb)	BATCH PROPORTIONS For 0.14 m^3 (5 ft^3)
Cement	256 (564)	47.4 (104)
Water	97 (214)	18.0 liters 4.75 gal
RCA	561 (1,236)	5 bag + 13.25 kg (5 bag + 29 lbs)
Limerock	193 (425)	1 bags + 17.5 kg (1 bags +39 lbs)
Sand	618 (1,361)	6 bags + 5.5 kg (6 bags + 12 lbs)

Table 10.4 Batch proportions for concrete mix

PHOTOGRAPH 13. Concrete Mixers: 0.25 m^3 (9 ft^3)

PHOTOGRAPH 14. Pouring and Placement of RCA Rigid Pavement

PHOTOGRAPH 15. Transfer Load Dowels

PHOTOGRAPH 16. Specimen Casting and Property Testing of Fresh Concrete

PHOTOGRAPH 17. Placement of Virgin Aggregate Concrete

PHOTOGRAPH 18. Application of Curing Compound

Flexible Pavement

Section Design

The RCA Base Course for this project was designed based on data from Florida's State Road 10 (SR 10), which was recently rehabilitated using RCA base material. The same material used on SR 10 was used at the UCF-CATT. The design data follows:

◊ Year of Opening = 1997

◊ Design Year = 2008

◊ 80 kN (18 kip) $ESAL_D$ = 1,498,000

◊ Design Speed = 85 km/hr (55 mph)

◊ Type of Work = Rehabilitation

◊ Lanes = 2 @ 3.66 m (12 ft)

◊ Environment = Rural

◊ Pavement Type = Flexible

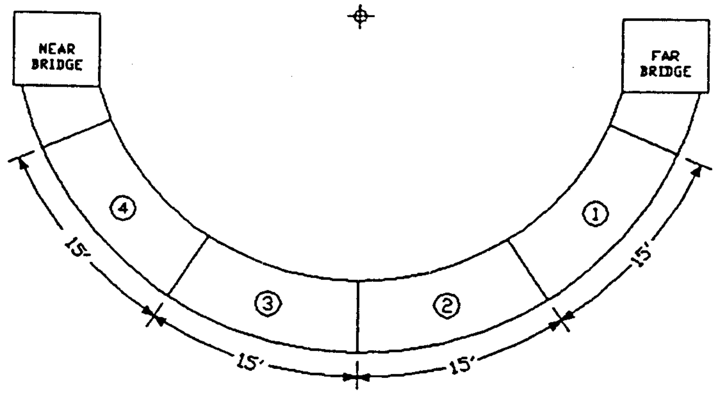
The Resilient Modulus (M_R), which is the measurement of the strength of the roadbed soil, was M_R = 144.3 MPa (20,929 psi). From the FDOT Design Manual Table 5.2, with a Rural Arterial road to be rehabilitated, the reliability (% R), which is the probability of achieving the design life that the DOT desires, is % R = 94. Also from Table A.6B with % R, M_R, and $ESAL_D$, the required Structural Number (SN_R), which is an index number representing the required strength of the pavement structure, is $SN_R = 2.7$. In other words, the SN_R for the cross-sections of Figure 10.4 must be greater than 2.7.

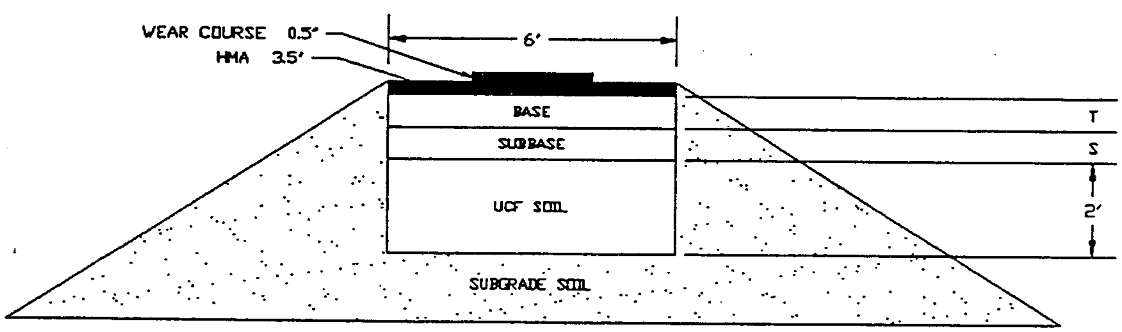
TABLE 10.5. Structural Number Calculation for Flexible Pavement Cross-Sections

GROUP	LAYER TYPE	LAYER COEFF. per mm
Structural Courses	Type S (I, II, III)	0.017
Base Courses	Limerock (LBR 100)	0.007
Base Courses	RCA (LBR 100)	0.006
Stabilized Sub-Grade	Type B (LBR 40)	0.003

LAYER	Section 1	Section 2	Section 3	Section 4
Friction Course	None	None	None	None
Structural Course **88.9 mm (3.5 in) Type S-I**	1.51	1.51	1.51	1.51
Base Course **Thickness mm (in)** **Type**	1.52 254 (10) RCA	1.42 203.2 (8) Limerock	1.22 203.2 (8) RCA	1.83 304.8 (12) RCA
Stabilized Sub-Grade **Thickness mm (in)**	0.46 152.4 (6)	0.61 203.2 (8)	0.61 203.2 (8)	0.30 101.6 (4)
TOTAL SN_R	**3.49**	**3.54**	**3.34**	**3.64**

Since the Structural Numbers calculated on Table 13 are well within FDOT specifications, the cross-sections of Figure 10.4 are valid for use at the UCF-CATT.





FLEXIBLE PAVEMENT		
Section	Base Course	T (in)
1	RCA	10
2	Limerock	8
3	RCA	8
4	RCA	12
Section	Subbase Course	S (in)
1	Red Clayey Sandy Soil	6
2	Red Clayey Sandy Soil	8
3	Red Clayey Sandy Soil	8
4	Red Clayey Sandy Soil	4

Figure 10.4 Flexible Pavement Cross Section

Base Compaction

As was the case with the rigid pavement sections, 61 cm (2 ft) of subgrade were removed and replaced with borrowed A-3 soil from the UCF Campus. On top of this soil, which was compacted to 95 % of the Modified Proctor value, different elevations of subbase material (red clayey sandy soil) were compacted . A RCA base course was then compacted in 2 lifts to heights of 254 mm (10 in), 203.2 mm (8 in), and 304.8 mm (12 in) on sections 1,3, and 4 respectively. Section 2 was the control with 203.2 mm (8 in) of virgin limerock base material. Photographs 19 through 21 depict the placement of the base courses.

PHOTOGRAPH 19. Placement of Virgin Base Course Material

PHOTOGRAPH 20. Compaction of Control Section

PHOTOGRAPH 21. Placement of RCA Base Course

Asphalt Overlay Placement

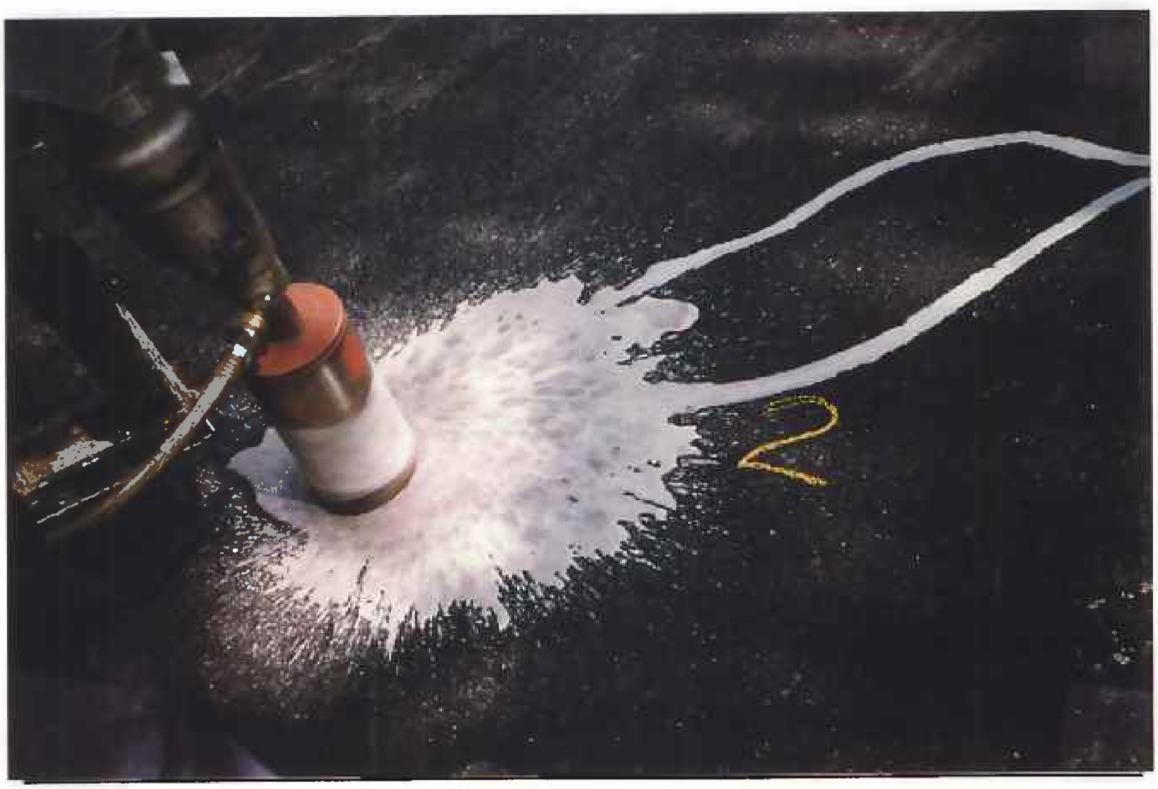
With all the base courses in place, a crew from the Orlando Paving Company applied a prime coat to the surfaces in preparation for the HMA. Once the coat had cured, a 12 men crew along with a paver, roller compactor, and other equipment, applied an 88.9 mm (3.5 in) layer of HMA over the base course in two equal lifts. Each lift was compacted by a dual steel wheel roller compactor and a portable hand compactor. After the asphalt layer had been placed, several cores were cut in order to test the properties of the HMA. The results from these cores along with the HMA mix design are found in Appendix A1. Photographs 22 through 26 summarize the paving procedure.

PHOTOGRAPH 22. Application of SS1 Tack Coat

PHOTOGRAPH 23. PF-115 Paver and Crew Placing HMA

PHOTOGRAPH 24. Portable Hand Compactor

PHOTOGRAPH 25. Steel Wheel Roller Compacting HMA



PHOTOGRAPH 26. Coring of Asphalt Samples

Wear Course Application

To prevent excessive deterioration of the asphalt, it was decided to apply a 12.7 mm (0.5 in) friction course layer over the HMA for protection. Delcrete, a flexible elastomeric concrete composed of fibers, sand, and epoxy designed for bridge joint header material, was purchased from D.S. Brown Company and applied at a width of 0.75 m (2.5 ft). The following procedure was utilized when placing the product:

- A thin layer of pure epoxy (without sand and fibers), mixed for 45 seconds at a ratio of 2:1 (resin to base), was applied at a width of 0.91 m (3 ft) over the asphalt and allowed to cure for one day (Photograph 27).

- The hardened layer of Delcrete was then primed with a special solution that prepared the surface for the next coating of epoxy (with sand and fibers).

- The 12.7 mm (0.5 in) of Delcrete were prepared by mixing the sand, fibers, base, and resin for 45 seconds with a butterfly paddle mounted on a power drill. The mix was then poured in the 0.75 m (2.5 ft) blockout over the wheel path where it was allowed to self settle. By working the material with trowels, a smooth finish was obtained.

Extreme care was maintained when mixing the Delcrete for its performance can be affected by any minimal modification. Photograph 28 shows the end result.

PHOTOGRAPH 27. Coating of HMA with Epoxy

PHOTOGRAPH 28. Delcrete Elastomeric Concrete Over HMA

CHAPTER 11

THEORETICAL ANALYSIS

The theoretical analysis was performed in order to model and predict the behavior of the test sections placed at the UCF-CATT. The analysis provided the number of repetitions for the fatigue and permanent deformation failure criteria to occur in the rigid and flexible pavements. This estimated number of repetitions was then compared for accuracy with those obtained from the testing of the sections at the UCF facility.

The theoretical analysis was performed in three stages. The first stage determined the deflection basins of the rigid and flexible pavements generated by different loads by the Falling Weight Deflectometer. The second involved the KENLAYER and KENSLABS computer programs (Huang, 1993) to estimate the in-situ material properties of the base, subbase, and subgrade materials by back calculating the deflection basins produced with the FWD test. The final stage utilized the same programs but with a different purpose. By knowing the dimensions of the slab and the properties of the materials of the cross sections, the maximum stresses and strains of the overlays under the given wheel load of 48.9 kN (11,000 lbs) were calculated. This data was then utilized to forecast when failure would most likely take place.

Falling Weight Deflectometer Test

The falling weight deflectometer (FWD) is a device that can deliver transient force impulses to pavement surfaces (Photograph 29). It is a nondestructive test. By varying the amount of weight and the height of drop, different impulse forces can be applied. The load, which is transmitted to the pavement through a loading plate 304.8 mm (12 in) in diameter resting on a thick rubber pad, provides a load pulse in the form of a half sine wave with a duration from 25 to 30 milliseconds that simulates the dynamic load applied by a moving vehicle. Surface deflections are measured by seven velocity transducers mounted on a bar that are lowered automatically to the pavement surface with the loading plate. One of the transducers is located at the center of the plate, while the remaining six can be placed at different locations up to 2.25 m (7.4 ft) from the center.

FDOT engineers performed the FWD test on the sections placed at the UCF-CATT (Photograph 30). The transducers were located at 203.2 mm (8 in), 304.8 mm (12 in), 457.2 mm (18 in), 609.6 mm(24 in), 914.4 mm (36 in), and 1,524 mm (60 in) from the center of the plate. Three dynamic loads were applied to each section by using the same weight but varying the height of the drop. The magnitude of the loads, which was measured by a load cell, ranged between 550 kPa (79 psi) and 1,000 kPa (145 psi).

Figures 11.1 through 11.9 depict the deflection basins produced by each of the applied loads to the individual test sections (assuming symmetric deflection responses). The figures show that the deflections for asphalt sections (sections 1 through 4) are on the average four times greater than those for concrete sections (sections 5 through 9). This is due to higher rigidity of Portland cement concrete over HMA.

PHOTOGRAPH 29. Falling Weight Deflectometer Test on Flexible Pavement

PHOTOGRAPH 30. Falling Weight Deflectometer Test on Rigid Pavement

SECTION 1: RCA Base Course 254 mm (10 in)													
q\\D	-60	-36	-24	-18	-12	-8	0	8	12	18	24	36	60
547 kPa	-0.049	-0.101	-0.149	-0.190	-0.258	-0.342	-0.506	-0.342	-0.258	-0.190	-0.149	-0.101	-0.049
693 kPa	-0.066	-0.131	-0.189	-0.240	-0.322	-0.424	-0.619	-0.424	-0.322	-0.240	-0.189	-0.131	-0.066
925 kPa	-0.085	-0.174	-0.253	-0.324	-0.437	-0.582	-0.850	-0.582	-0.437	-0.324	-0.253	-0.174	-0.085

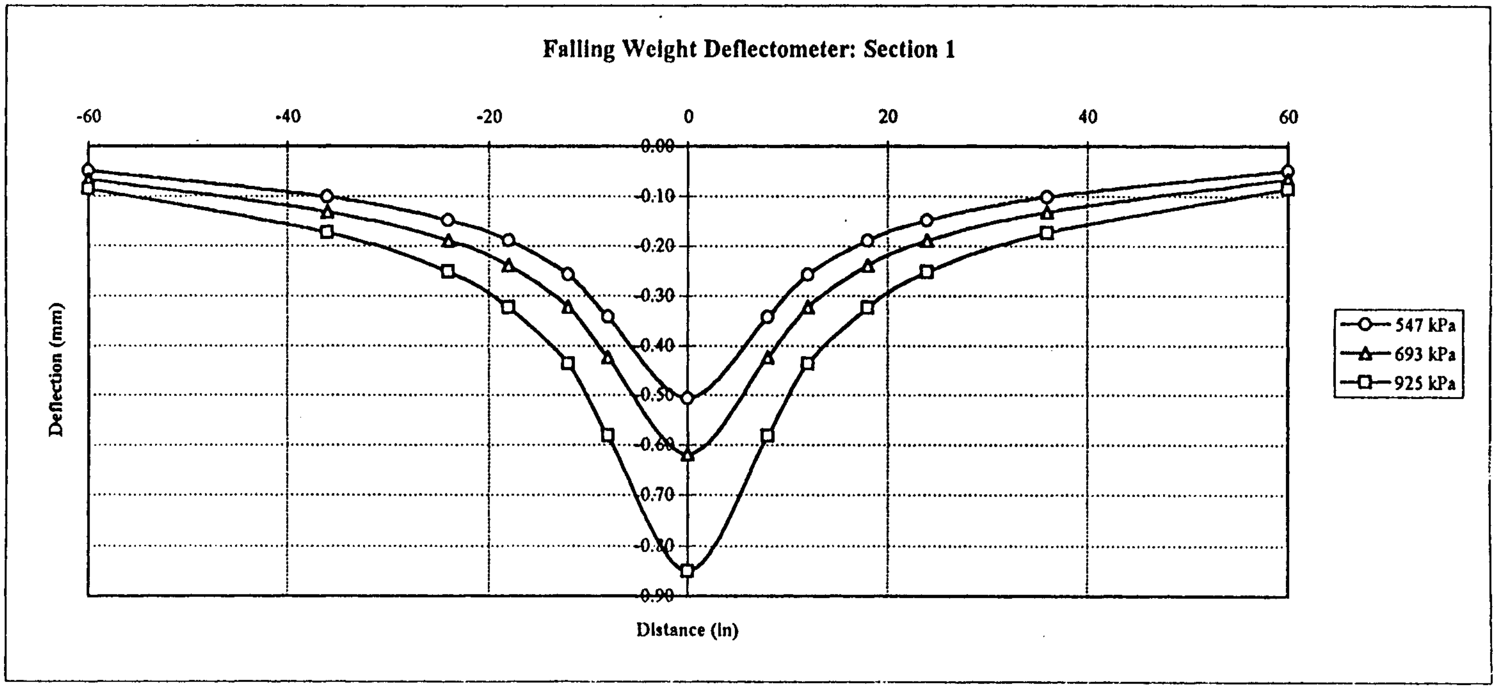


Fig 11.1 FWD Data and Deflection Basin on Section 1

SECTION 2: Limerock Base Course 203.2 mm (8 in)													
q\\D	-60	-36	-24	-18	-12	-8	0	8	12	18	24	36	60
553 kPa	-0.046	-0.084	-0.129	-0.181	-0.282	-0.416	-0.643	-0.416	-0.282	-0.181	-0.129	-0.084	-0.046
697 kPa	-0.060	-0.109	-0.160	-0.222	-0.340	-0.492	-0.755	-0.492	-0.340	-0.222	-0.160	-0.109	-0.060
932 kPa	-0.080	-0.142	-0.215	-0.299	-0.456	-0.655	-0.985	-0.655	-0.456	-0.299	-0.215	-0.142	-0.080

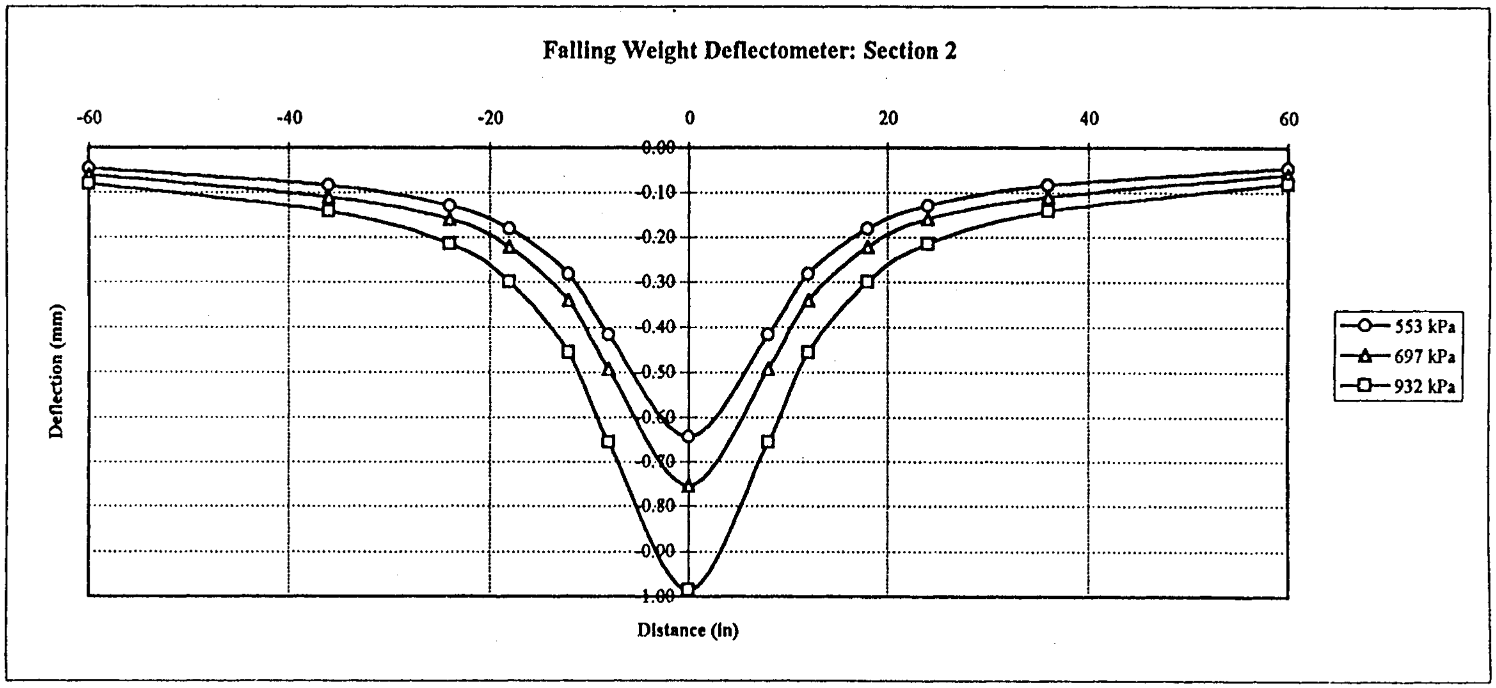


Fig 11.2 FWD Data and Deflection Basin on Section 2

SECTION 3: RCA Base Course 203.2 mm (8 in)													
q\\D	-60	-36	-24	-18	-12	-8	0	8	12	18	24	36	60
552 kPa	-0.048	-0.091	-0.123	-0.159	-0.236	-0.355	-0.677	-0.355	-0.236	-0.159	-0.123	-0.091	-0.048
692 kPa	-0.061	-0.115	-0.156	-0.202	-0.297	-0.436	-0.770	-0.436	-0.297	-0.202	-0.156	-0.115	-0.061
929 kPa	-0.080	-0.148	-0.208	-0.272	-0.408	-0.599	-0.997	-0.599	-0.408	-0.272	-0.208	-0.148	-0.080

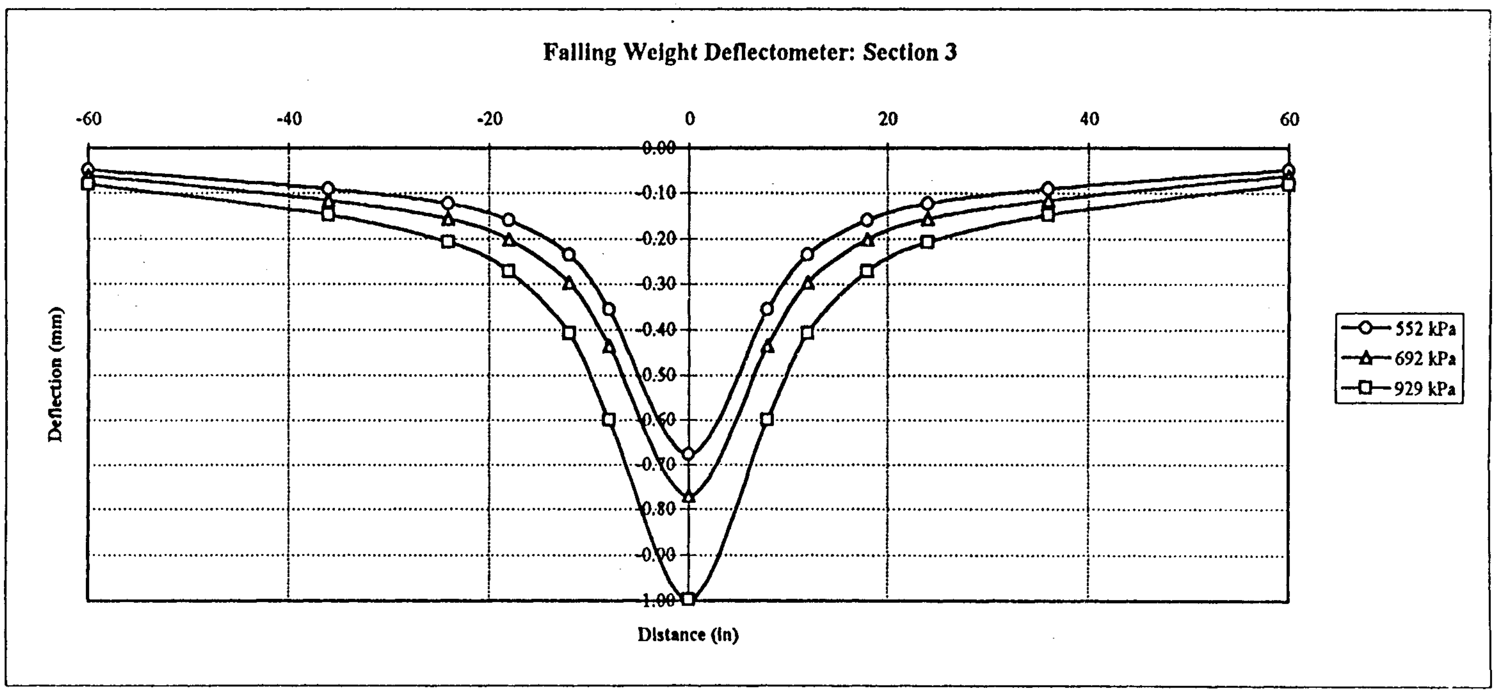


Fig 11.3 FWD Data and Deflection Basin on Section 3

SECTION 4: RCA Base Course 304.8 mm (12 in)													
q\\D	-60	-36	-24	-18	-12	-8	0	8	12	18	24	36	60
556 kPa	-0.048	-0.091	-0.123	-0.163	-0.249	-0.367	-0.579	-0.367	-0.249	-0.163	-0.123	-0.091	-0.048
696 kPa	-0.061	-0.115	-0.156	-0.207	-0.309	-0.448	-0.703	-0.448	-0.309	-0.207	-0.156	-0.115	-0.061
938 kPa	-0.080	-0.148	-0.208	-0.276	-0.412	-0.599	-0.931	-0.599	-0.412	-0.276	-0.208	-0.148	-0.080

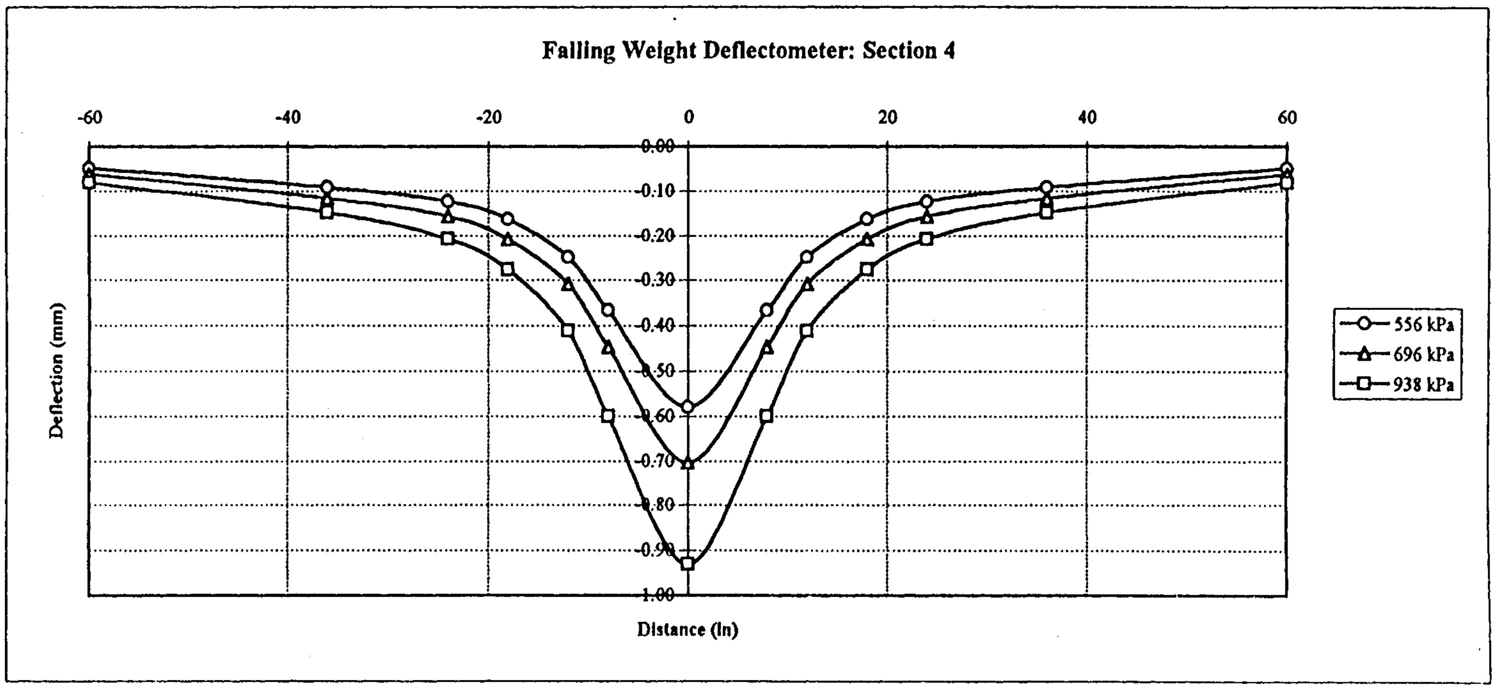


Fig 11.4 FWD Data and Deflection Basin on Section 4

SECTION 5: 25 % RCA + 75 % VA													
q\\D	-60	-36	-24	-18	-12	-8	0	8	12	18	24	36	60
581 kPa	-0.060	-0.086	-0.097	-0.102	-0.107	-0.110	-0.112	-0.110	-0.107	-0.102	-0.097	-0.086	-0.060
724 kPa	-0.078	-0.109	-0.123	-0.128	-0.135	-0.139	-0.142	-0.139	-0.135	-0.128	-0.123	-0.109	-0.078
999 kPa	-0.099	-0.140	-0.159	-0.166	-0.175	-0.179	-0.184	-0.179	-0.175	-0.166	-0.159	-0.140	-0.099

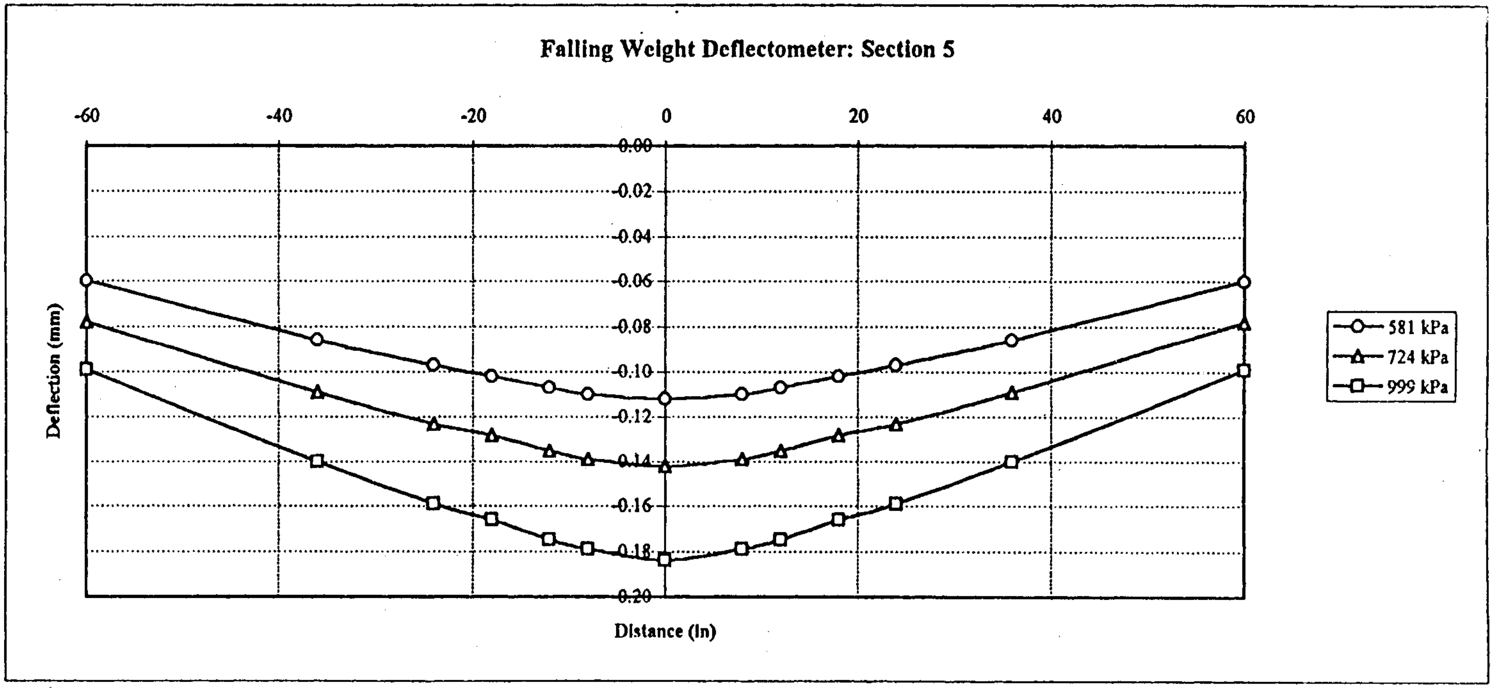


Fig 11.5 FWD Data and Deflection Basin on Section 5

SECTION 6: 100% VA													
q\\D	-60	-36	-24	-18	-12	-8	0	8	12	18	24	36	60
599 kPa	-0.055	-0.087	-0.102	-0.110	-0.115	-0.119	-0.126	-0.119	-0.115	-0.110	-0.102	-0.087	-0.055
708 kPa	-0.069	-0.110	-0.129	-0.139	-0.145	-0.149	-0.157	-0.149	-0.145	-0.139	-0.129	-0.110	-0.069
1010 kPa	-0.093	-0.145	-0.169	-0.181	-0.190	-0.196	-0.208	-0.196	-0.190	-0.181	-0.169	-0.145	-0.093

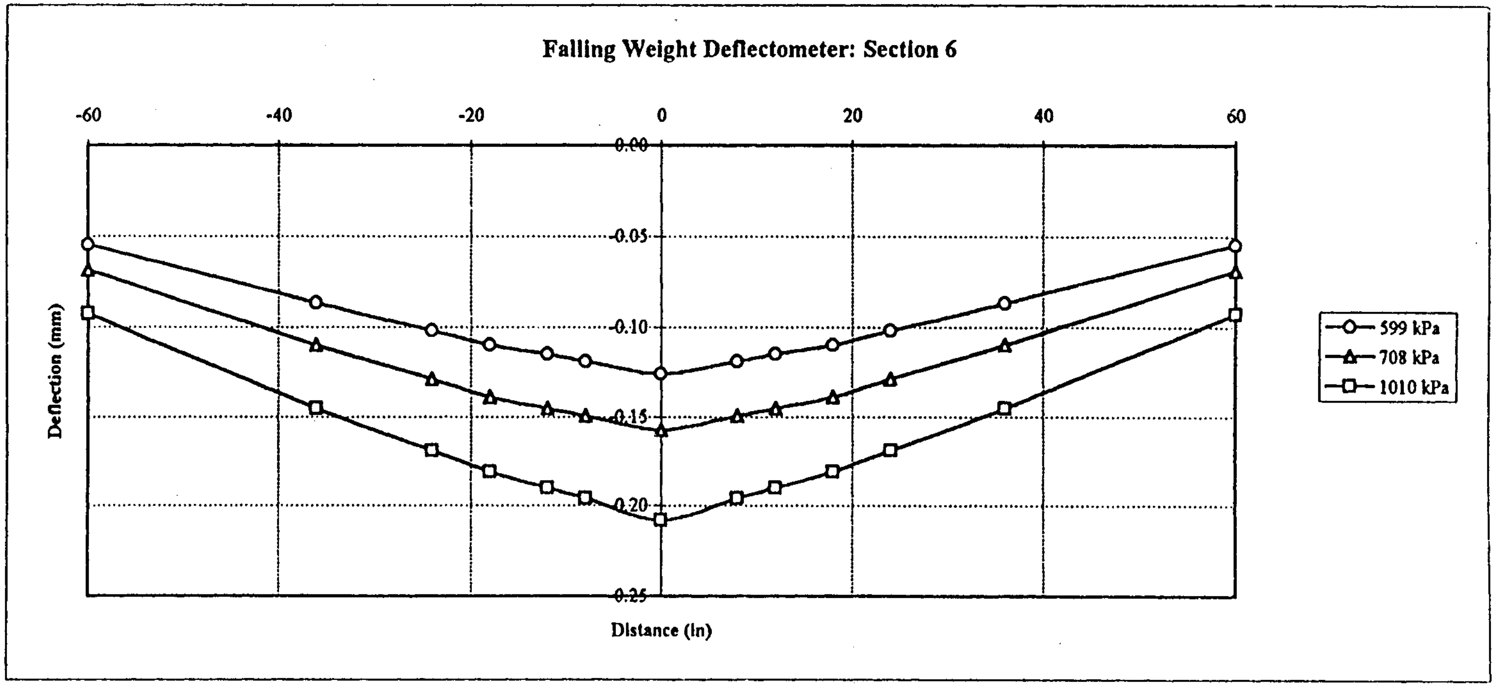


Fig 11.6 FWD Data and Deflection Basin on Section 6

SECTION 7: 100% RCA													
q\\D	-60	-36	-24	-18	-12	-8	0	8	12	18	24	36	60
569 kPa	-0.053	-0.089	-0.105	-0.114	-0.120	-0.125	-0.132	-0.125	-0.120	-0.114	-0.105	-0.089	-0.053
729 kPa	-0.069	-0.112	-0.134	-0.143	-0.150	-0.155	-0.166	-0.155	-0.150	-0.143	-0.134	-0.112	-0.069
996 kPa	-0.090	-0.147	-0.175	-0.187	-0.196	-0.203	-0.218	-0.203	-0.196	-0.187	-0.175	-0.147	-0.090

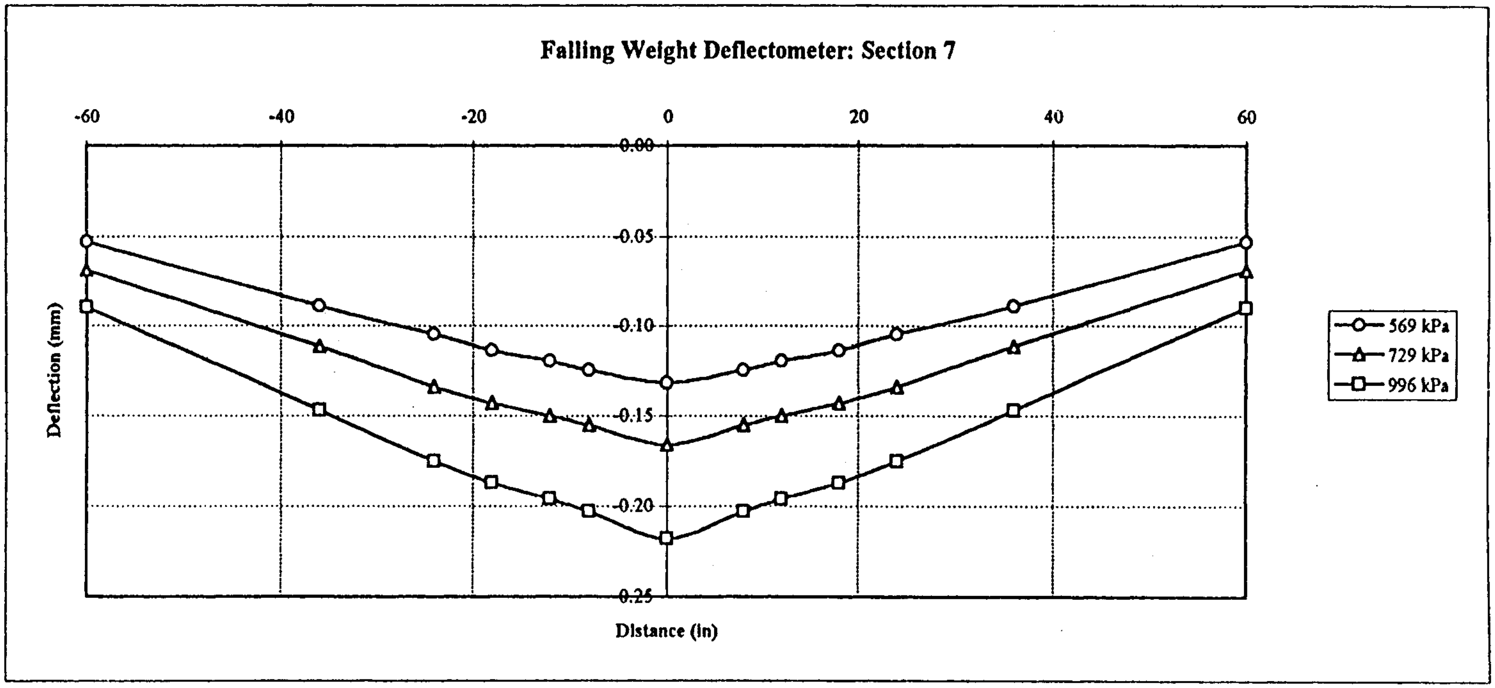


Fig 11.7 FWD Data and Deflection Basin on Section 7

SECTION 8: 75 % RCA + 25 % VA													
q\\D	-60	-36	-24	-18	-12	-8	0	8	12	18	24	36	60
568 kPa	-0.059	-0.095	-0.112	-0.119	-0.127	-0.131	-0.136	-0.131	-0.127	-0.119	-0.112	-0.095	-0.059
732 kPa	-0.074	-0.119	-0.139	-0.149	-0.158	-0.162	-0.170	-0.162	-0.158	-0.149	-0.139	-0.119	-0.074
990 kPa	-0.096	-0.156	-0.184	-0.195	-0.206	-0.212	-0.223	-0.212	-0.206	-0.195	-0.184	-0.156	-0.096

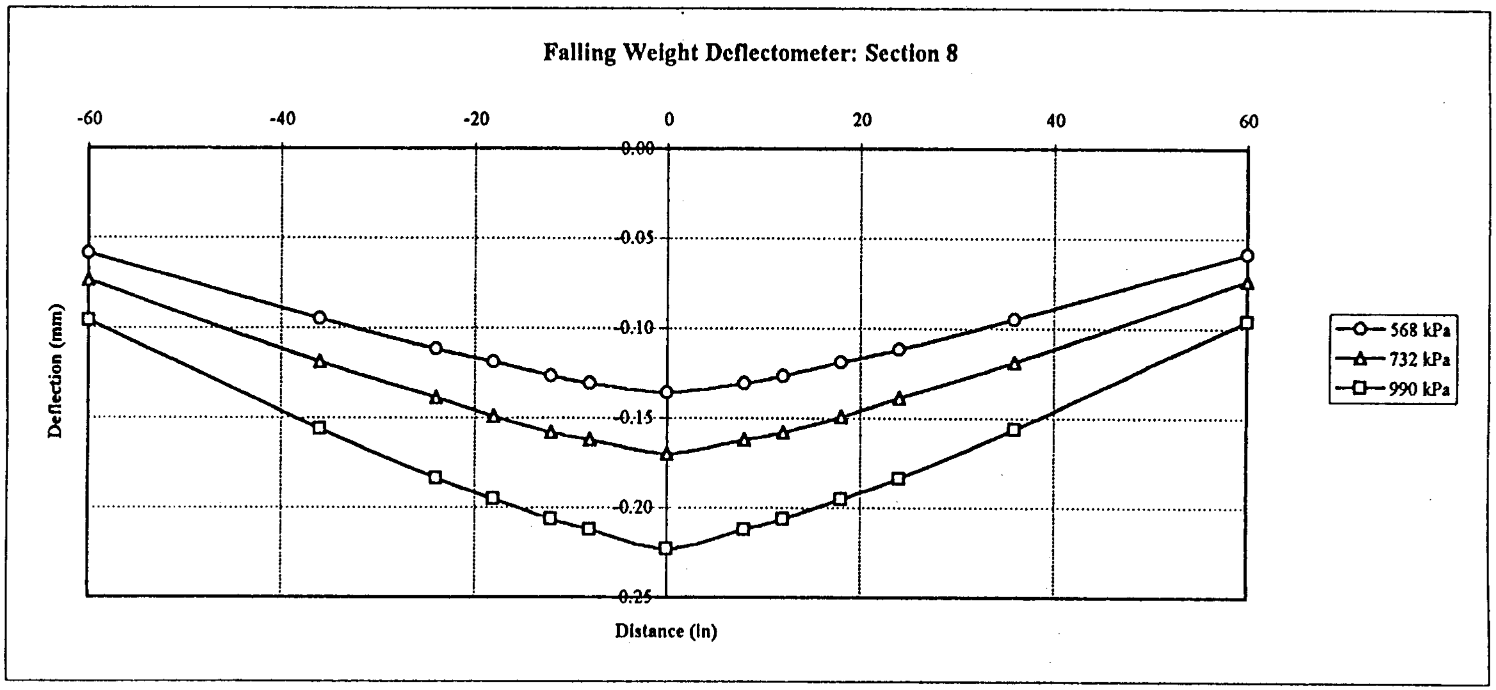


Fig 11.8 FWD Data and Deflection Basin on Section 8

SECTION 9: 100% VA													
q\\D	-60	-36	-24	-18	-12	-8	0	8	12	18	24	36	60
575 kPa	-0.050	-0.080	-0.090	-0.096	-0.106	-0.107	-0.112	-0.107	-0.106	-0.096	-0.090	-0.080	-0.050
741 kPa	-0.065	-0.102	-0.115	-0.122	-0.133	-0.135	-0.143	-0.135	-0.133	-0.122	-0.115	-0.102	-0.065
989 kPa	-0.087	-0.133	-0.153	-0.162	-0.172	-0.177	-0.186	-0.177	-0.172	-0.162	-0.153	-0.133	-0.087

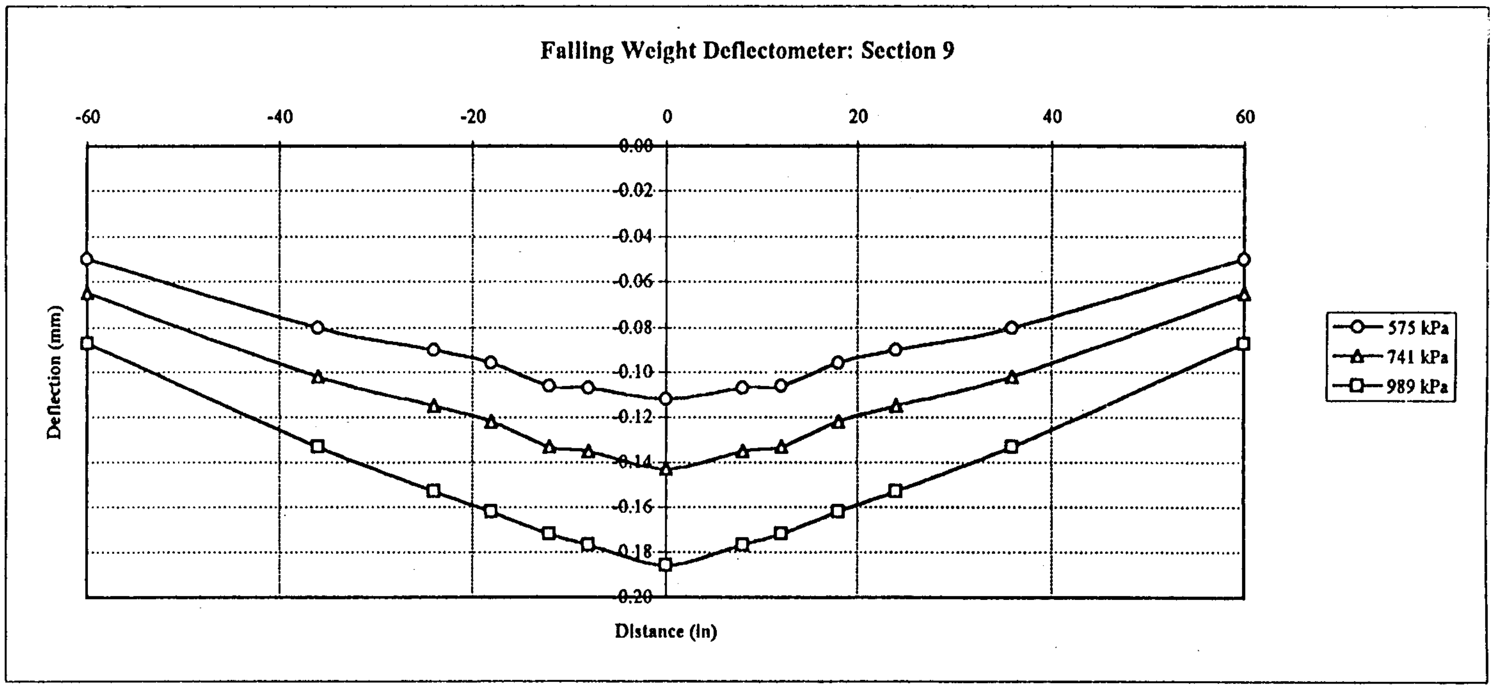


Fig 11.9 FWD Data and Deflection Basin on Section 9

Back-Calculation of In-situ Elastic Modulus Using KENSLABS

One of the useful applications of nondestructive testing (NDT) is to back-calculate the moduli of pavement components, including the subgrade. The procedure is based on measuring the deflection basin by varying the set of moduli until a best match between the computed and measured FWD deflections is obtained. The KENSLABS computer program (Huang, 1992) was developed to analyze rigid pavements, such as PCC and composite pavements. The software is based on the finite element method, where a slab is sub-divided into rectangular finite elements with a large number of nodes. The wheel loads and the subgrade reactions are applied to the slab as vertical concentrated forces at these nodes. A solid foundation (Boussinesq foundation) is assumed such that the deflection at any nodal point depends not only on the force at the node itself but also on the forces at all other nodes.

This program was used for theoretical analysis of test sections 5 through 9 for two reasons. First, with the load-deflection data from the FWD test and the modulus of elasticity of the concrete determined at the laboratory, it was possible to back-calculate the modulus of elasticity of the base, subbase, and subgrade soils by trying to best fit the deflection basin profiles as shown in Figures 11.5 through 11.9. Secondly, by knowing the modulus of elasticity of the layered components placed at the track (Figure 10.3) and the load applied by the UCF-CATT apparatus, the flexural stress of each slab was then calculated and used to determine the allowable number of repetitions for the fatigue life of each test section.

Figure 11.10 shows the finite element model layout that was used with the KENSLABS program to determine the elastic modulus of the soils below the concrete slab. The model represents the 1.83 x 3.66 m (6 x 12 ft) test sections that were poured at UCF track. Node 11 denotes the point of load application of the FWD while nodes 18, 25, 32, 39, 46, and 53 symbolize the location of the velocity transducers. After trials with numerous combinations of the modulus values, the moduli of the layered components that best fit the deflection basin of sections 5 through 9 (Figures 11.11 through 11.25) were found to be: for $E_{RED\ SOIL}$ = 221 MPa (32,000 psi), $E_{UCF\ SOIL}$ = 186 MPa (27,000 psi), and $E_{SUBGRADE}$ = 172 MPa (25,000 psi).

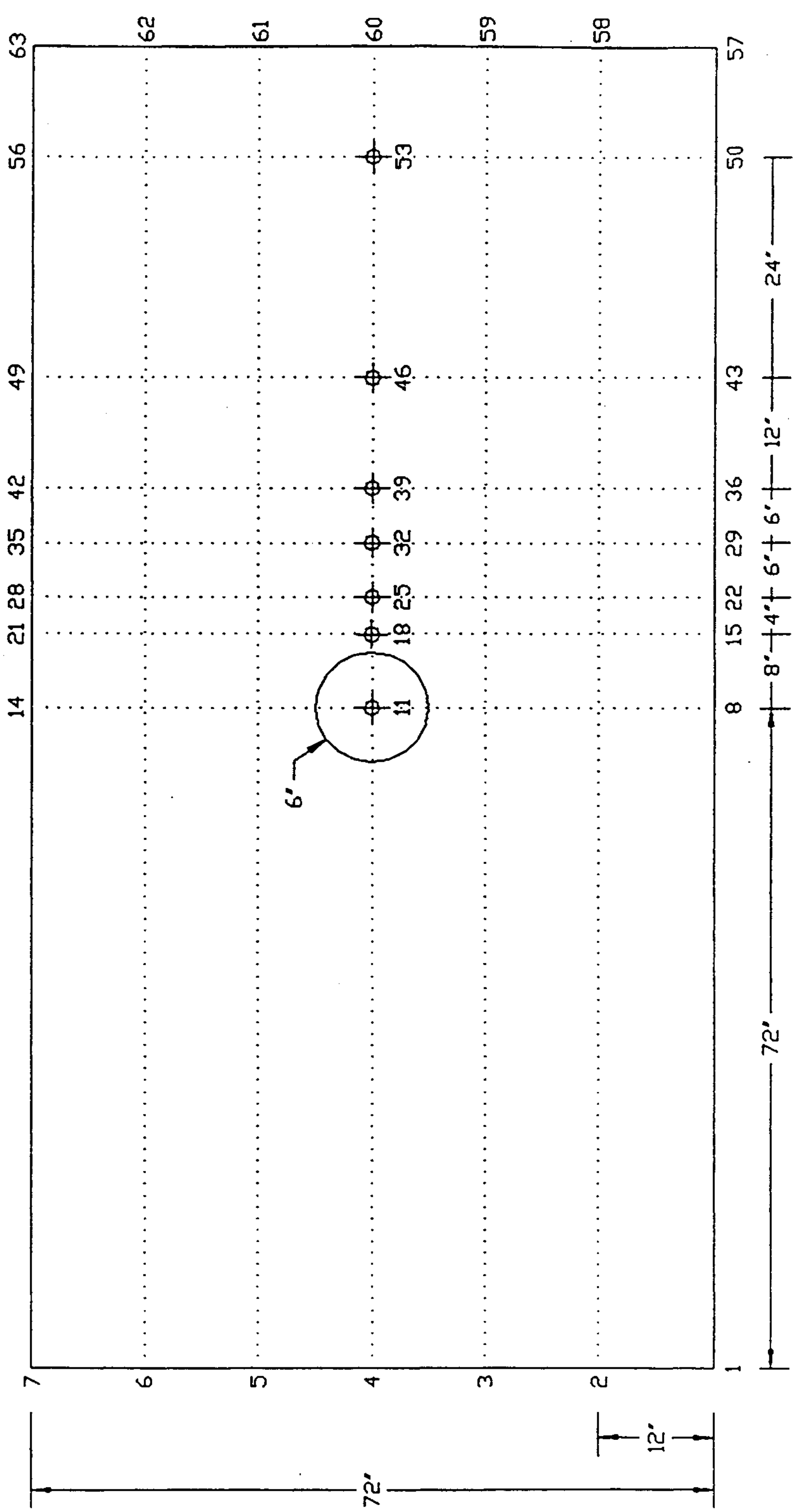
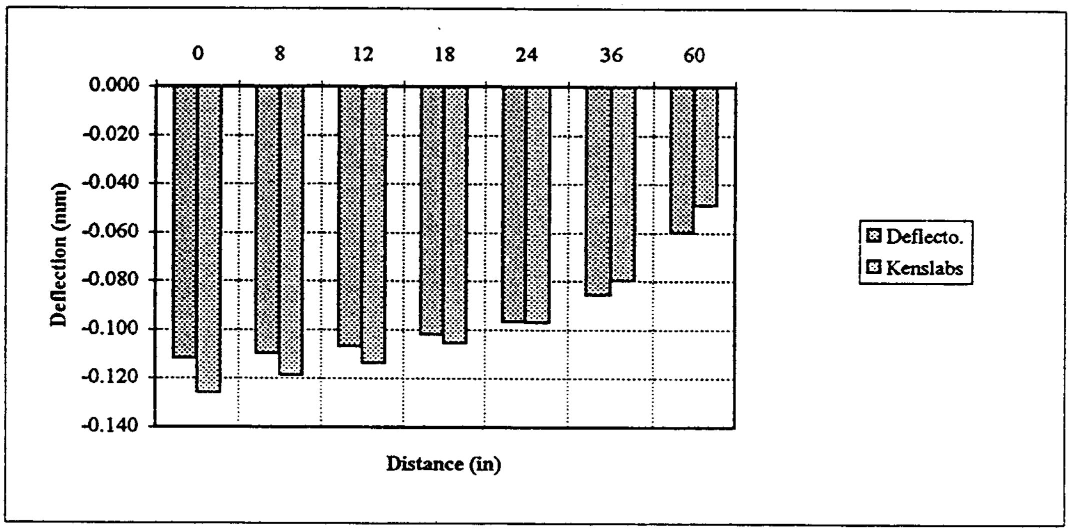


Fig 11.10 Finite Element Model for KENSLABS

Section 5: 25 % RCA + 75 % VA Concrete Load: 581 kPa (9,523 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.112	-0.126	
8	203.2	-0.110	-0.119	
12	304.8	-0.107	-0.114	$E_{CONCRETE} = 4.85 \times 10^6$ psi
18	457.2	-0.102	-0.106	$E_{RED\ SOIL} = 32{,}000$ psi
24	609.6	-0.097	-0.097	$E_{UCF\ SOIL} = 27{,}000$ psi
36	914.4	-0.086	-0.080	$E_{SUBGRADE} = 25{,}000$ psi
60	1524.0	-0.060	-0.049	



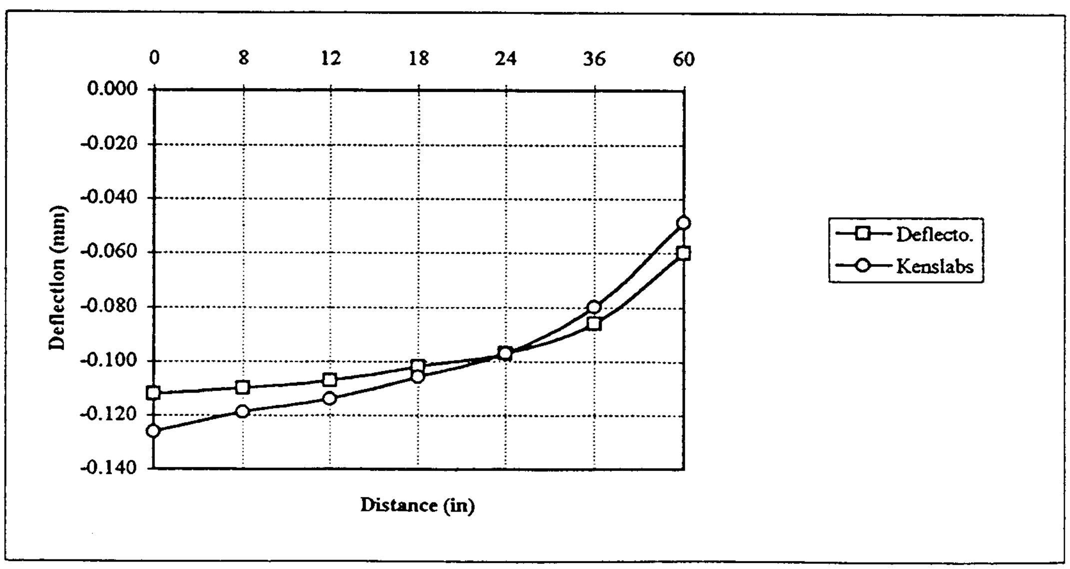
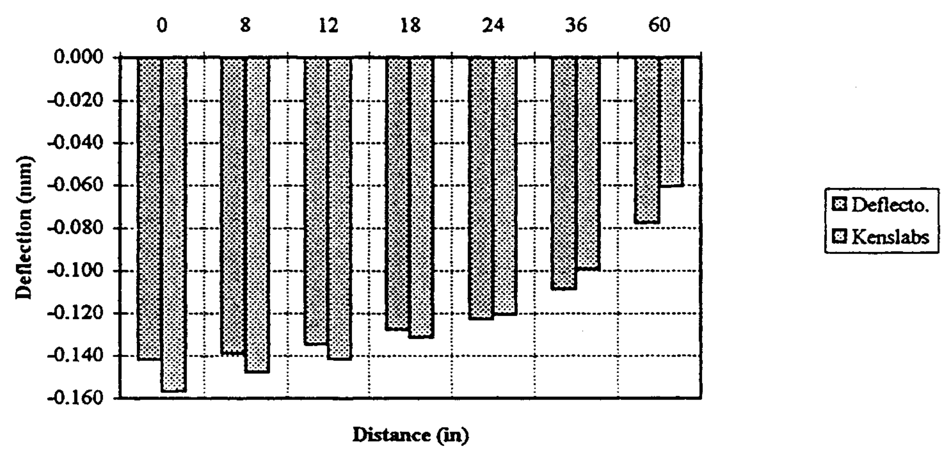


Fig 11.11 Best-Fit Deflection Profile for Section 5 (581 kPa)

Section 5: 25 % RCA + 75 % VA Concrete Load: 724 kPa (11,867 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.142	-0.157	
8	203.2	-0.139	-0.148	
12	304.8	-0.135	-0.142	$E_{CONCRETE} = 4.85 \times 10^6$ psi
18	457.2	-0.128	-0.132	$E_{RED\ SOIL} = 32,000$ psi
24	609.6	-0.123	-0.121	$E_{UCF\ SOIL} = 27,000$ psi
36	914.4	-0.109	-0.100	$E_{SUBGRADE} = 25,000$ psi
60	1524.0	-0.078	-0.061	



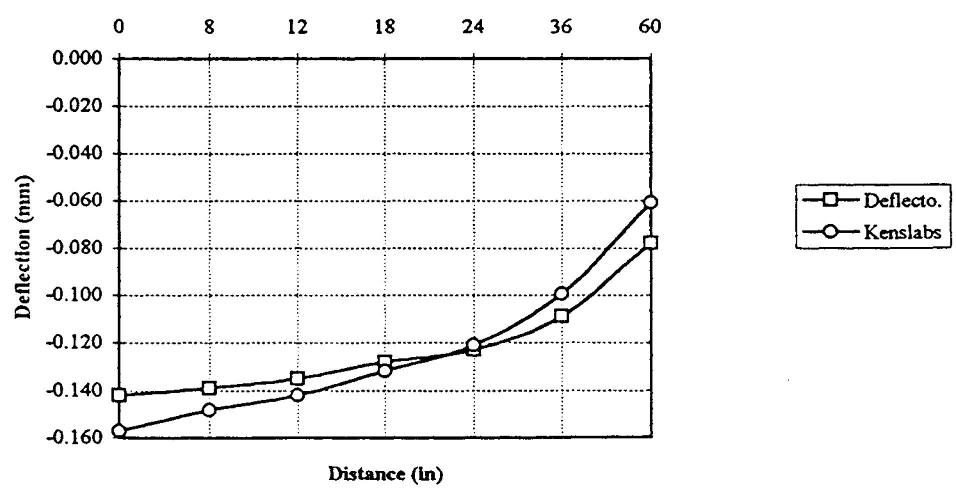
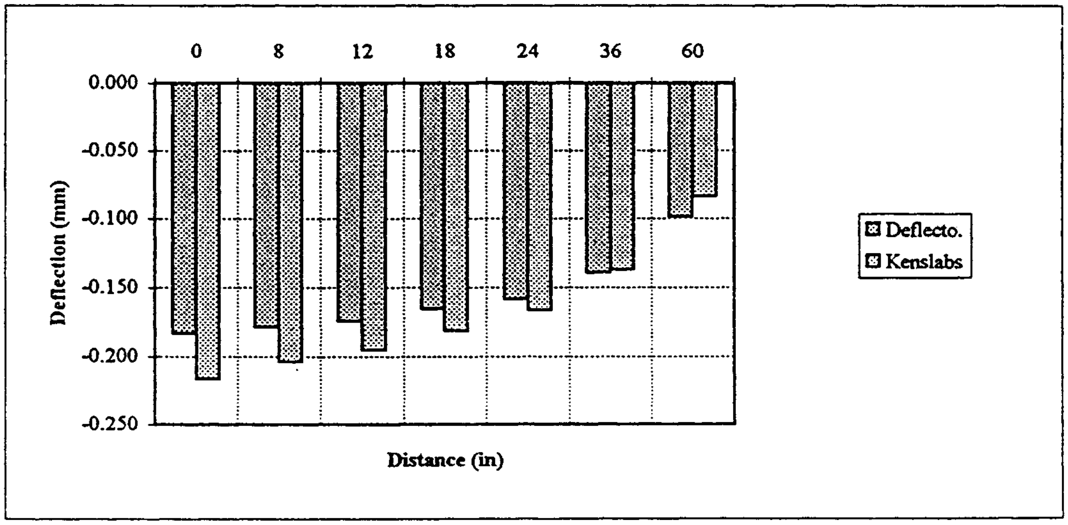


Fig 11.12 Best-Fit Deflection Profile for Section 5 (742 kPa)

Section 5: 25 % RCA + 75 % VA Concrete Load: 999 kPa (16,375 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.184	-0.217	
8	203.2	-0.179	-0.204	
12	304.8	-0.175	-0.196	$E_{CONCRETE} = 4.85 \times 10^6$ psi
18	457.2	-0.166	-0.182	$E_{RED\ SOIL} = 32{,}000$ psi
24	609.6	-0.159	-0.167	$E_{UCF\ SOIL} = 27{,}000$ psi
36	914.4	-0.140	-0.137	$E_{SUBGRADE} = 25{,}000$ psi
60	1524.0	-0.099	-0.084	



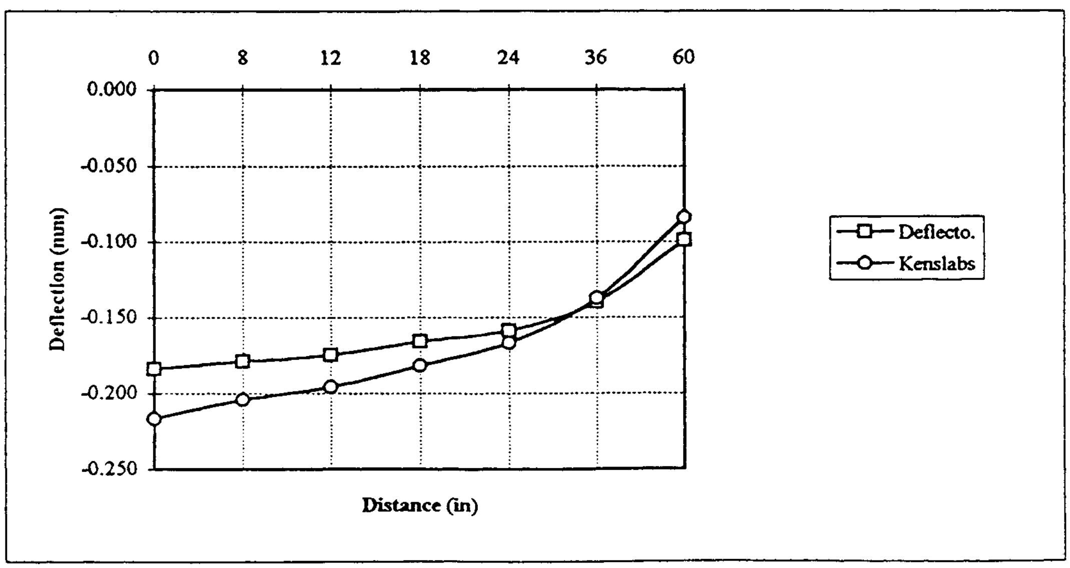
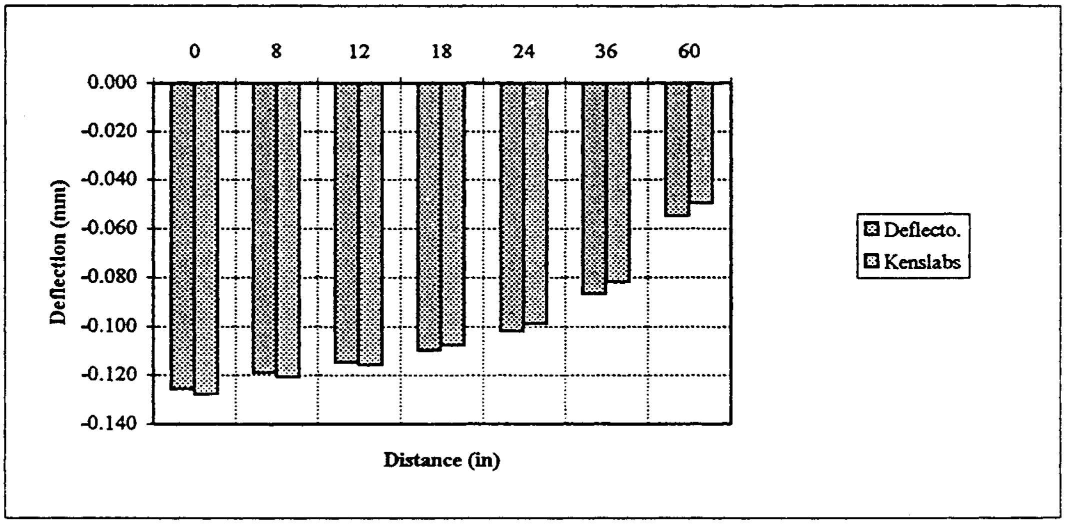


Fig 11.13 Best-Fit Deflection Profile for Section 5 (999 kPa)

Section 6: 100 % VA Concrete Load: 599 kPa (9,818 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.126	-0.128	
8	203.2	-0.119	-0.121	
12	304.8	-0.115	-0.116	$E_{CONCRETE} = 5.17 \times 10^6$ psi
18	457.2	-0.110	-0.108	$E_{RED\ SOIL} = 32{,}000$ psi
24	609.6	-0.102	-0.099	$E_{UCF\ SOIL} = 27{,}000$ psi
36	914.4	-0.087	-0.082	$E_{SUBGRADE} = 25{,}000$ psi
60	1524.0	-0.055	-0.050	



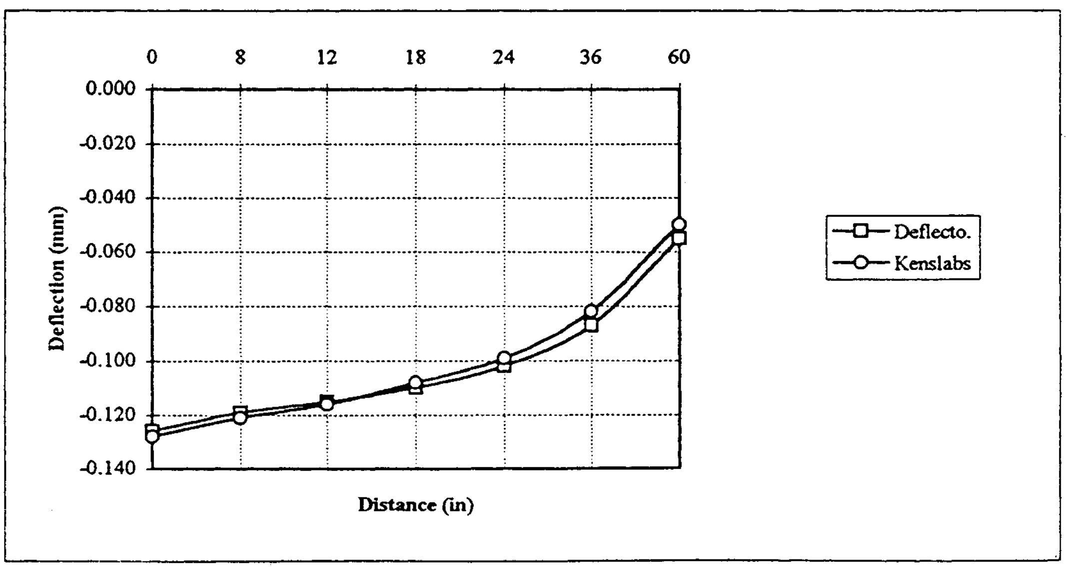
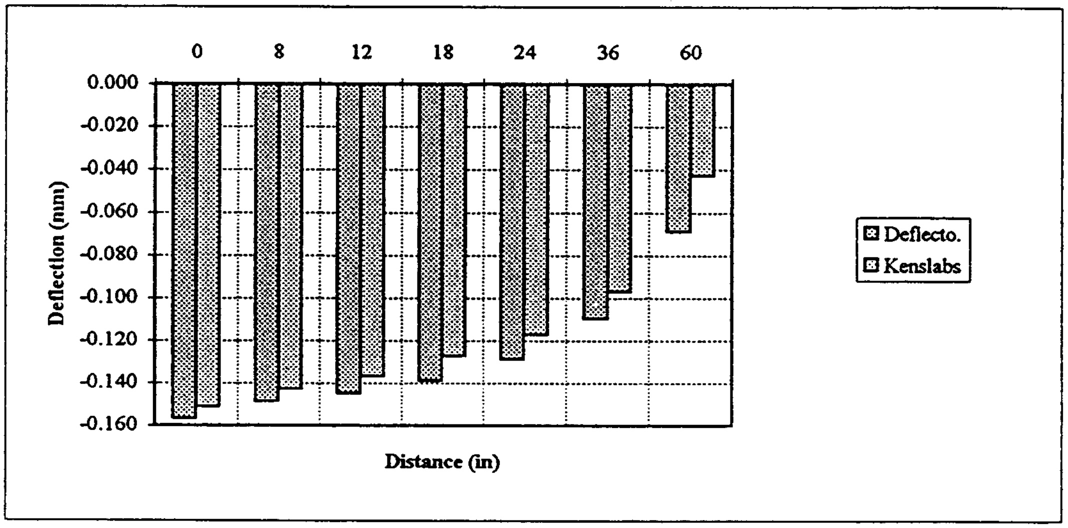


Fig 11.14 Best-Fit Deflection Profile for Section 6 (599 kPa)

Section 6: 100 % VA Concrete Load: 708 kPa (11,605 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.157	-0.151	
8	203.2	-0.149	-0.143	
12	304.8	-0.145	-0.137	$E_{CONCRETE} = 5.17 \times 10^6$ psi
18	457.2	-0.139	-0.127	$E_{RED\ SOIL} = 32{,}000$ psi
24	609.6	-0.129	-0.117	$E_{UCF\ SOIL} = 27{,}000$ psi
36	914.4	-0.110	-0.097	$E_{SUBGRADE} = 25{,}000$ psi
60	1524.0	-0.069	-0.043	



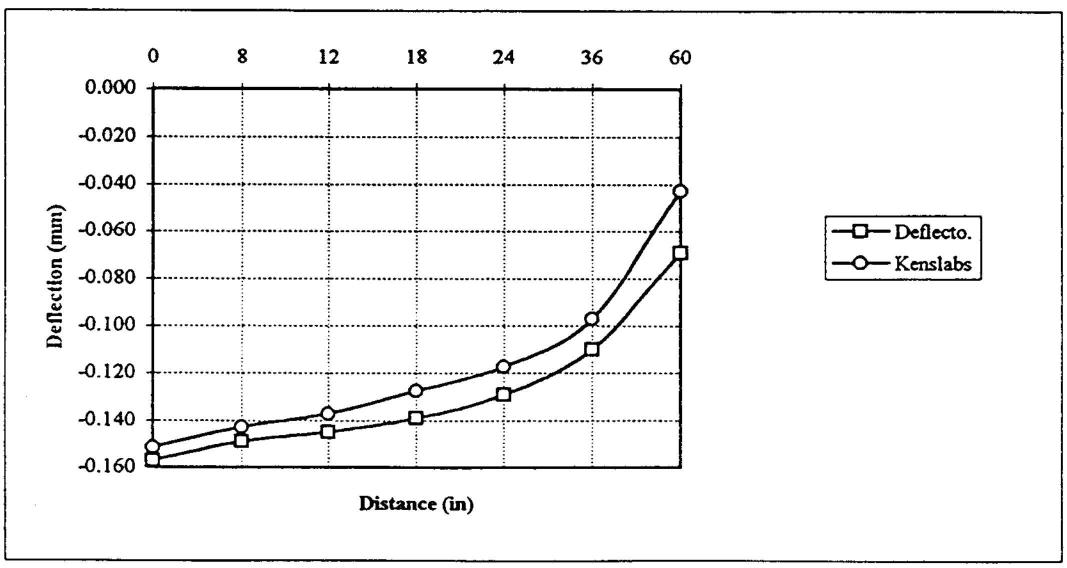
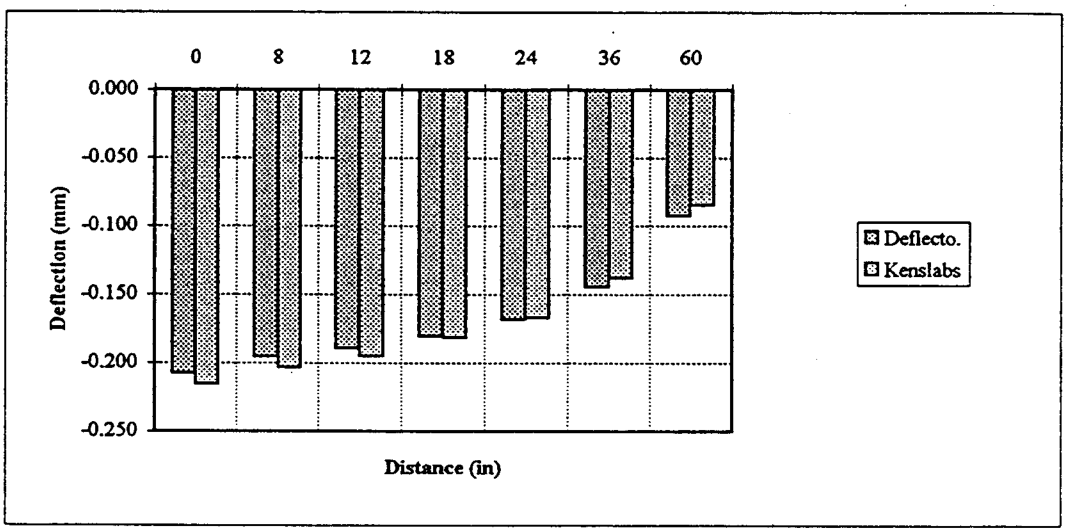


Fig 11.15 Best-Fit Deflection Profile for Section 6 (708 kPa)

Section 6: 100 % VA Concrete Load: 1,010 kPa (16,555 lbs)					
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program	
0	0.0	-0.208	-0.216		
8	203.2	-0.196	-0.204		
12	304.8	-0.190	-0.196	$E_{CONCRETE} = 5.17 \times 10^6$ psi	
18	457.2	-0.181	-0.182	$E_{RED\ SOIL} = 32{,}000$ psi	
24	609.6	-0.169	-0.167	$E_{UCF\ SOIL} = 27{,}000$ psi	
36	914.4	-0.145	-0.138	$E_{SUBGRADE} = 25{,}000$ psi	
60	1524.0	-0.093	-0.085		



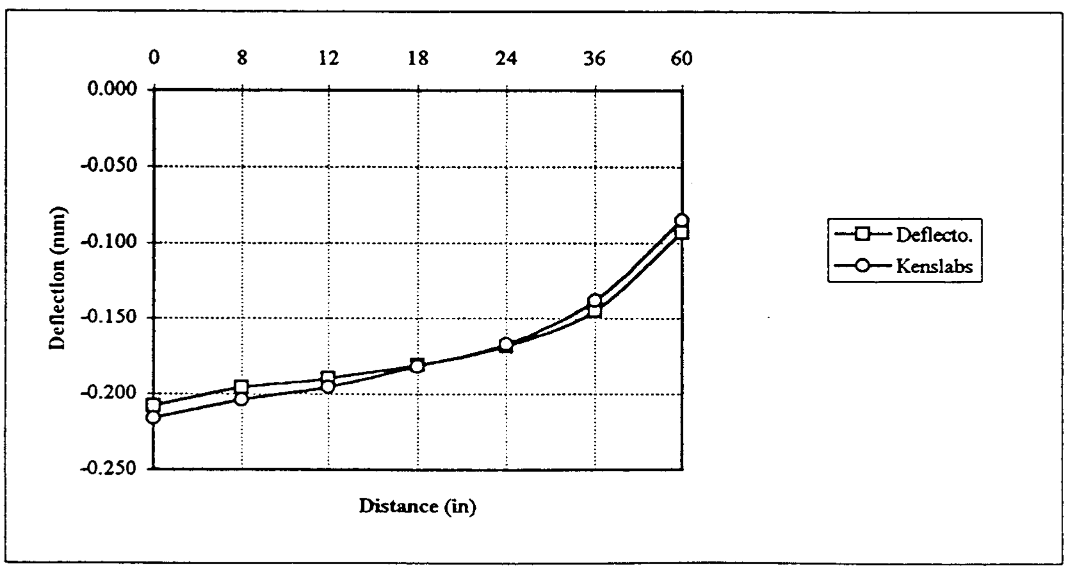
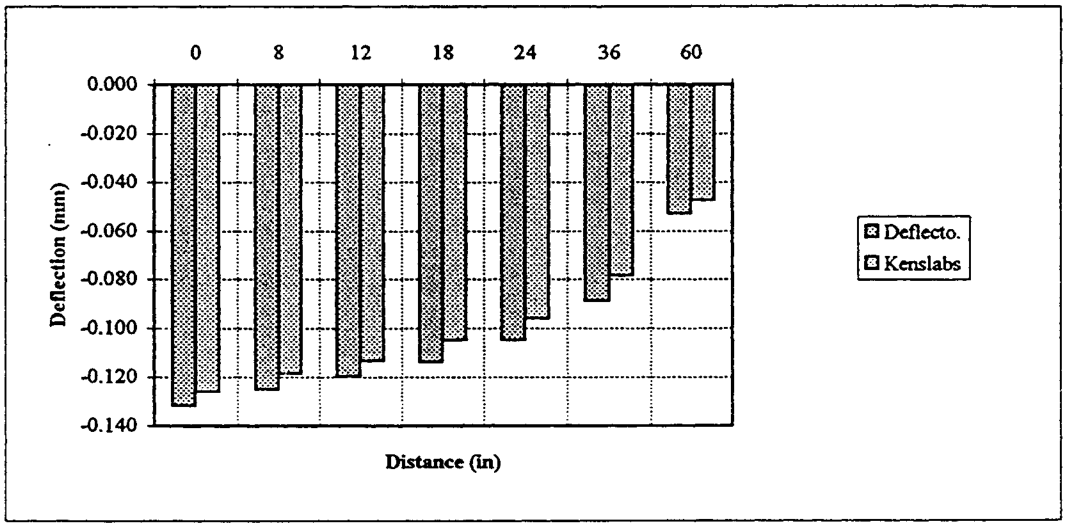


Fig 11.16 Best-Fit Deflection Profile for Section 6 (1010 kPa)

Section 7: 100 % RCA Concrete Load: 569 kPa (9,325 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.132	-0.126	
8	203.2	-0.125	-0.119	
12	304.8	-0.120	-0.113	$E_{CONCRETE} = 4.42 \times 10^6$ psi
18	457.2	-0.114	-0.105	$E_{RED\ SOIL} = 32{,}000$ psi
24	609.6	-0.105	-0.096	$E_{UCF\ SOIL} = 27{,}000$ psi
36	914.4	-0.089	-0.079	$E_{SUBGRADE} = 25{,}000$ psi
60	1524.0	-0.053	-0.048	



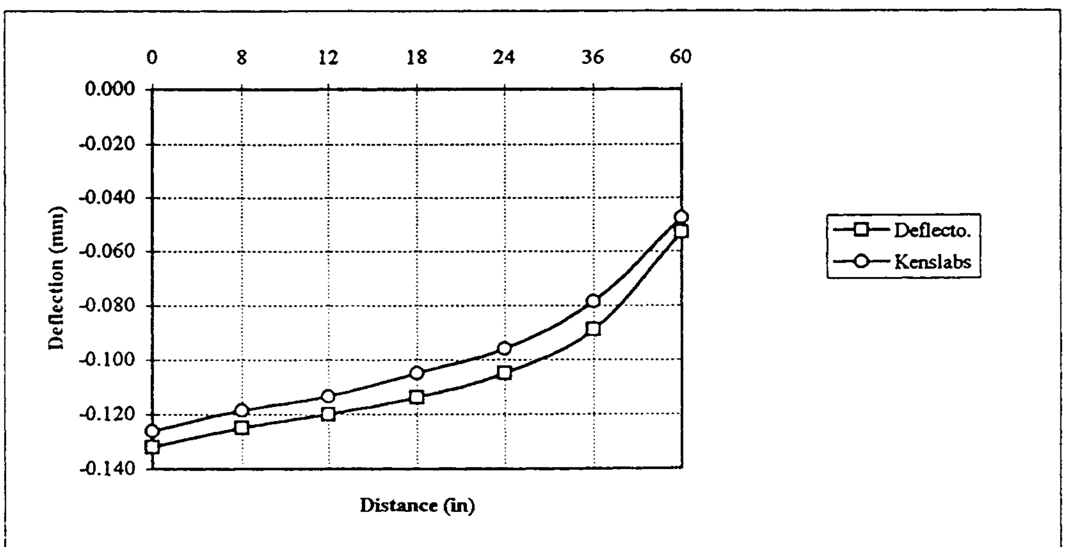
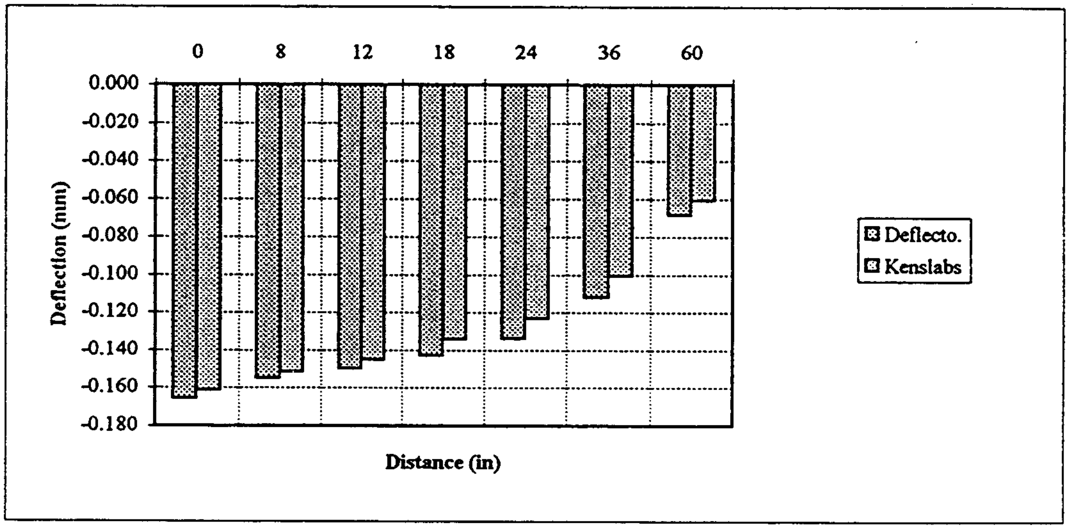


Fig 11.17 Best-Fit Deflection Profile for Section 7 (569 kPa)

Section 7: 100 % RCA Concrete Load: 729 kPa (11,949 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.166	-0.162	
8	203.2	-0.155	-0.152	
12	304.8	-0.150	-0.145	$E_{CONCRETE} = 4.42 \times 10^6$ psi
18	457.2	-0.143	-0.134	$E_{RED\ SOIL} = 32{,}000$ psi
24	609.6	-0.134	-0.123	$E_{UCF\ SOIL} = 27{,}000$ psi
36	914.4	-0.112	-0.101	$E_{SUBGRADE} = 25{,}000$ psi
60	1524.0	-0.069	-0.061	



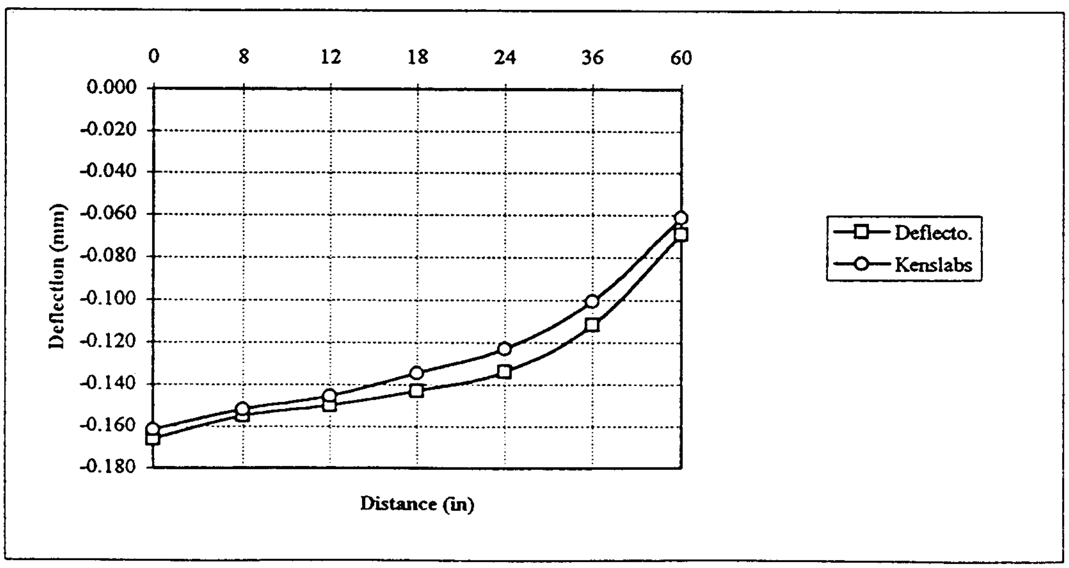
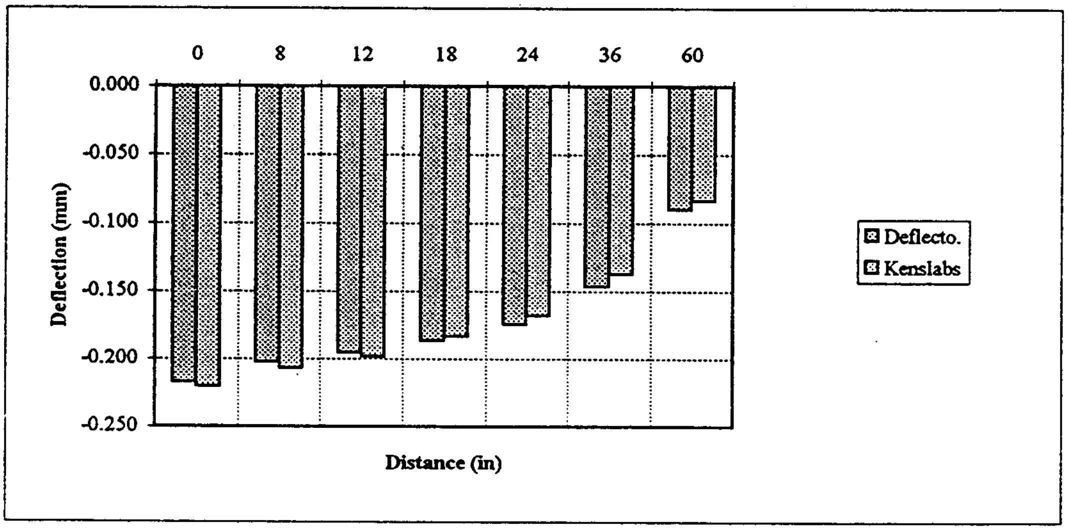


Fig 11.18 Best-Fit Deflection Profile for Section 7 (729 kPa)

Section 7: 100 % RCA Concrete Load: 996 kPa (16,325 lbs)					
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program	
0	0.0	-0.218	-0.221		
8	203.2	-0.203	-0.208		
12	304.8	-0.196	-0.199	$E_{CONCRETE} = 4.42 \times 10^6$ psi	
18	457.2	-0.187	-0.184	$E_{RED\ SOIL} = 32{,}000$ psi	
24	609.6	-0.175	-0.168	$E_{UCF\ SOIL} = 27{,}000$ psi	
36	914.4	-0.147	-0.138	$E_{SUBGRADE} = 25{,}000$ psi	
60	1524.0	-0.090	-0.083		



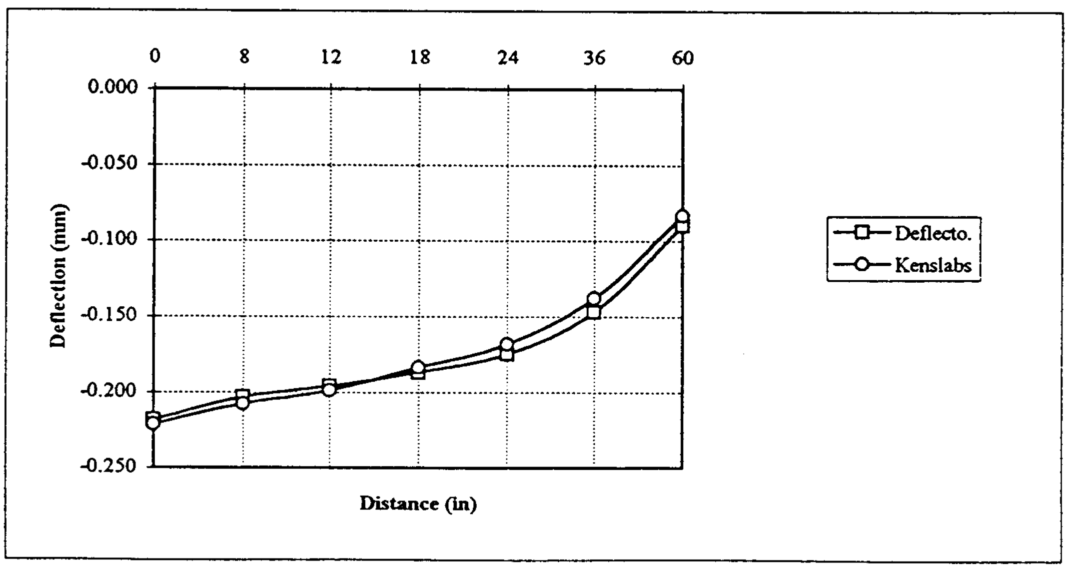
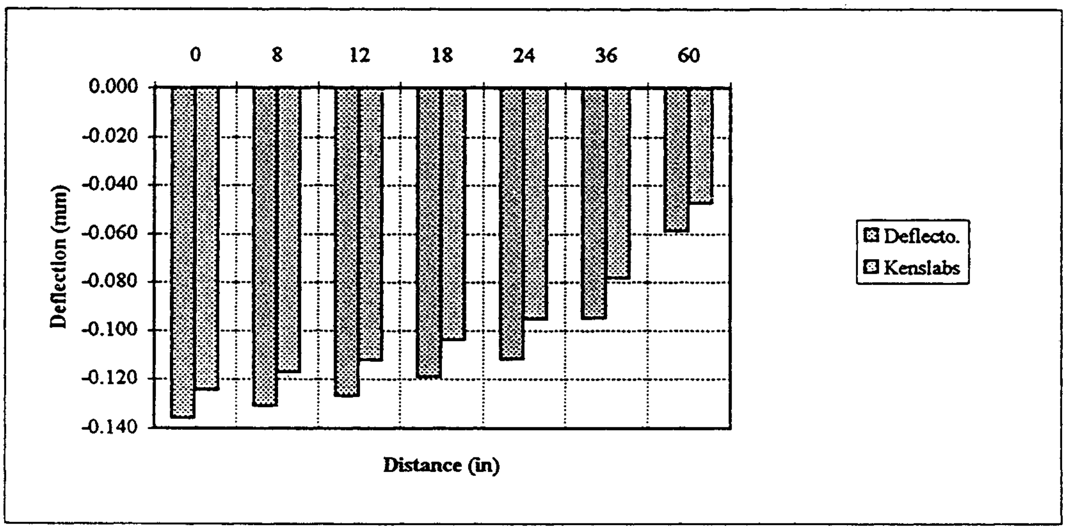


Fig 11.19 Best-Fit Deflection Profile for Section 7 (996 kPa)

Section 8: 75 % RCA + 25 % VA Concrete Load: 568 kPa (9,310 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.136	-0.125	
8	203.2	-0.131	-0.117	
12	304.8	-0.127	-0.112	$E_{CONCRETE} = 4.64 \times 10^6$ psi
18	457.2	-0.119	-0.104	$E_{RED\ SOIL} = 32{,}000$ psi
24	609.6	-0.112	-0.095	$E_{UCF\ SOIL} = 27{,}000$ psi
36	914.4	-0.095	-0.078	$E_{SUBGRADE} = 25{,}000$ psi
60	1524.0	-0.059	-0.048	



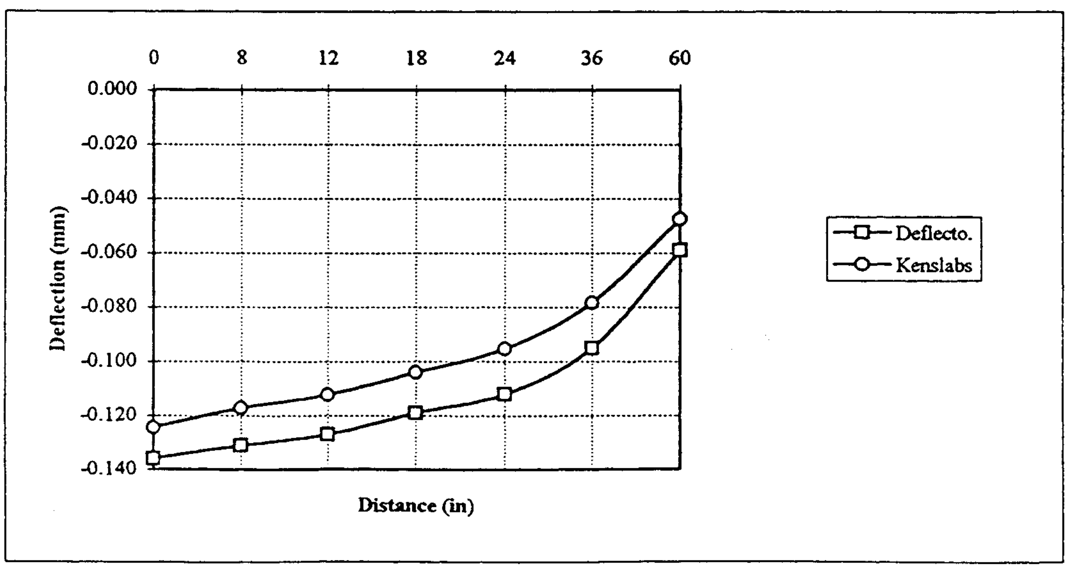
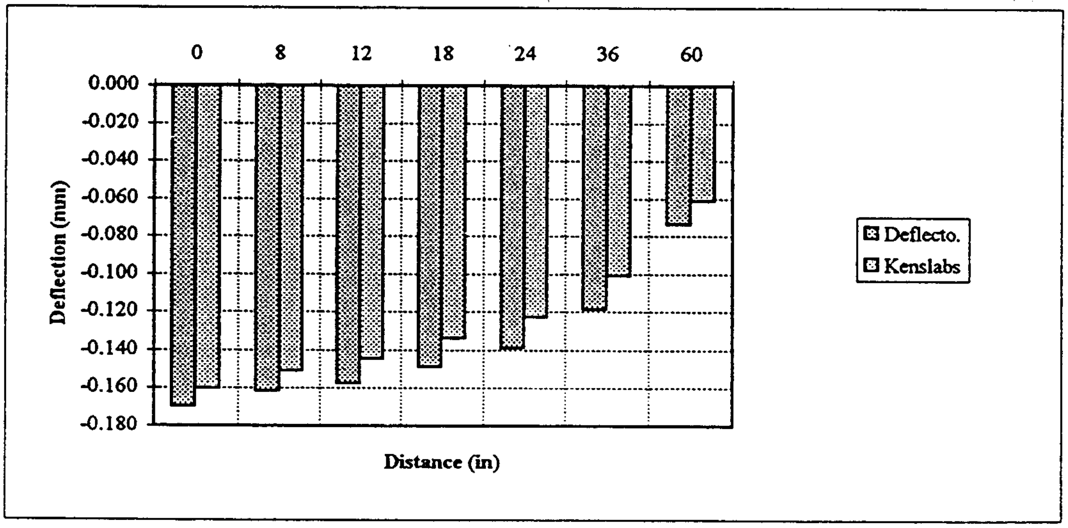


Fig 11.20 Best-Fit Deflection Profile for Section 8 (568 kPa)

Section 8: 75 % RCA + 25 % VA Concrete Load: 732 kPa (11,998 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.170	-0.161	
8	203.2	-0.162	-0.151	
12	304.8	-0.158	-0.145	$E_{CONCRETE} = 4.64 \times 10^6$ psi
18	457.2	-0.149	-0.134	$E_{RED\ SOIL} = 32{,}000$ psi
24	609.6	-0.139	-0.123	$E_{UCF\ SOIL} = 27{,}000$ psi
36	914.4	-0.119	-0.101	$E_{SUBGRADE} = 25{,}000$ psi
60	1524.0	-0.074	-0.061	



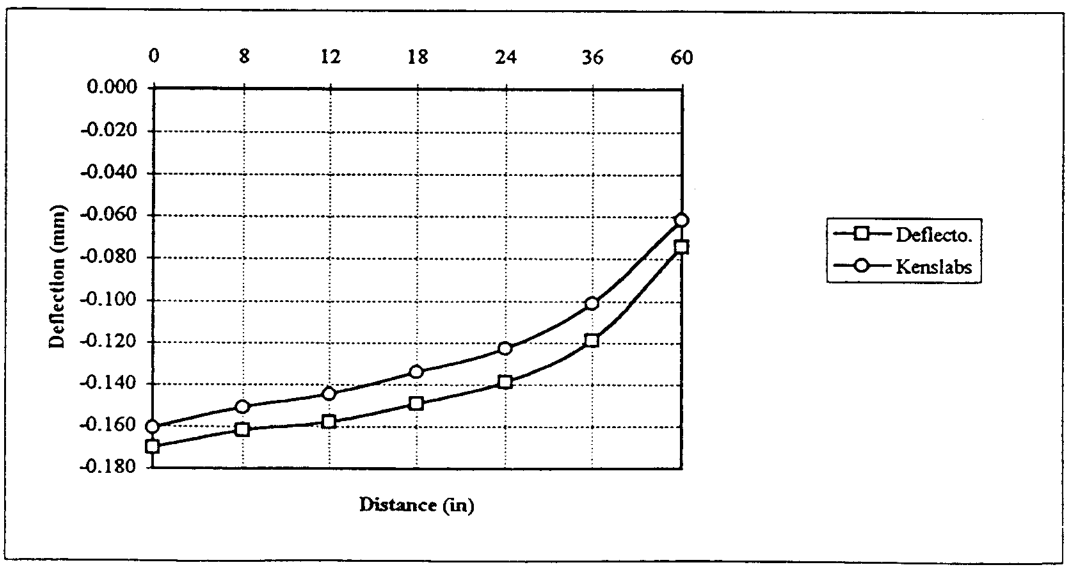
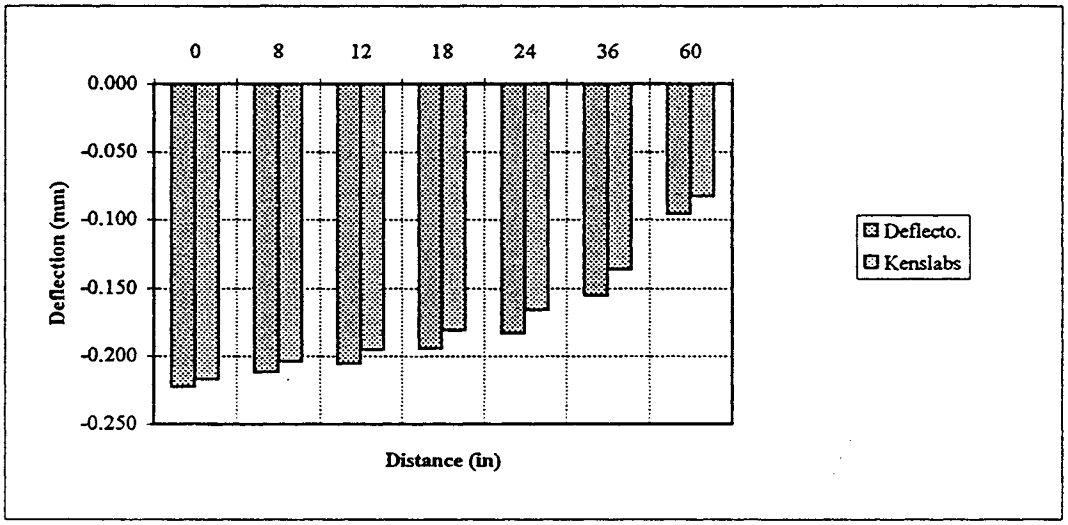


Fig 11.21 Best-Fit Deflection Profile for Section 8 (732 kPa)

Section 8: 75 % RCA + 25 % VA Concrete Load: 990 kPa (16,227 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.223	-0.217	
8	203.2	-0.212	-0.204	
12	304.8	-0.206	-0.196	$E_{CONCRETE} = 4.64 \times 10^6$ psi
18	457.2	-0.195	-0.181	$E_{RED\ SOIL} = 32{,}000$ psi
24	609.6	-0.184	-0.166	$E_{UCF\ SOIL} = 27{,}000$ psi
36	914.4	-0.156	-0.136	$E_{SUBGRADE} = 25{,}000$ psi
60	1524.0	-0.096	-0.083	



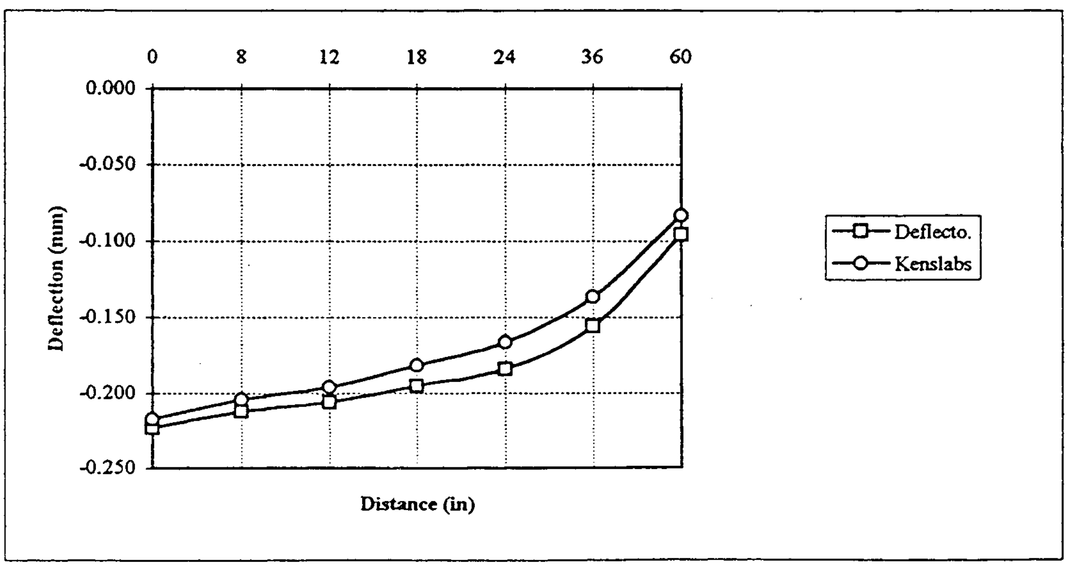
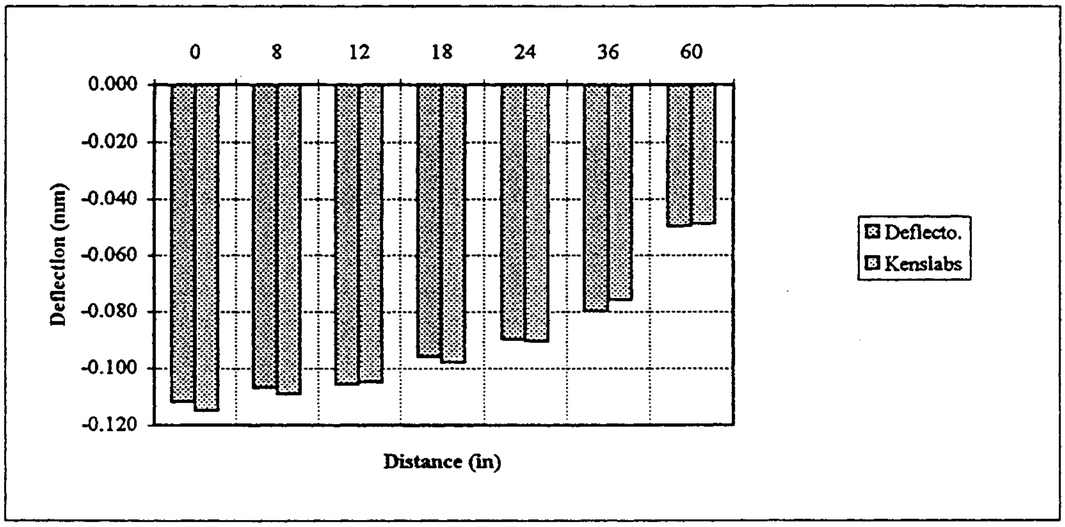


Fig 11.22 Best-Fit Deflection Profile for Section 8 (990 kPa)

Section 9: 100 % VA Concrete with RCA Base Course 254 mm (10 in) Load: 575 kPa (9,425 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.112	-0.115	
8	203.2	-0.107	-0.109	
12	304.8	-0.106	-0.105	$E_{CONCRETE} = 5.17 \times 10^6$ psi
18	457.2	-0.096	-0.098	$E_{RCA} = 100{,}000$ psi
24	609.6	-0.090	-0.091	$E_{UCF\ SOIL} = 27{,}000$ psi
36	914.4	-0.080	-0.076	$E_{SUBGRADE} = 25{,}000$ psi
60	1524.0	-0.050	-0.049	



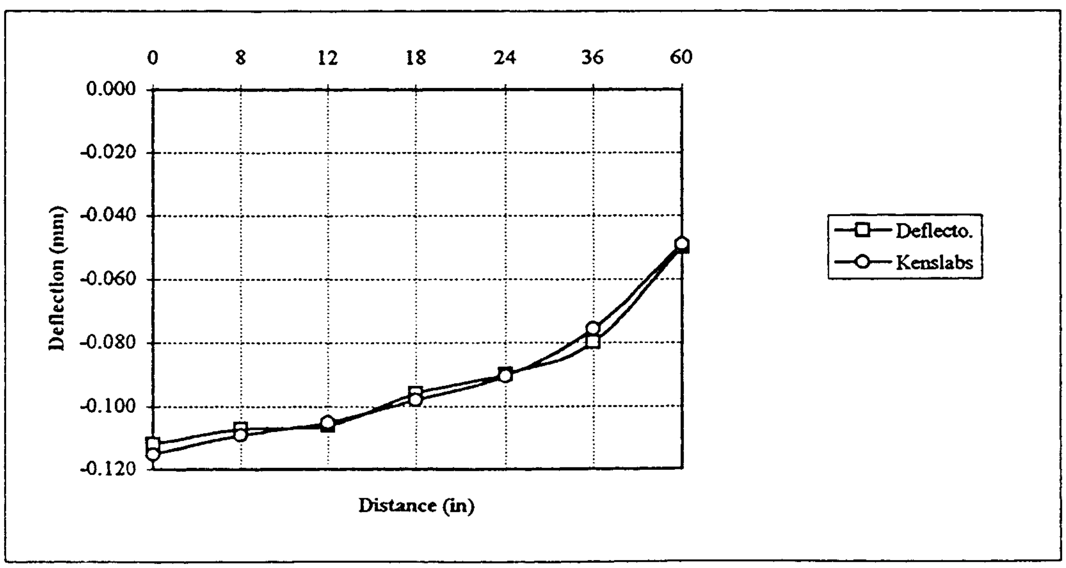
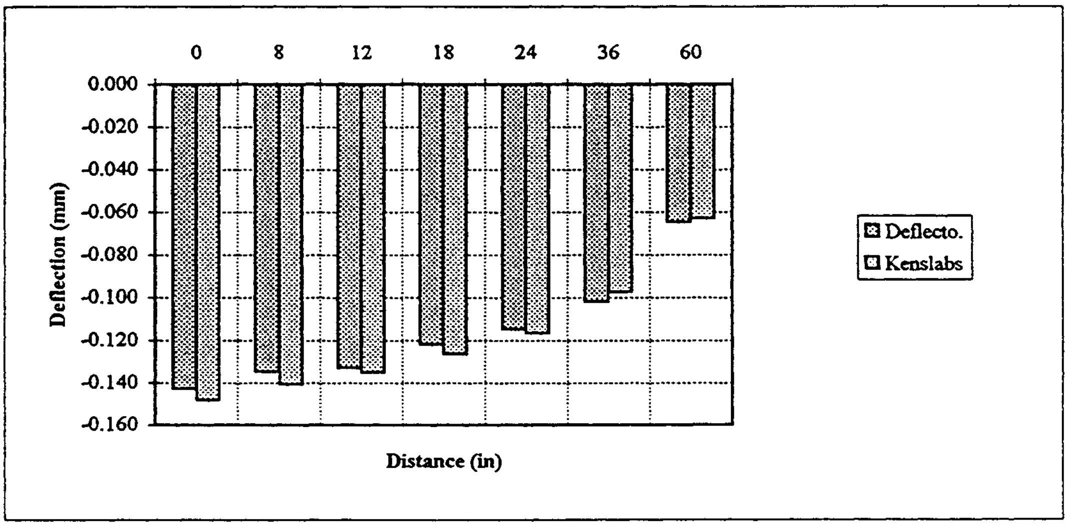


Fig 11.23 Best-Fit Deflection Profile for Section 9 (5875kPa)

Section 9: 100 % VA Concrete with RCA Base Course 254 mm (10 in) Load: 741 kPa (12,146 lbs)					
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenslabs Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program
0	0.0	-0.143	-0.148	
8	203.2	-0.135	-0.141	
12	304.8	-0.133	-0.135	$E_{CONCRETE} = 5.17 \times 10^6$ psi
18	457.2	-0.122	-0.126	E_{RCA} = 100,000 psi
24	609.6	-0.115	-0.117	$E_{UCF\ SOIL}$ = 27,000 psi
36	914.4	-0.102	-0.098	$E_{SUBGRADE}$ = 25,000 psi
60	1524.0	-0.065	-0.063	



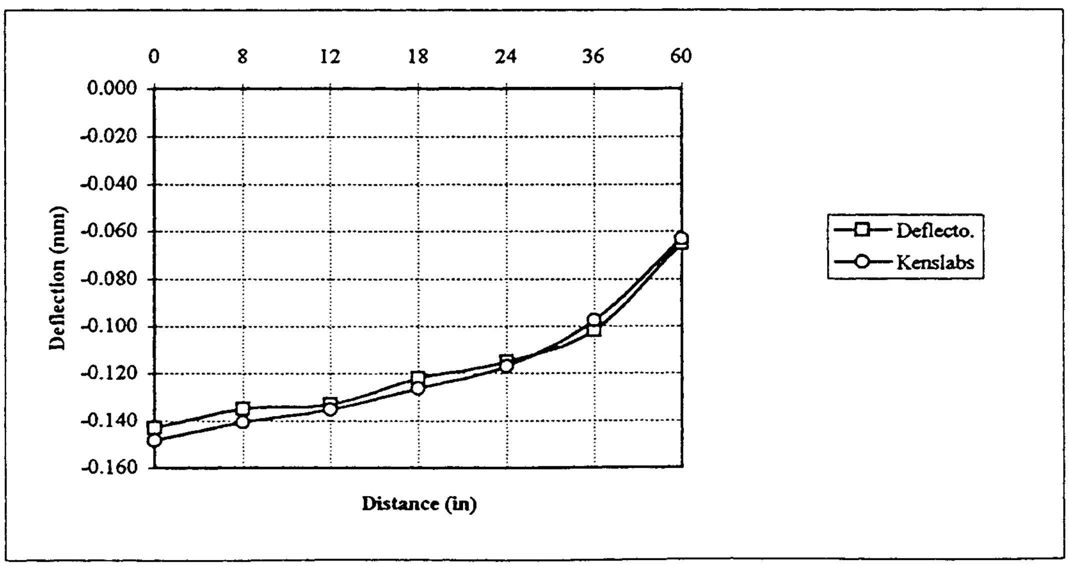


Fig 11.24 Best-Fit Deflection Profile for Section 9 (741 kPa)

<table>
<tr><th colspan="5">Section 9: 100 % VA Concrete with RCA Base Course 254 mm (10 in)
Load: 989 kPa (16,210 lbs)</th></tr>
<tr><td colspan="2">Horizontal Distance From Point of Load Application
(in) (mm)</td><td>Deflectometer Deflection
(mm)</td><td>Kenslabs Program
(mm)</td><td>Modulus of Elasticity Input Values for Deflection Calculation in KENSLABS Computer Program</td></tr>
<tr><td>0</td><td>0.0</td><td>-0.186</td><td>-0.198</td><td rowspan="7">$E_{CONCRETE}$ = 5.17 x 10^6 psi
E_{RCA} = 100,000 psi
$E_{UCF\ SOIL}$ = 27,000 psi
$E_{SUBGRADE}$ = 25,000 psi</td></tr>
<tr><td>8</td><td>203.2</td><td>-0.177</td><td>-0.188</td></tr>
<tr><td>12</td><td>304.8</td><td>-0.172</td><td>-0.181</td></tr>
<tr><td>18</td><td>457.2</td><td>-0.162</td><td>-0.169</td></tr>
<tr><td>24</td><td>609.6</td><td>-0.153</td><td>-0.156</td></tr>
<tr><td>36</td><td>914.4</td><td>-0.133</td><td>-0.130</td></tr>
<tr><td>60</td><td>1524.0</td><td>-0.087</td><td>-0.084</td></tr>
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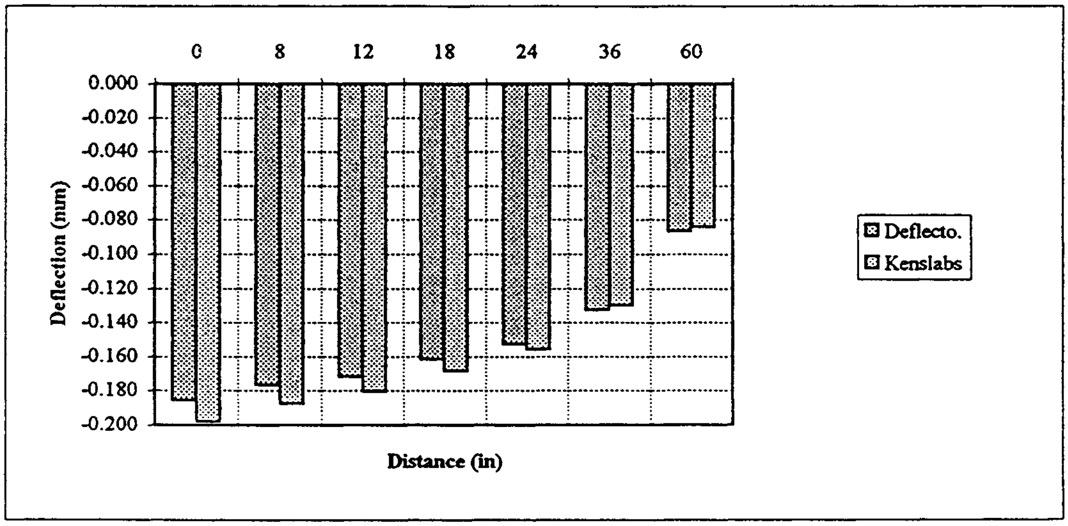


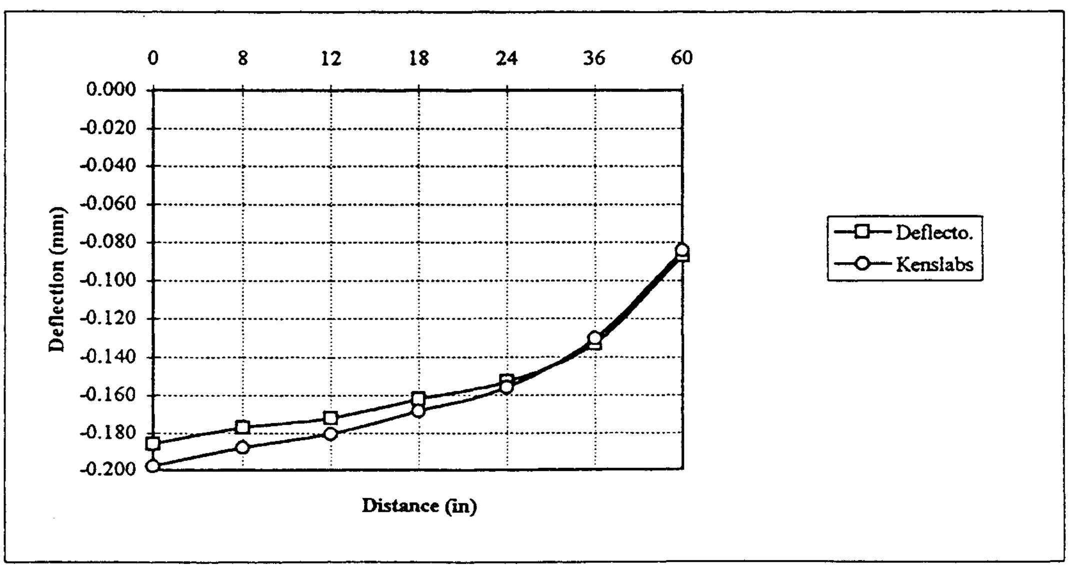


Fig 11.25 Best-Fit Deflection Profile for Section 9 (989 kPa)

Fatigue Analysis of Rigid Pavement

The same finite element layout was used to determine the flexural stress of each slab. This model, a 1.83 x 3.66 m (6 x 12 ft) section, had a dual-tire load applied to a pre-calculated tire contact area at its center as shown in Figure 11.26. The tire contact area was calculated based on the Portland Cement Association (PCA) method for the foot print of the tire on pavements. This method assumes that each tire carries a load that is uniformly distributed over a rectangular contact area.

The wheel load applied by the UCF-CATT represents the Florida legal axle load of 98 kN (22,000 lbs), or a half axle of 49 kN (11,000 lbs). Each tire carries an assumed equal load of 24.5 kN (5,500 lbs) as shown in Figure 11.27. Knowing that the tire pressure was kept constant at 759 kPa (110 psi), the area of tire contact can be calculated by dividing the wheel load by the tire pressure, resulting in 323 cm^2 (50 in^2). The dimensions of the rectangle were then calculated by the equations from PCA:

$$AREA = 0.5227 * L^2 \quad (5)$$

$$LENGTH = 0.8712 * L \quad (6)$$

$$WIDTH = 0.6 * L \quad (7)$$

The results yielded:

Length : 217 mm (8.53 in)
Width : 149 mm (5.87 in)

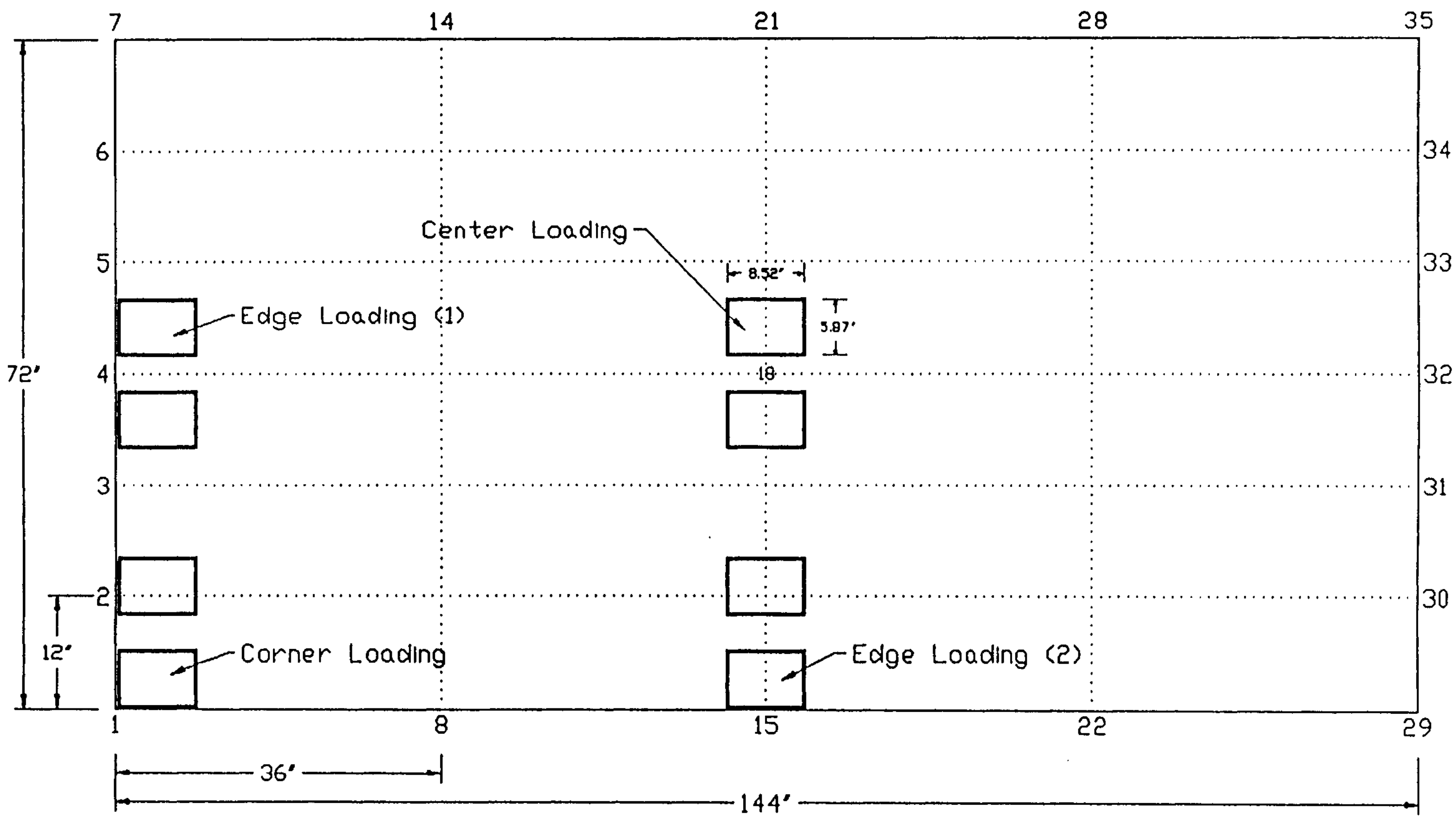


Fig 11.26 Dual Wheel Finite Element Model for KENSLABS

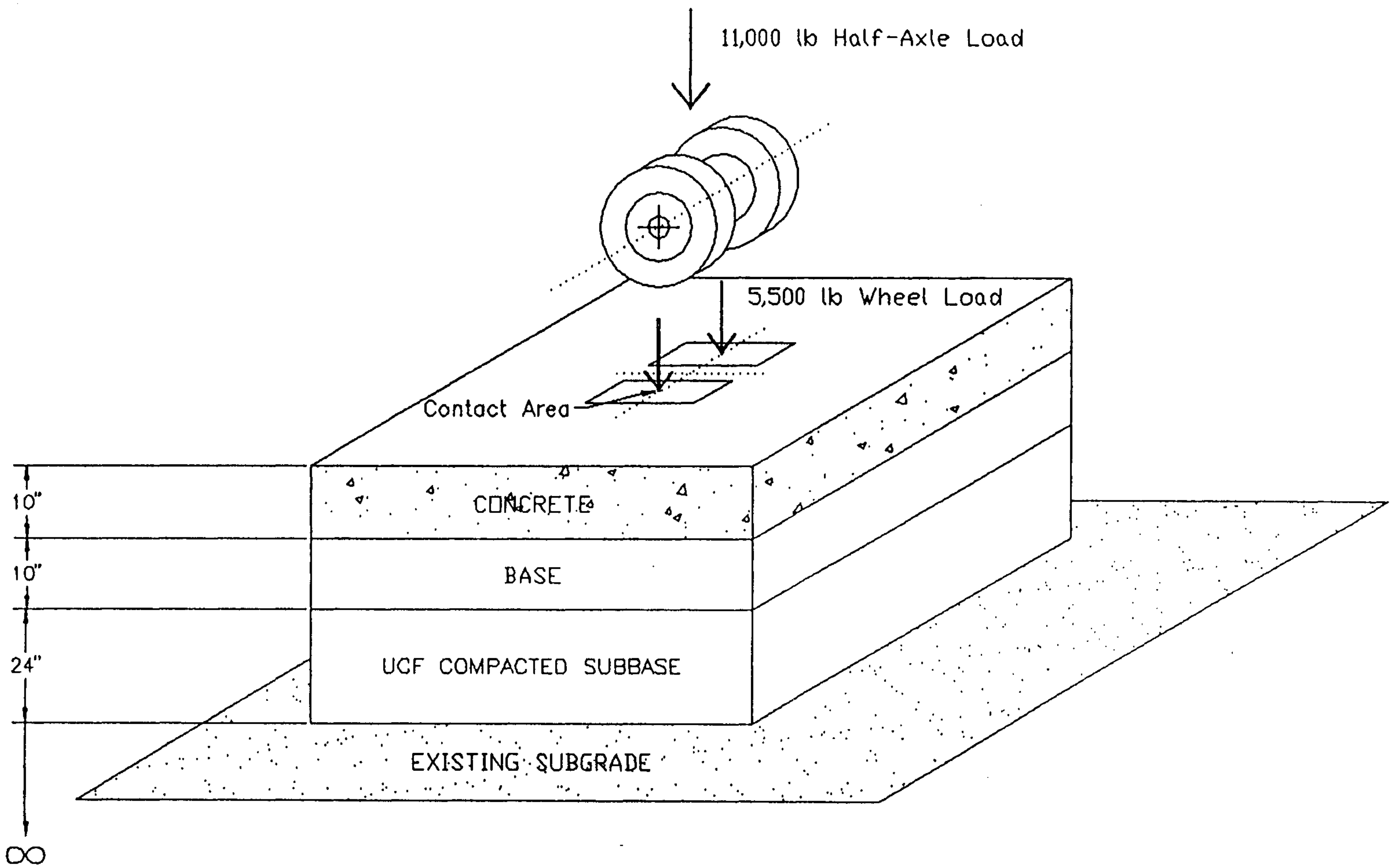


Fig 11.27 Half-Axle Load on Concrete Slab

By transferring the known input parameter data to the KENSLABS program; wheel load, tire contact areas, layer dimensions, modulus of each layer, the maximum flexural stresses at the center, edge, and corner of each concrete slab were calculated. The results are shown in Table 11.1. From all test sections, it is revealed that the maximum stresses at the bottom of the slab were located in the middle of the contact areas from the center and corner loading, and at nodes 4 and 1 of the edge loading. Notice that the Edge Load (1) and Edge Load (2) are two different locations, as seen in Figure 11.26. A typical KENSLABS output file can be found in Appendix B.

TABLE 11.1 Maximum Flexural Stresses Determined by KENSLABS Program

Rigid Test Section	Center Load σ_{MAX} (psi)	Edge Load (1) σ_{MAX} (psi)	Corner Load σ_{MAX} (psi)	Edge Load (2) σ_{MAX} (psi)
Section 5	109	224	234	167
Section 6	111	224	235	170
Section 7	106	224	234	161
Section 8	107	224	234	164
Section 9	105	174	117	150

The fatigue equations for concrete pavement slabs used by the PCA are presented as follows:

$$\text{For } \sigma/S_c \geq 0.55: \ \log N_f = 11.737 - 12.077 * (\sigma/Sc) \quad (8)$$

$$\text{For } 0.45 < \sigma/S_c < 0.55: \ N_f = \left[\frac{4.2577}{\left(\frac{\sigma}{Sc}\right) - 0.4325}\right]^{3.26} \quad (9)$$

$$\text{For } \sigma/S_c \leq 0.45 : \; N_f = \text{unlimited} \tag{10}$$

where N_f = allowable number of repetitions

σ = flexural stress in the slab

S_c = modulus of rupture of concrete

The ratio of flexural stress from each loading mechanism over the modulus of rupture are listed in Table 11.2. The modulus of rupture of concrete from each section were obtained from laboratory tests as given in Table 4.11 in Chapter 4.

TABLE 11.2 Ratio of Flexural Stress Over Modulus of Rupture

Rigid Test Section	S_c (psi)	σ_{CENTER}/S_c	$\sigma_{EDGE\,(1)}/S_c$	σ_{CORNER}/S_c	$\sigma_{EDGE\,(2)}/S_c$
Section 5	720	0.151	0.311	0.325	0.232
Section 6	749	0.148	0.299	0.314	0.227
Section 7	605	0.175	0.370	0.387	0.266
Section 8	653	0.164	0.343	0.358	0.251
Section 9	749	0.140	0.232	0.156	0.200

Since the σ/S_c ratios for all sections are less than 0.45 from any loading as shown in Table 11.2, it implies that the RCA and VA concrete pavement sections tested at the UCF-CATT can theoretically withstand an unlimited number of 49 kN (11,000 lb) wheel load repetitions. In other words, there will be no failure to any of the concrete sections by fatigue cracking, which is defined as transverse cracks across the slab induced by edge loading or longitudinal cracks along the wheel path induced by joint loading. Cracks developed in the concrete slab will allow water to reach the base and subgrade courses. With the repeated passing of heavy traffic loads, a mixture of water and base material will be ejected to the surface, called pumping, thus leaving voids underneath the slab and eventually resulting in large portions of the slab breaking off. Pumping is a very common occurrence in concrete pavement.

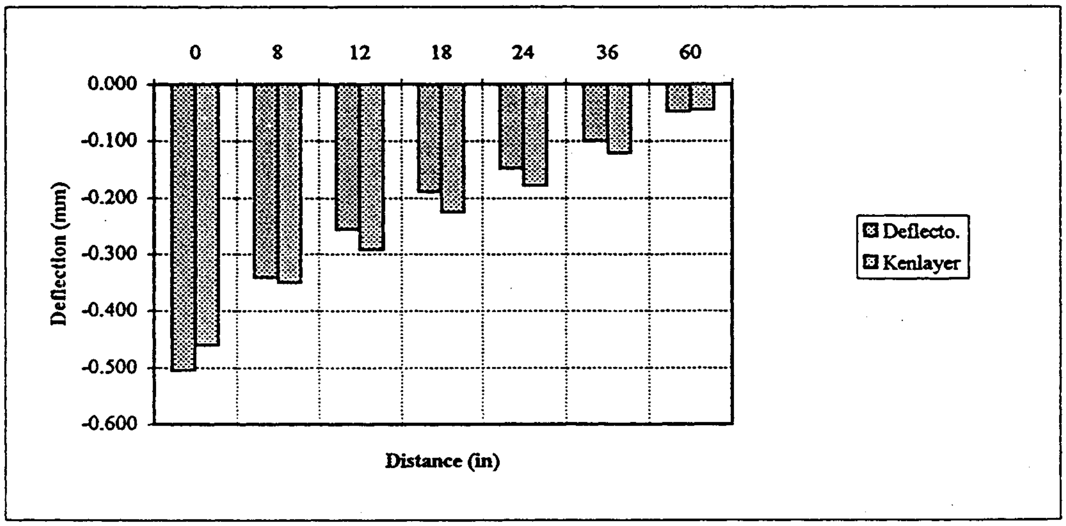
Back-Calculation of In-situ Elastic Modulus Using KENLAYER

One of the useful applications of nondestructive testing (NDT) is to back-calculate the moduli of pavement components, including the subgrade. The procedure is based on measuring the deflection basin by varying the set of moduli until a best match between the computed and measured FWD deflections is obtained. The KENLAYER computer software (Huang, 1992) was designed to analyze flexible pavements that do not have joints or rigid layers as part of their structure. The program is capable of examining circular loaded areas (single, dual, dual-tandem, or dual-tridem wheels) on multi-layered systems that have either elastic, non-elastic, or visco-elastic behaviors. The backbone of KENLAYER is the solution for an elastic multilayer system under a circular loaded area. The solutions are superimposed for multiple wheels. The damage caused by fatigue cracking and permanent deformation can be calculated to evaluate the design life.

As was the case with KENSLABS and the rigid pavement, KENLAYER was employed to try to back-calculate the modulus of elasticity of the RCA base material placed on sections 1 through 4 by using the load-deflection data obtained from the FWD test. The same layout of Figure 11.10 was applied by KENLAYER to try to best-fit the deflection basins of Figures 11.1through 11.4. After trials with numerous combinations of the modulus values, the moduli of the layered components that best fit the deflection basin of sections 1 through 4 (Figures 11.28 through 11.39) were found to be: for E_{RCA} = 690 MPa (100,000 psi). Figures 11.28 through 11.39 illustrate the accuracy of the best-fit execution. A typical KENLAYER program output file can be found in Appendix B.

To check the exactness of this value, the deflections of section 9 were calculated by programming E_{RCA} into KENSLABS, since this section also contained RCA as a base material. The vertical displacements obtained were then compared to the FWD test data and as can be seen from Figures 11.23 through 11.25, the values are almost identical. The deflection change ranges between $\Delta = 0.001 - 0.012$ mm ($3.94 \times 10^{-5} - 4.72 \times 10^{-4}$ in) for an error below 5 %.

Section 1: RCA Base Course 254 mm (10 in) Load: 547 kPa (8,966 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.506	-0.461	
8	203.2	-0.342	-0.352	
12	304.8	-0.258	-0.293	E_{HMA} = 375,000 psi
18	457.2	-0.190	-0.226	E_{RCA} = 100,000 psi
24	609.6	-0.149	-0.179	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.101	-0.122	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.049	-0.046	$E_{SUBGRADE}$ = 25,000 psi



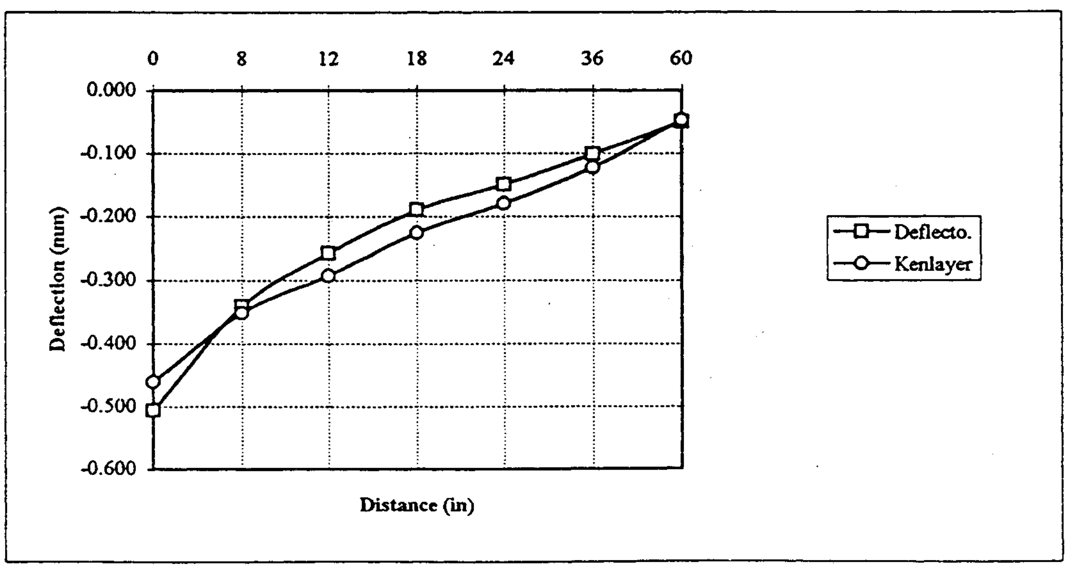
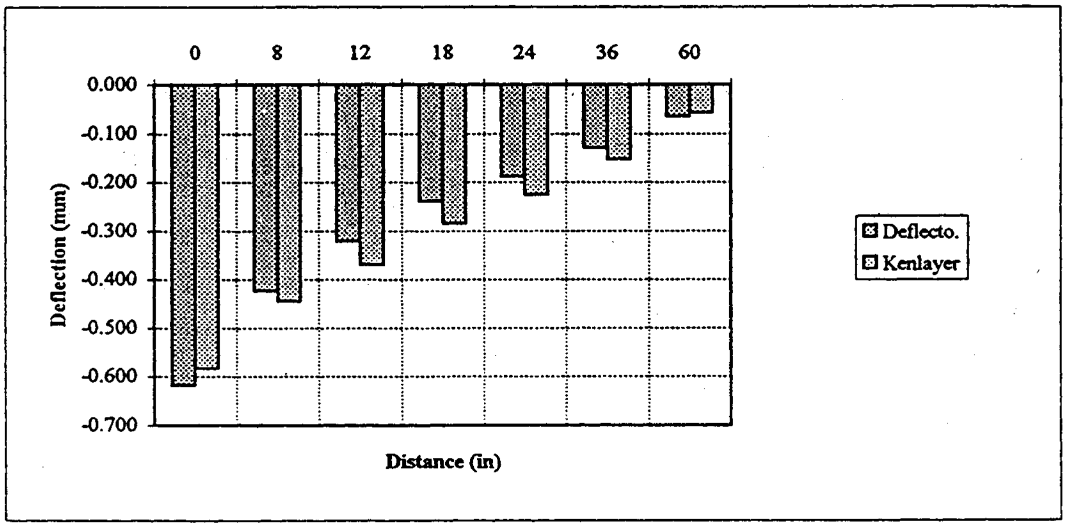


Fig 11.28 Best-Fit Deflection Profile for Section 1 (547 kPa)

Section 1: RCA Base Course 254 mm (10 in) Load: 693 kPa (11,359 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.619	-0.583	
8	203.2	-0.424	-0.445	
12	304.8	-0.322	-0.371	E_{HMA} = 375,000 psi
18	457.2	-0.240	-0.286	E_{RCA} = 100,000 psi
24	609.6	-0.189	-0.227	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.131	-0.154	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.066	-0.058	$E_{SUBGRADE}$ = 25,000 psi



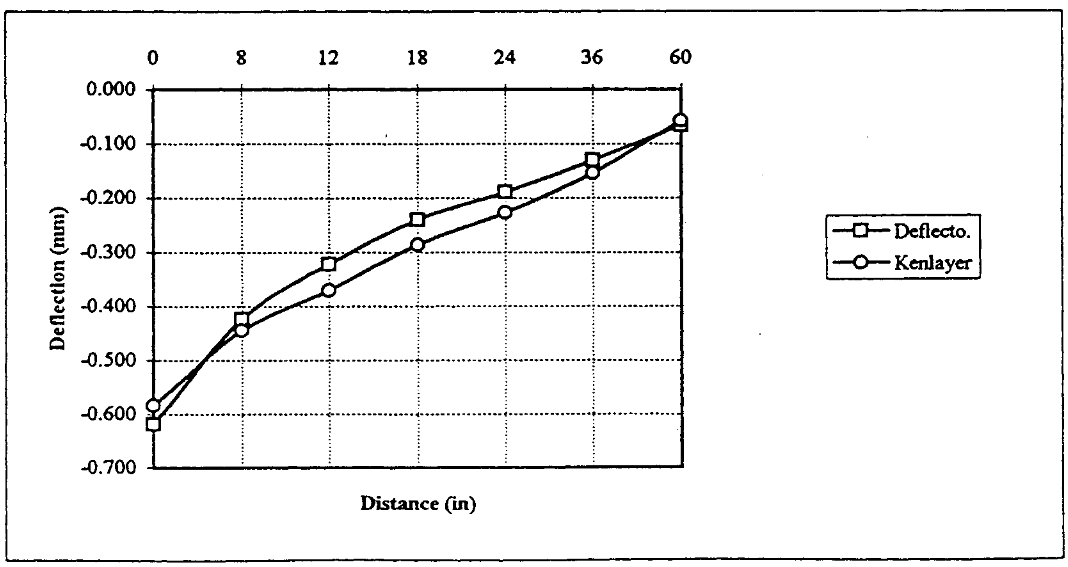
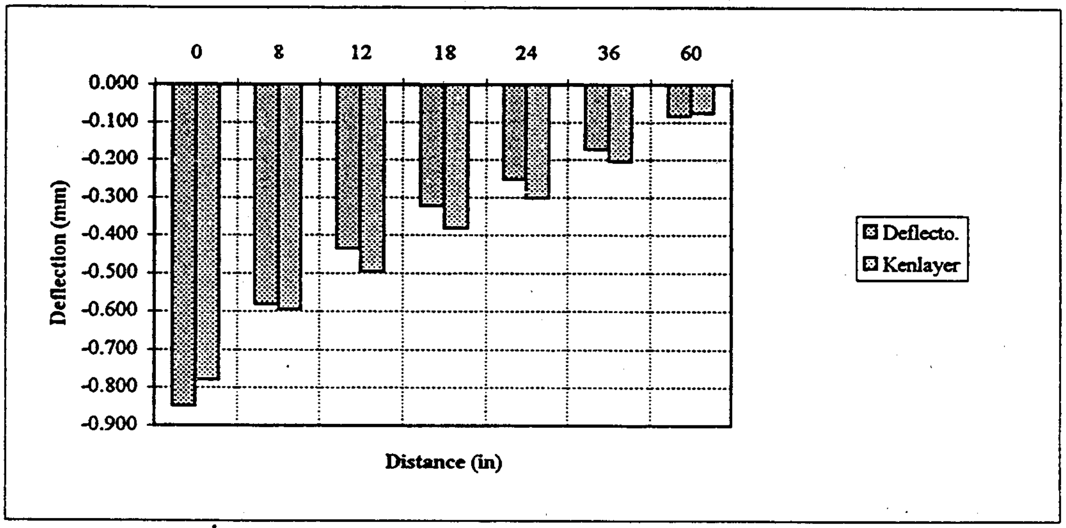


Fig 11.29 Best-Fit Deflection Profile for Section 1 (693 kPa)

Section 1: RCA Base Course 254 mm (10 in) Load: 925 kPa (15,162 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.850	-0.781	
8	203.2	-0.582	-0.596	
12	304.8	-0.437	-0.497	E_{HMA} = 375,000 psi
18	457.2	-0.324	-0.384	E_{RCA} = 100,000 psi
24	609.6	-0.253	-0.304	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.174	-0.207	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.085	-0.078	$E_{SUBGRADE}$ = 25,000 psi



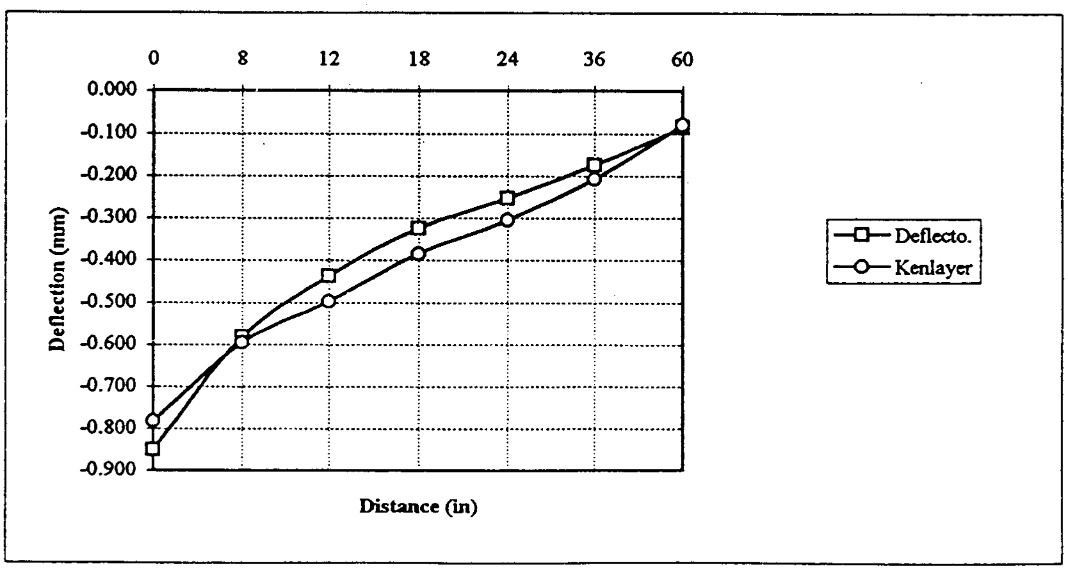
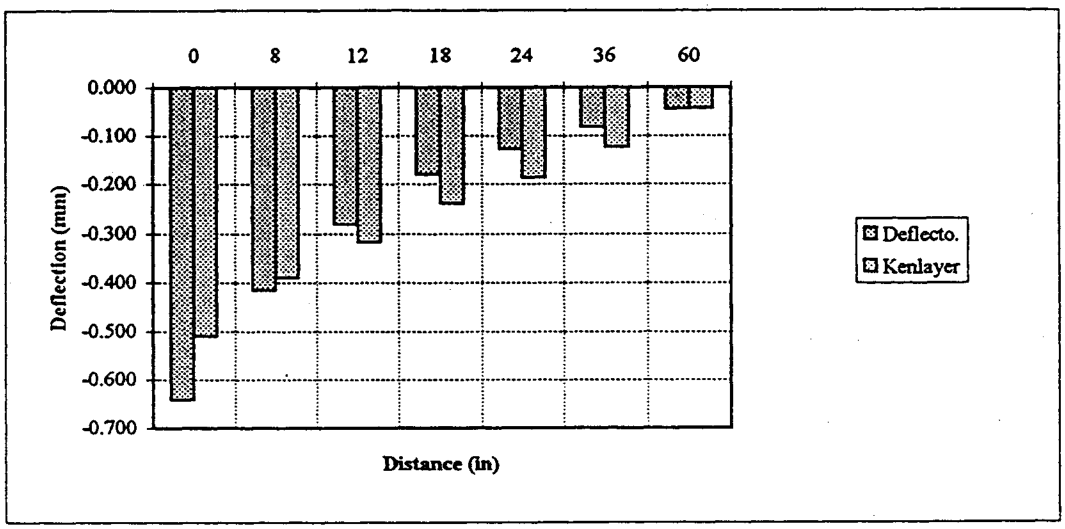


Fig 11.30 Best-Fit Deflection Profile for Section 1 (925 kPa)

Section 2: Limerock Base Course 203.2 mm (8 in) Load: 553 kPa (9,064 lbs)					
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.643	-0.510	
8	203.2	-0.416	-0.391	
12	304.8	-0.282	-0.319	E_{HMA} = 375,000 psi
18	457.2	-0.181	-0.241	$E_{LIMEROCK}$ = 120,000 psi
24	609.6	-0.129	-0.188	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.084	-0.126	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.046	-0.045	$E_{SUBGRADE}$ = 25,000 psi



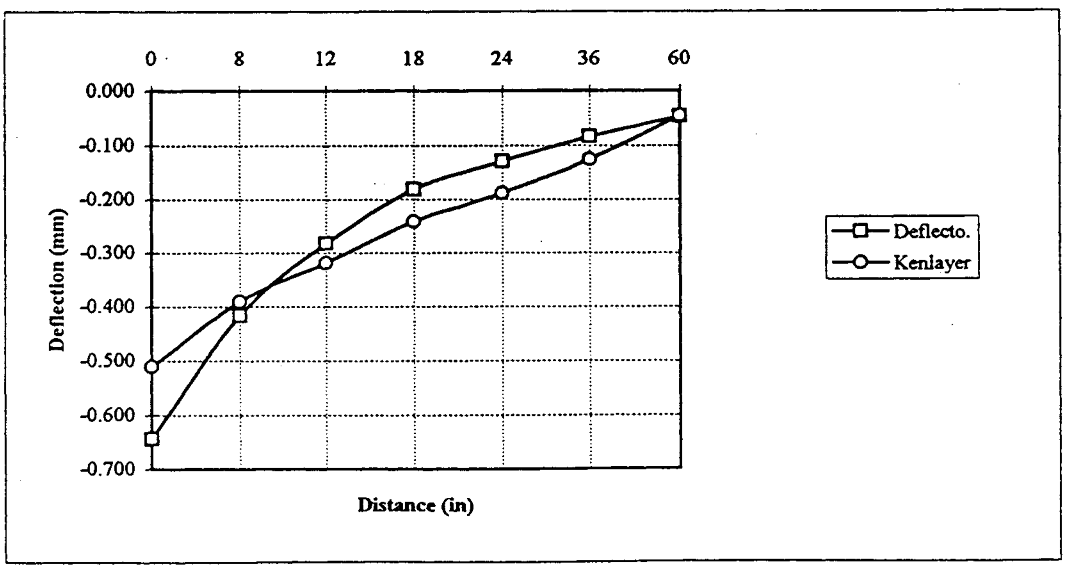
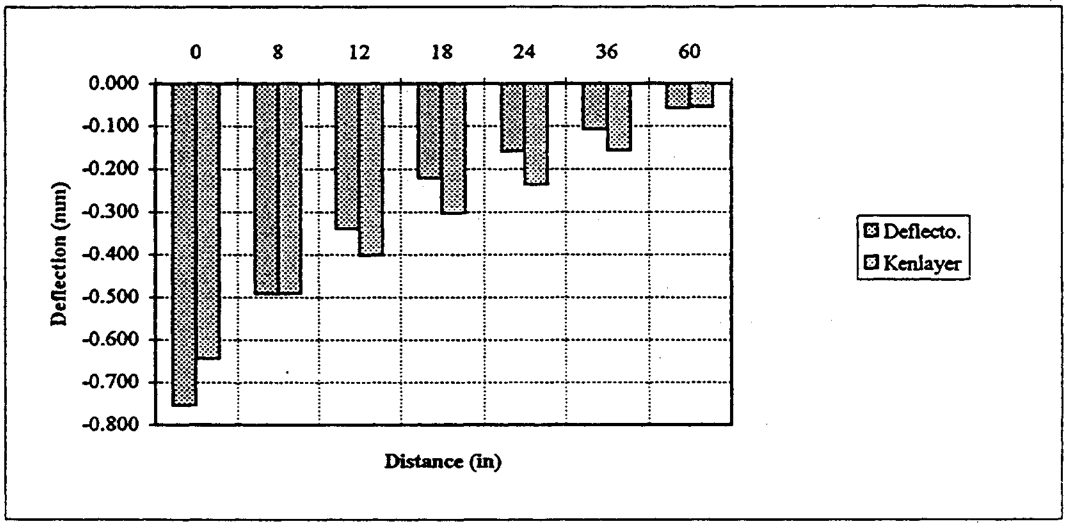


Fig 11.31 Best-Fit Deflection Profile for Section 2 (553 kPa)

Section 2: Limerock Base Course 203.2 mm (8 in) Load: 697 kPa (11,425 lbs)					
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program	
0	0.0	-0.755	-0.644		
8	203.2	-0.492	-0.493		
12	304.8	-0.340	-0.403	E_{HMA} = 375,000 psi	
18	457.2	-0.222	-0.304	$E_{LIMEROCK}$ = 120,000 psi	
24	609.6	-0.160	-0.237	$E_{RED\ SOIL}$ = 32,000 psi	
36	914.4	-0.109	-0.159	$E_{UCF\ SOIL}$ = 27,000 psi	
60	1524.0	-0.060	-0.056	$E_{SUBGRADE}$ = 25,000 psi	



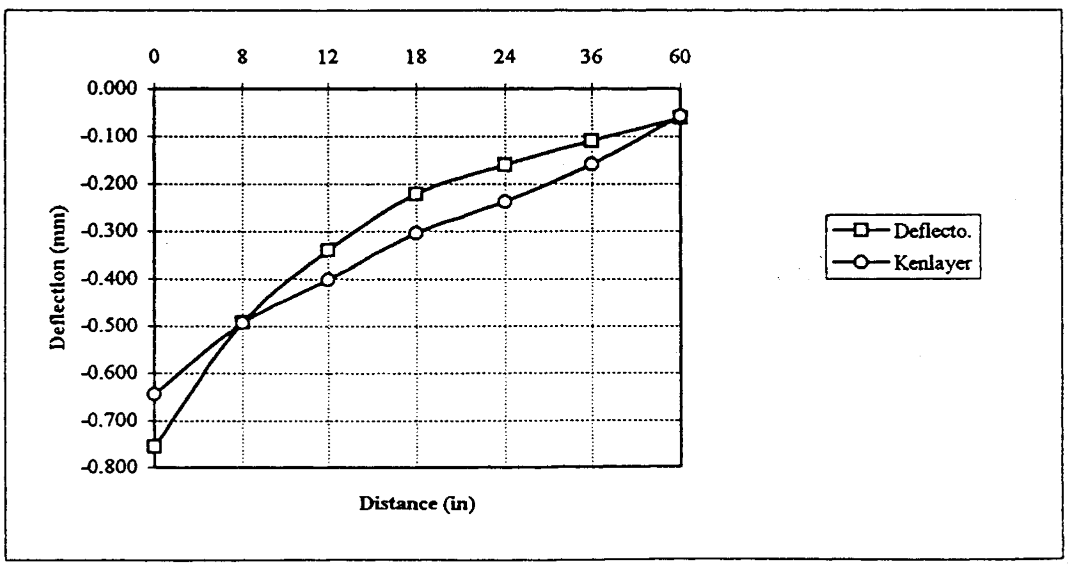
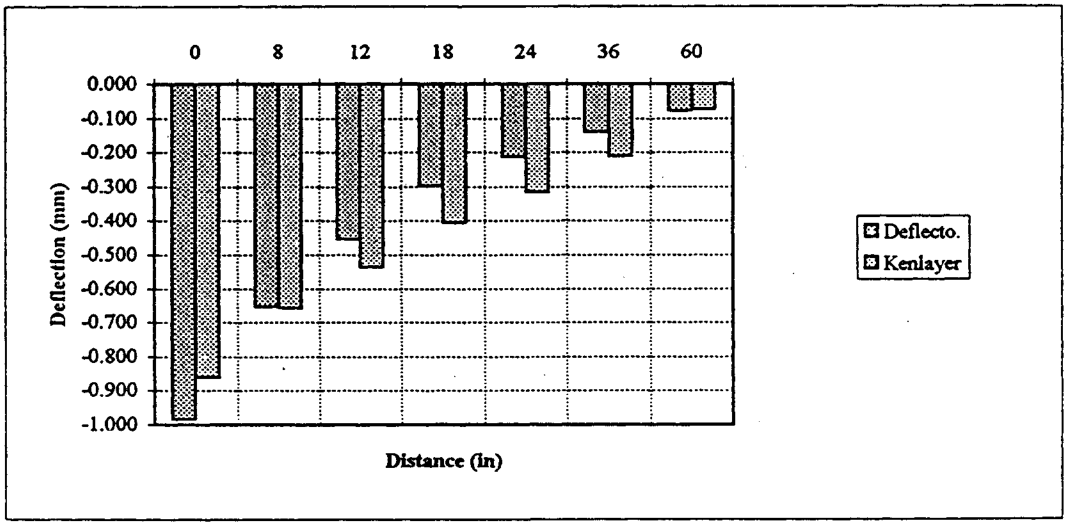


Fig 11.32 Best-Fit Deflection Profile for Section 2 (697 kPa)

Section 2: Limerock Base Course 203.2 mm (8 in) Load: 932 kPa (15,276 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.985	-0.861	
8	203.2	-0.655	-0.659	
12	304.8	-0.456	-0.538	E_{HMA} = 375,000 psi
18	457.2	-0.299	-0.406	$E_{LIMEROCK}$ = 120,000 psi
24	609.6	-0.215	-0.317	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.142	-0.212	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.080	-0.075	$E_{SUBGRADE}$ = 25,000 psi



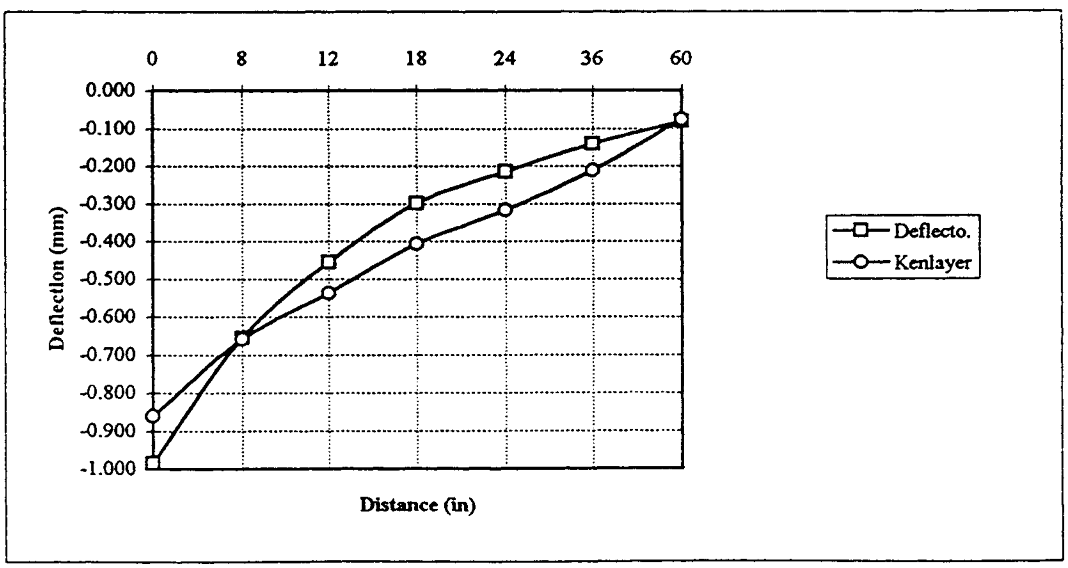
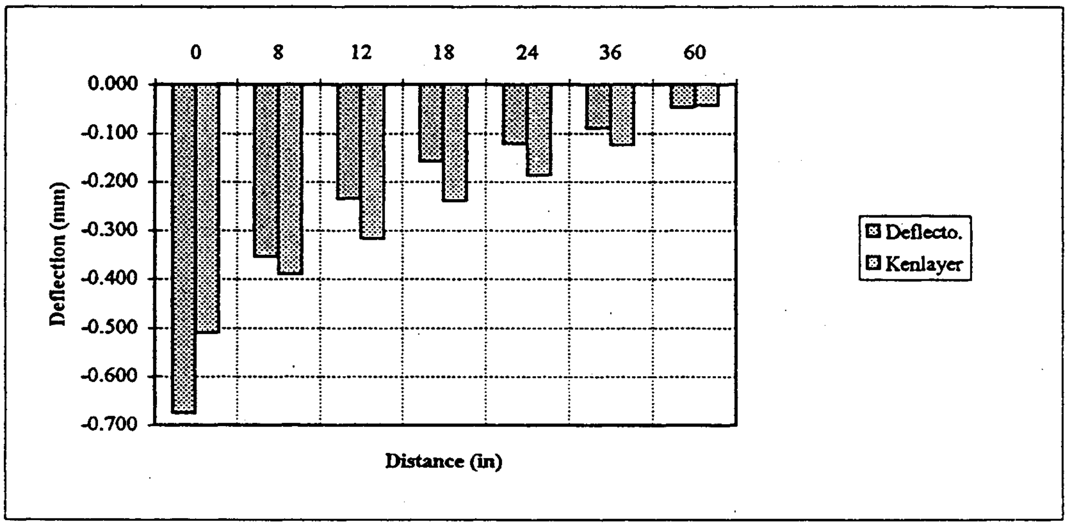


Fig 11.33 Best-Fit Deflection Profile for Section 2 (932 kPa)

Section 3: RCA Base Course 203.2 mm (8 in) Load: 552 kPa (9,048 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.677	-0.510	
8	203.2	-0.355	-0.391	
12	304.8	-0.236	-0.319	E_{HMA} = 375,000 psi
18	457.2	-0.159	-0.241	E_{RCA} = 100,000 psi
24	609.6	-0.123	-0.188	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.091	-0.126	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.048	-0.045	$E_{SUBGRADE}$ = 25,000 psi



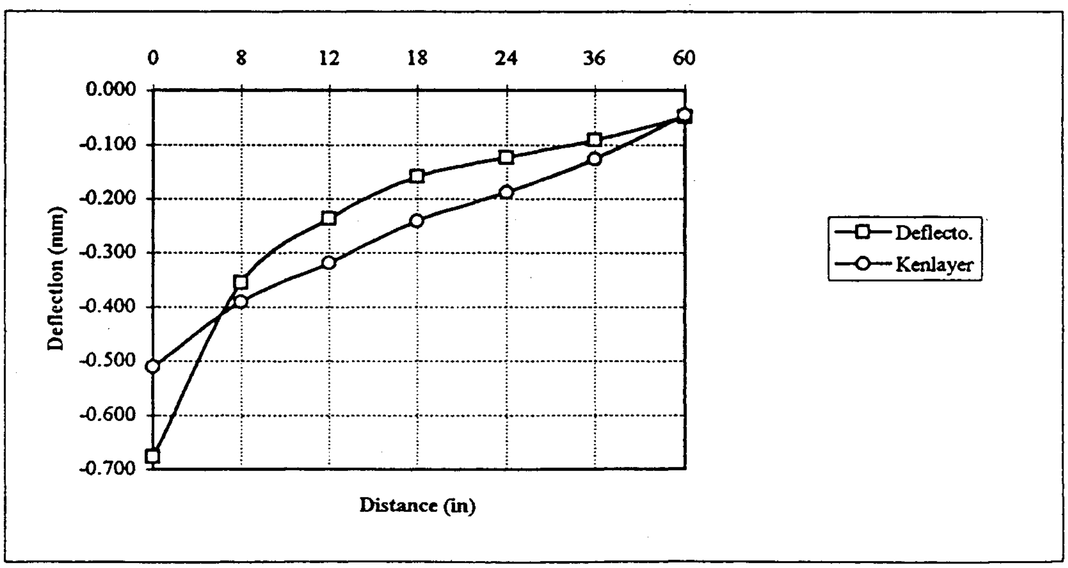
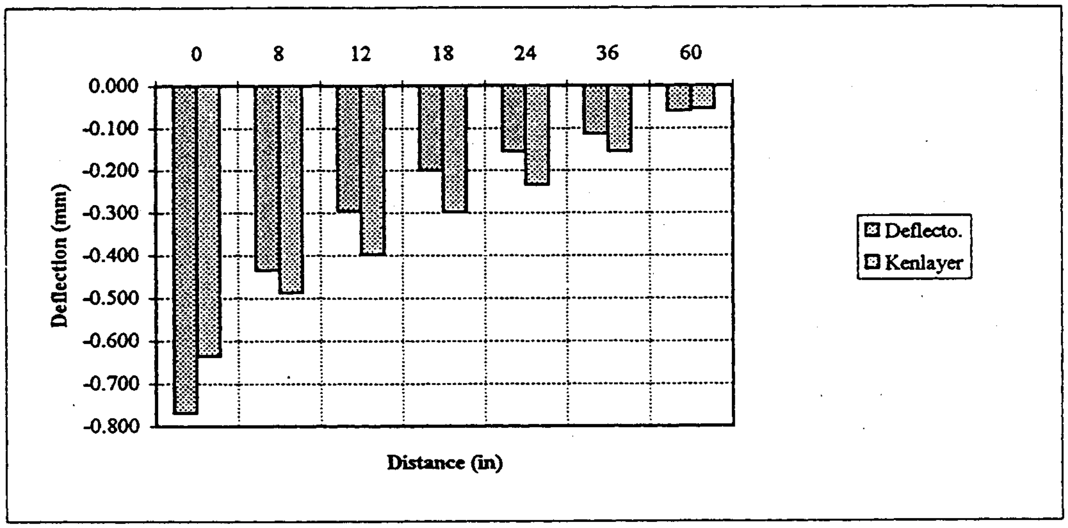


Fig 11.34 Best-Fit Deflection Profile for Section 3 (552kPa)

Section 3: RCA Base Course 203.2 mm (8 in) Load: 692 kPa (11,343 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.770	-0.638	
8	203.2	-0.436	-0.488	
12	304.8	-0.297	-0.399	E_{HMA} = 375,000 psi
18	457.2	-0.202	-0.301	E_{RCA} = 100,000 psi
24	609.6	-0.156	-0.235	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.115	-0.157	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.061	-0.056	$E_{SUBGRADE}$ = 25,000 psi



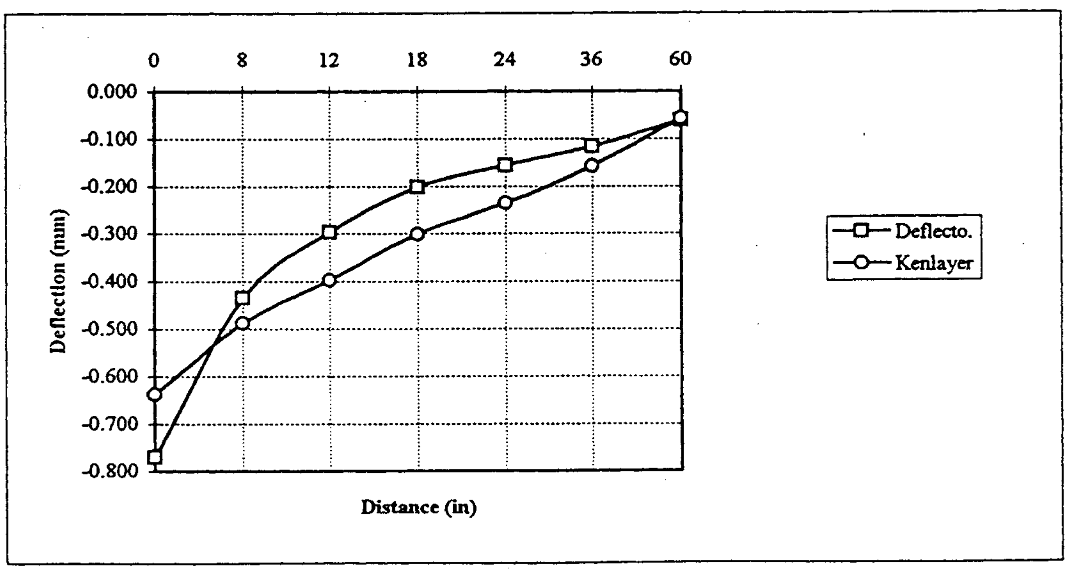
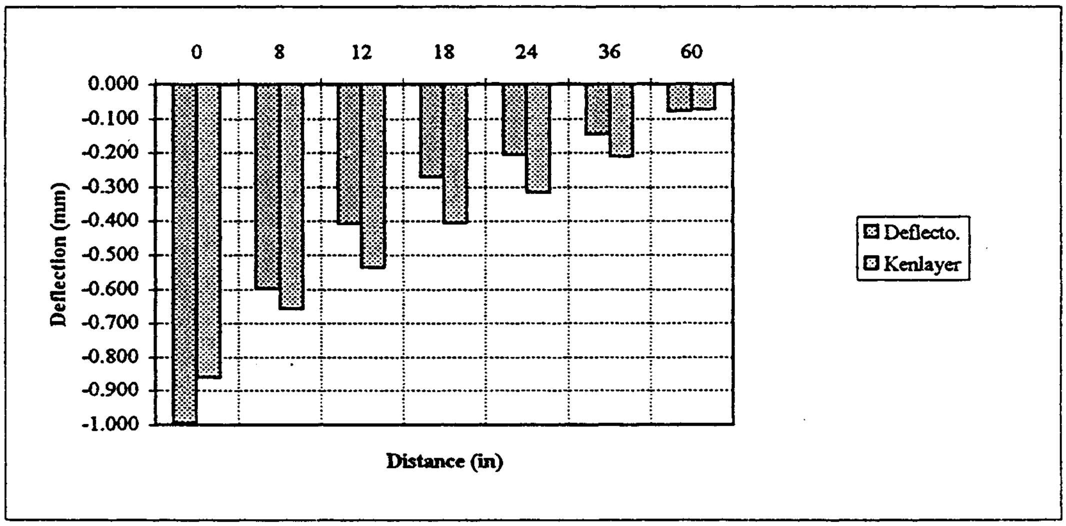


Fig 11.35 Best-Fit Deflection Profile for Section 3 (692 kPa)

Section 3: RCA Base Course 203.2 mm (8 in) Load: 929 kPa (15,227 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.997	-0.861	
8	203.2	-0.599	-0.659	
12	304.8	-0.408	-0.538	E_{HMA} = 375,000 psi
18	457.2	-0.272	-0.406	E_{RCA} = 100,000 psi
24	609.6	-0.208	-0.317	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.148	-0.212	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.080	-0.075	$E_{SUBGRADE}$ = 25,000 psi



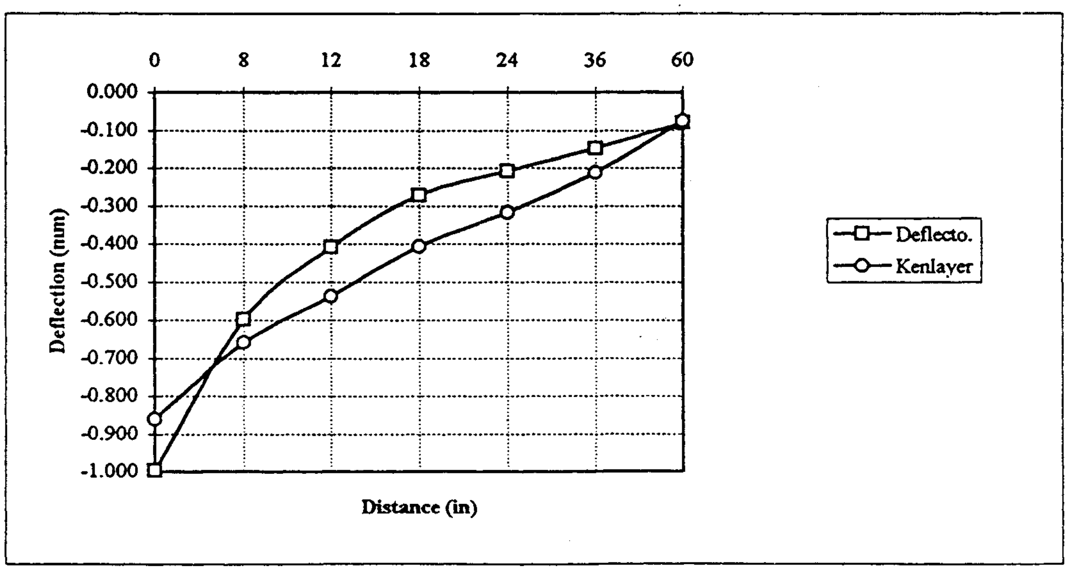
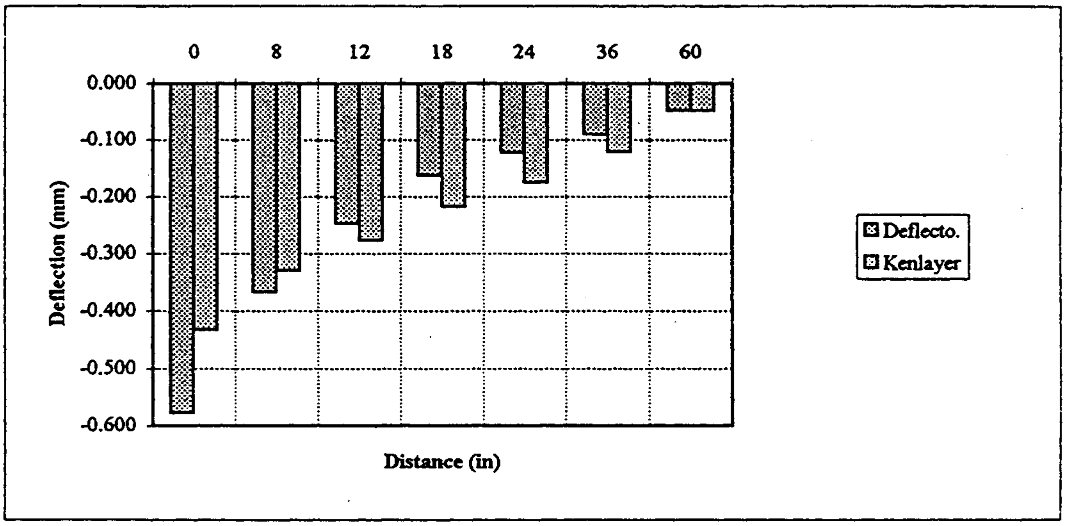


Fig 11.36 Best-Fit Deflection Profile for Section 3 (929 kPa)

Section 4: RCA Base Course 304.8 mm (12 in) Load: 556 kPa (9,113 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.579	-0.433	
8	203.2	-0.367	-0.330	
12	304.8	-0.249	-0.278	E_{HMA} = 375,000 psi
18	457.2	-0.163	-0.218	E_{RCA} = 100,000 psi
24	609.6	-0.123	-0.176	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.091	-0.122	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.048	-0.048	$E_{SUBGRADE}$ = 25,000 psi



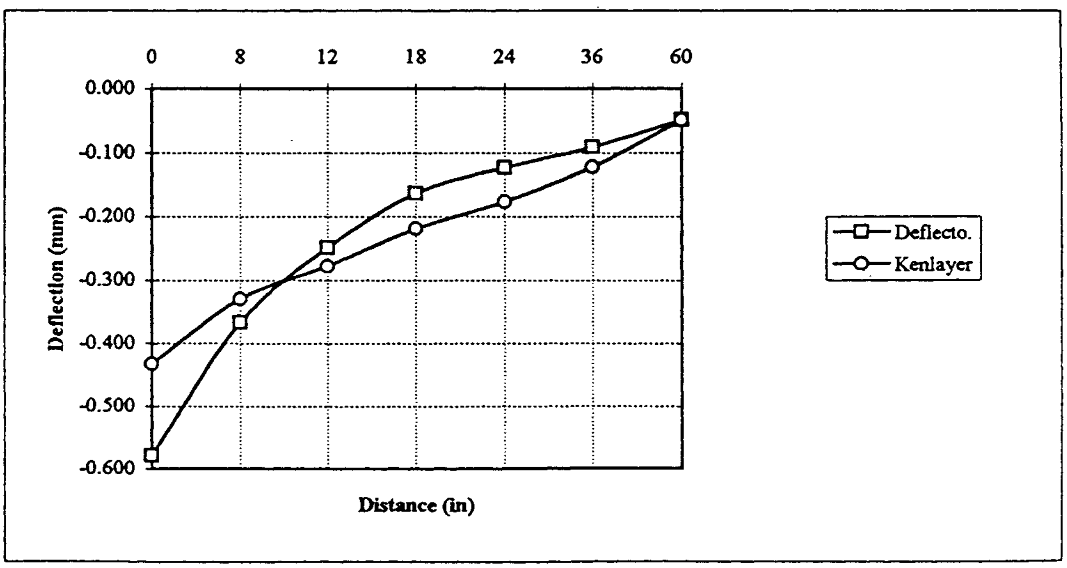
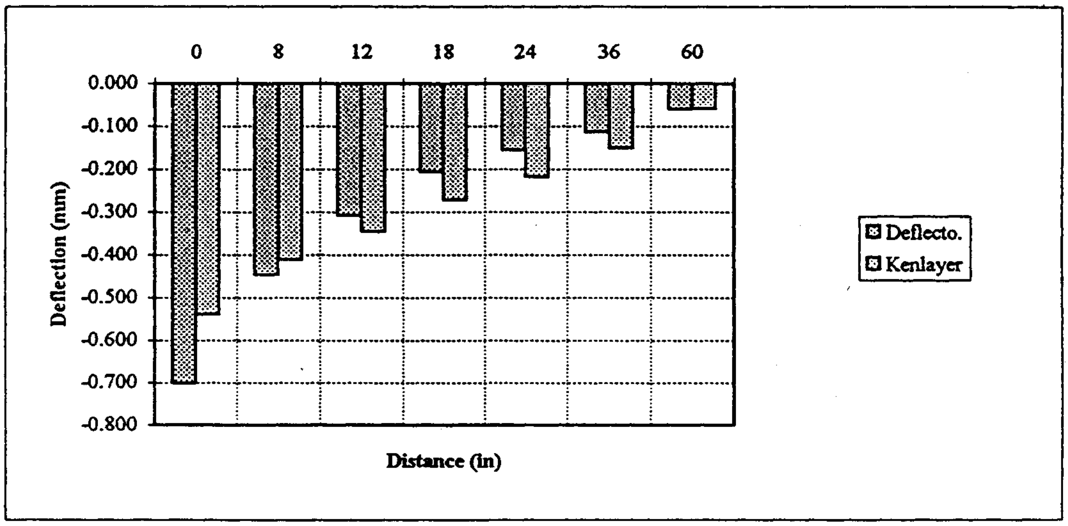


Fig 11.37 Best-Fit Deflection Profile for Section 4 (556 kPa)

Section 4: RCA Base Course 304.8 mm (12 in) Load: 696 kPa (11,408 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.703	-0.540	
8	203.2	-0.448	-0.412	
12	304.8	-0.309	-0.347	E_{HMA} = 375,000 psi
18	457.2	-0.207	-0.273	E_{RCA} = 100,000 psi
24	609.6	-0.156	-0.220	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.115	-0.152	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.061	-0.060	$E_{SUBGRADE}$ = 25,000 psi



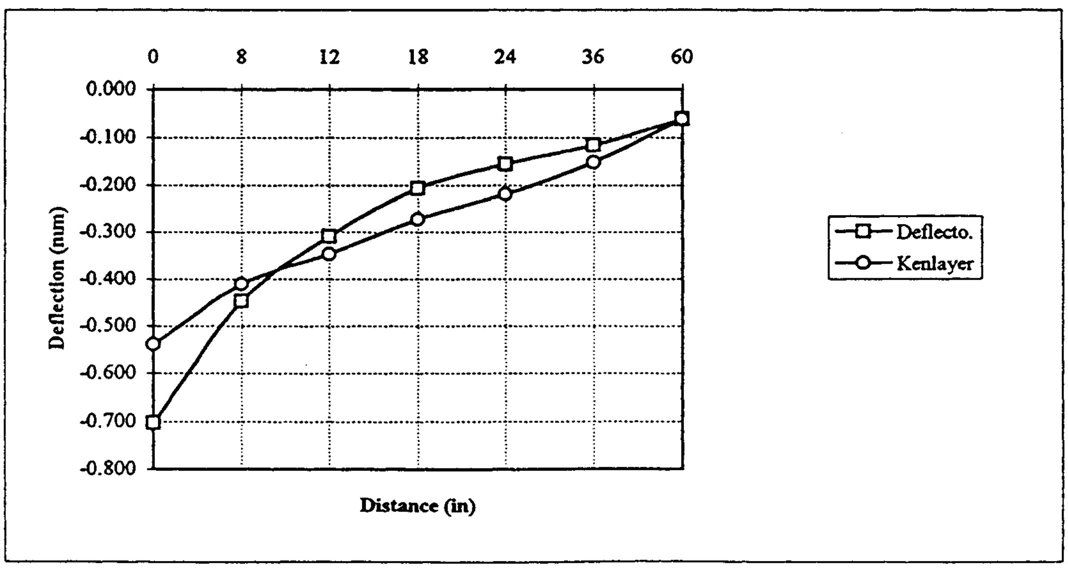
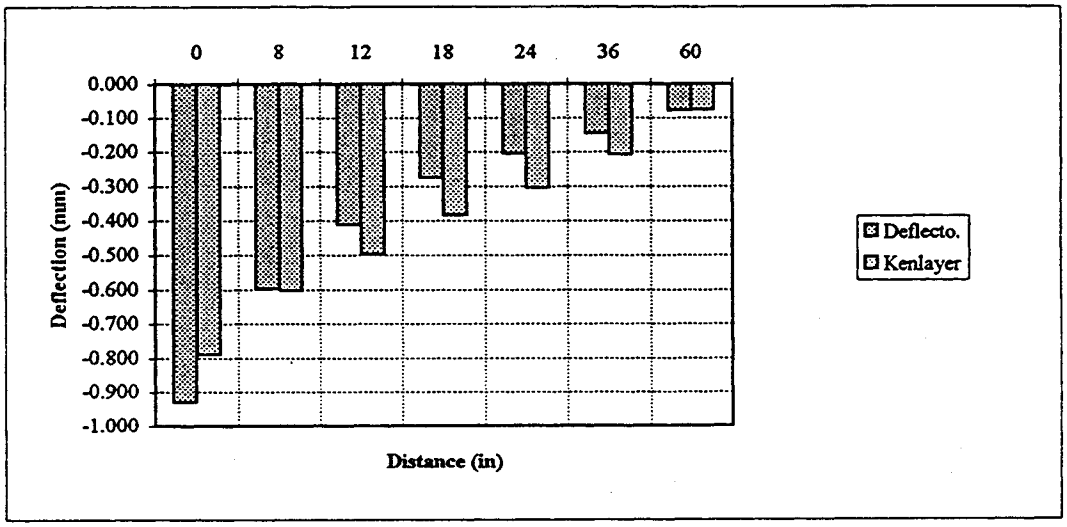


Fig 11.38 Best-Fit Deflection Profile for Section 4 (696 kPa)

Section 4: RCA Base Course 304.8 mm (12 in) Load: 938 kPa (15,375 lbs)				
Horizontal Distance From Point of Load Application (in)	(mm)	Deflectometer Deflection (mm)	Kenlayer Program (mm)	Modulus of Elasticity Input Values for Deflection Calculation in KENLAYER Computer Program
0	0.0	-0.931	-0.791	
8	203.2	-0.599	-0.604	
12	304.8	-0.412	-0.498	E_{HMA} = 375,000 psi
18	457.2	-0.276	-0.384	E_{RCA} = 100,000 psi
24	609.6	-0.208	-0.306	$E_{RED\ SOIL}$ = 32,000 psi
36	914.4	-0.148	-0.209	$E_{UCF\ SOIL}$ = 27,000 psi
60	1524.0	-0.080	-0.078	$E_{SUBGRADE}$ = 25,000 psi



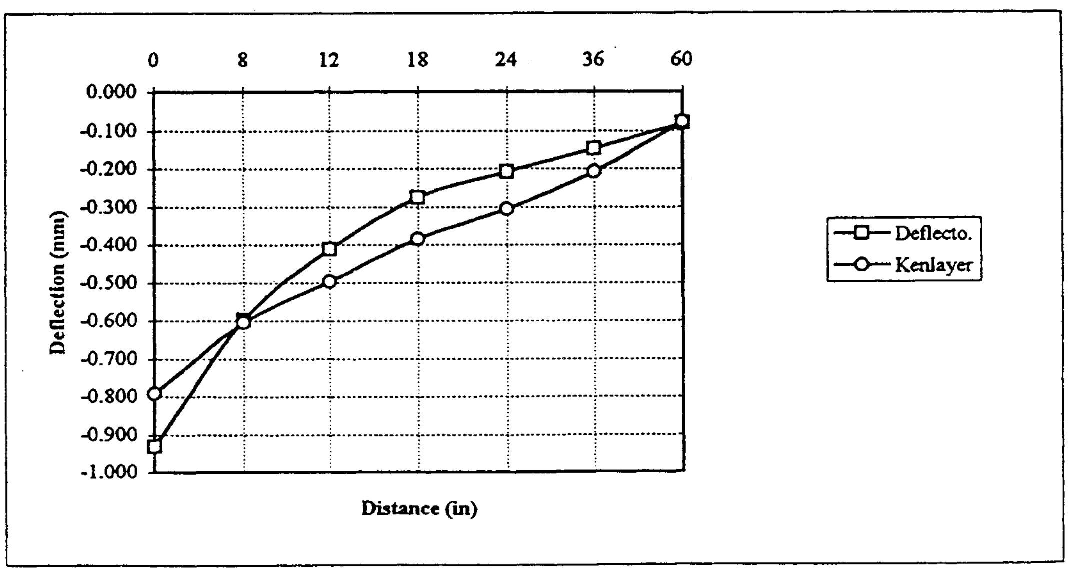


Fig 11.39 Best-Fit Deflection Profile for Section 4 (938 kPa)

Failure Criteria of Flexible Pavements

The theoretical failure criteria of flexible pavements are fatigue cracking and permanent deformation (rutting). The equations of fatigue and rutting criteria are proposed by the Asphalt Institute, Shell, Univ. of Nottingham, and other agencies as:

$$N_f = f_1 * (\varepsilon_t)^{-f2} * (E_1)^{-f3} \tag{11}$$

$$N_d = f_4 * (\varepsilon_c)^{-f5} \tag{12}$$

where N_f = number of allowable load repetitions to prevent fatigue cracking

ε_t = tensile strain at the bottom of the asphalt layer

E_1 = elastic modulus of asphalt layer

f_1, f_2, f_3 = constants determined from laboratory fatigue tests

N_d = number of allowable load repetitions to limit permanent deformation

ε_c = compressive strain on top of subgrade

f_4, f_5 = constants determined from road tests or road performance

Table 11.3 lists the constants of criteria recommended by three agencies.

TABLE 11.3 Recommended Constant Values By Various Institutions

Constant	Asphalt Institute	Shell Oil Company	U. of Nottingham
f_1	0.0796	0.0685	***
f_2	3.291	5.671	***
f_3	0.854	2.363	***
f_4	1.365×10^{-9}	6.15×10^{-7}	1.13×10^{-6}
f_5	4.477	4.0	3.571

Unlike KENSLABS, which utilized rectangular loaded contact areas, KENLAYER examined circular loaded areas only. Therefore, it was necessary to determine the contact area for each load carrying 24.5 kN (5,500 lbs) and having a tire pressure of 759 kPa (110 psi) by using the following formula:

$$\text{Radius} = \{(\text{Wheel Load} / \text{Tire Pressure}) / \pi\}^{1/2} \tag{13}$$

As can be seen on Figure 11.40, the contact radius for each tire load applied at the UCF-CATT was 101 mm (3.99 in).

By transferring the known input parameter data to the KENLAYER program; wheel load, tire contact areas, layer dimensions, modulus of each layer, the tensile strain at the bottom of the 88.9 mm (3.5 in) asphalt layer, and the compressive strain on top of the subgrade at a depth of 495 mm (19.5 in) were calculated (Figure 11.40). The results are presented on Table 11.4.

TABLE 11.4 Tensile and Compressive Strains Calculated by KENLAYER

Flexible Test Section	Tensile Strain (ε_t)	Compressive Strain (ε_c)
Section 1	0.3811×10^{-3}	0.4345×10^{-3}
Section 2	0.3850×10^{-3}	0.4964×10^{-3}
Section 3	0.4080×10^{-3}	0.5179×10^{-3}
Section 4	0.3615×10^{-3}	0.3490×10^{-3}

The values in Table 11.4 were used in conjunction with criterion equations to evaluate the allowable number of repetitions for fatigue and rutting of the test sections. The computed N_f and N_d from Equations 11 and 12 are given in Table 11.5 and 11.6.

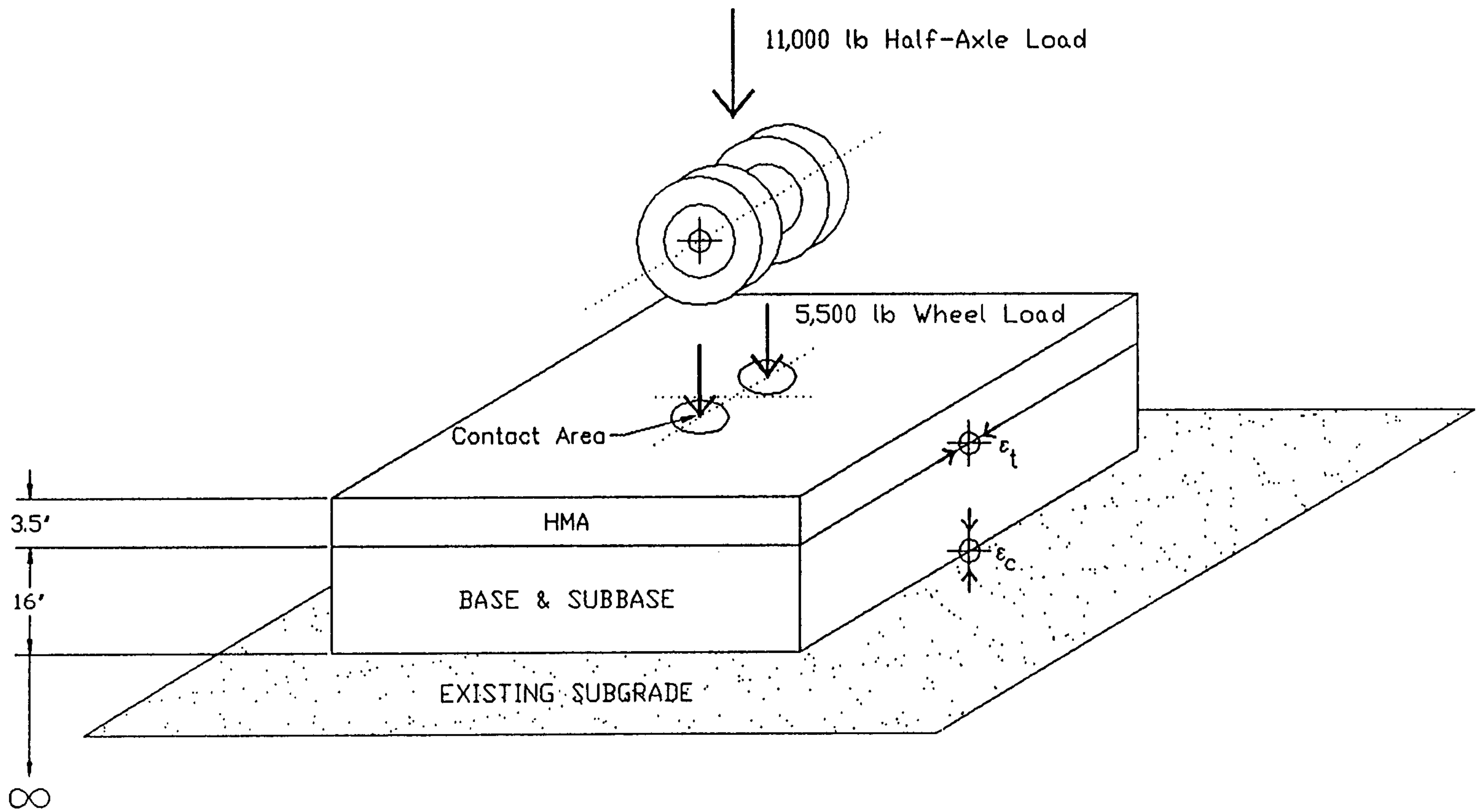


Fig 11.40 Half-Axle Load on HMA

TABLE 11.5. Number of Allowable Reps to Fatigue Failure

Flexible Test Section	Asphalt Institute	Shell Oil Company
Section 1	246,883	113,027
Section 2	238,748	106,686
Section 3	197,246	76,772
Section 4	293,735	152,483

TABLE 11.6. Number of Allowable Reps to Rutting Failure

Flexible Section	Asphalt Institute	Shell Oil Company	U. of Nottingham
Section 1	1,537,632	17,255,041	1,145,030
Section 2	847,020	10,128,567	711,645
Section 3	700,574	8,548,530	611,655
Section 4	4,101,127	41,454,668	2,504,084

As can be seen from the above tables, each Institution predicts failure of the pavement at different repetition intervals. N_f values fell far below the N_d values. This implies that the HMA will fail under fatigue well before rutting caused by subgrade deformation. From a sensitivity analysis of flexible pavements systems, either a higher quality of HMA or a thicker layer of HMA will be required to improve the fatigue life. The reason for the use of the low modulus value of HMA was because the asphalt mixture contained 4.5% recycled aggregate and the air voids in the asphalt mix are showing 9.4% and 11.7%, as seen on Figure 8. It must be pointed out that while the mix design called for an air content of 4.6%, the cores had an average of 10.6%. When the air voids are above approximately 8%, the mix is permeable to air and water (Roberts, 1991). The excess water within the HMA layer will eventually lead to the stripping of the fine aggregate in the asphalt mixture, eventually inducing failure. With the low modulus of elasticity of HMA, the strains computed by the KENLAYER program were high, thus yielding a low number of load repetitions against fatigue.

The results of Table 11.5 and 11.6 are used to compare with the performance of the test sections at the UCF-CATT.

CHAPTER 12

ACCELERATED PERFORMANCE TESTING

Life Expectancy Analysis

It is comprehensible that pavement systems are submitted to a wide range of vehicles. To consider the number of load repetitions for different axle loads and evaluate its damage is considered a very tedious task. For the design of pavement systems, a simplified and widely accepted procedure relies on converting each load group into an equivalent 80 kN (18-kip) single axle load as proposed by Asphalt Institute (AI) and AASHTO. "An equivalent axle load factor defines the damage per pass to a pavement by the axle in question relative to the damage per pass of a standard axle load which is usually the 80 kN (18 kips) single axle load" (Huang, 1993). Since the Florida Legal Load truck authorized by the FDOT can have a maximum single axle load of 97.86 kN (22 kips), it was chosen to apply a dual wheel load of 48.9 kN (11 kips) from the accelerated testing machine. This dual wheel loading, which is equivalent to the 97.89 kN (22 kips) single axle load, is heavier than the standard 80 kN (18 kips) single axle load. Therefore, it was necessary to transform the repetitions administered by the 97.89 kN (22 kips) to an equivalent amount of repetitions produced by a standard 80 kN (18 kips) equivalent single axle load (ESAL) as specified by the AASHTO standard truck. An equivalent axle load factor (EALF) can either be defined by utilizing AASHTO's convention tables from the 1986 manual, or by simply using Equation 14 which is based on the fatigue criterion concept. An $ESAL_{18}$ is then defined by Equation 15.

$$\text{EALF} = \left(\frac{Lx}{18}\right)^4 \tag{14}$$

$$\text{ESAL}_{18} = N_{22}{*}\text{EALF} \tag{15}$$

where L_x = load of the applied single axle = 97.89 kN (22 kips)

N_{22} = the number of passes of the 97.86 kN (22 kip) load during the traffic period

$ESAL_{18}$ = the number of 80 kN (18 kips) corresponding to N_{22}

The sum of the repetitions successfully endured at the UCF-CATT can be used to equate the tested paving materials simulated life expectancy (SLE) if it were applied to normal highway use. The SLE has been tailored to site specific applications through the use of actual traffic volumes. Therefore, the actual yearly truck traffic must be evaluated. As an example, for an average daily traffic (ADT) volume of 7,500 for a typical medium-heavy traffic highway with an average percent of trucks of 6% the annual volume of heavy truck traffic can be calculated as follows:

$$\text{ADT x T x L x 365 days} = \text{AHTT} \tag{16}$$

where ADT = average daily traffic

T = percentage of trucks in the ADT

L = lane distribution factor (0.9 for the multi-lane highways)

AHTT = annual heavy truck traffic

Unlike actual field conditions, the test track applied the load over the same path during each revolution. So for analysis purposes, an assumed probability of occurrence of 1/3 can be assumed. In other words, every third dual wheel load was believed to cover the same path along the pavement. The following equation equated the test track results to a simulated one year life expectancy:

$$N \times EALF / P = AHTT \tag{17}$$

where N = number of test track repetitions required per year

EALF = equivalent axle load factor (Equation 14)

AHTT = annual heavy truck traffic (Equation 16)

P = probability of occurrence

The simulated life expectancy of the tested material can then be computed through the use of Equation 18:

$$SLE = (CATT_{REPS} / N) \tag{18}$$

where SLE = simulated life expectancy

$CATT_{REPS}$ = total repetitions applied by UCF-CATT

N = number of test track repetitions required per year (Equation 18)

By using the above equations along with the data collected at the UCF-CATT, the computed values from Equations 14 through 18 are obtained and given in Table 12.1.

TABLE 12.1. Simulated Life Expectancy Analysis

VARIABLE	EQUATION	OUTPUT
EALF	14	2.24
18-kip ESAL	15	299,340 Reps
AHTT	16	98,550 Trucks
N	17	14,665 Reps
SLE	18	9.11 Years

Performance Test of Asphaltic Sections at UCF-CATT

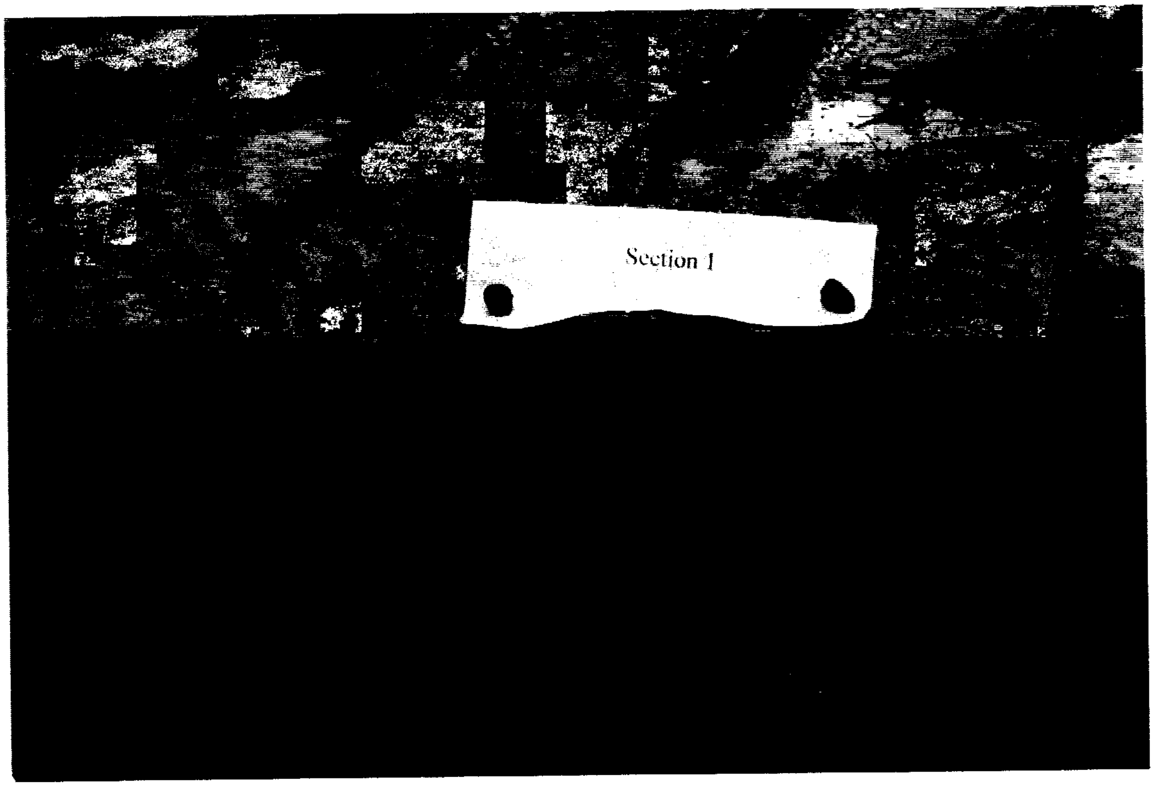
The accelerated test track was run for approximately 60,000 load repetitions, when it became apparent that a problem had occurred between the wear course and asphalt course. It was observed that the Delcrete wear course failed to bond with the underlying asphalt. This was possibly due to the fact that the Delcrete and the asphalt, having different coefficients of thermal expansion and under the Florida summer sun, expanded and contracted differentially with the changes in temperature. This occurred in spite of the 9.53 mm (3/8 in) strips of neoprene rubber which were placed every 2.13 m (7 ft) to serve as expansion joints.

The lack of bonding between the Delcrete and asphalt permitted water to seep in between these layers. The repeated loading of the test track wheels, caused a pumping action, which pressurized this water. Core tests of the asphalt, which were performed by FDOT, revealed that the asphalt had been improperly compacted, and possessed an excessive amount of air void content (11.5 %) and asphalt content (0.8 %). These characteristics made the asphalt pavement highly porous, allowing the pressurized water to seep into the air voids and delaminate the aggregates in the asphalt mix.

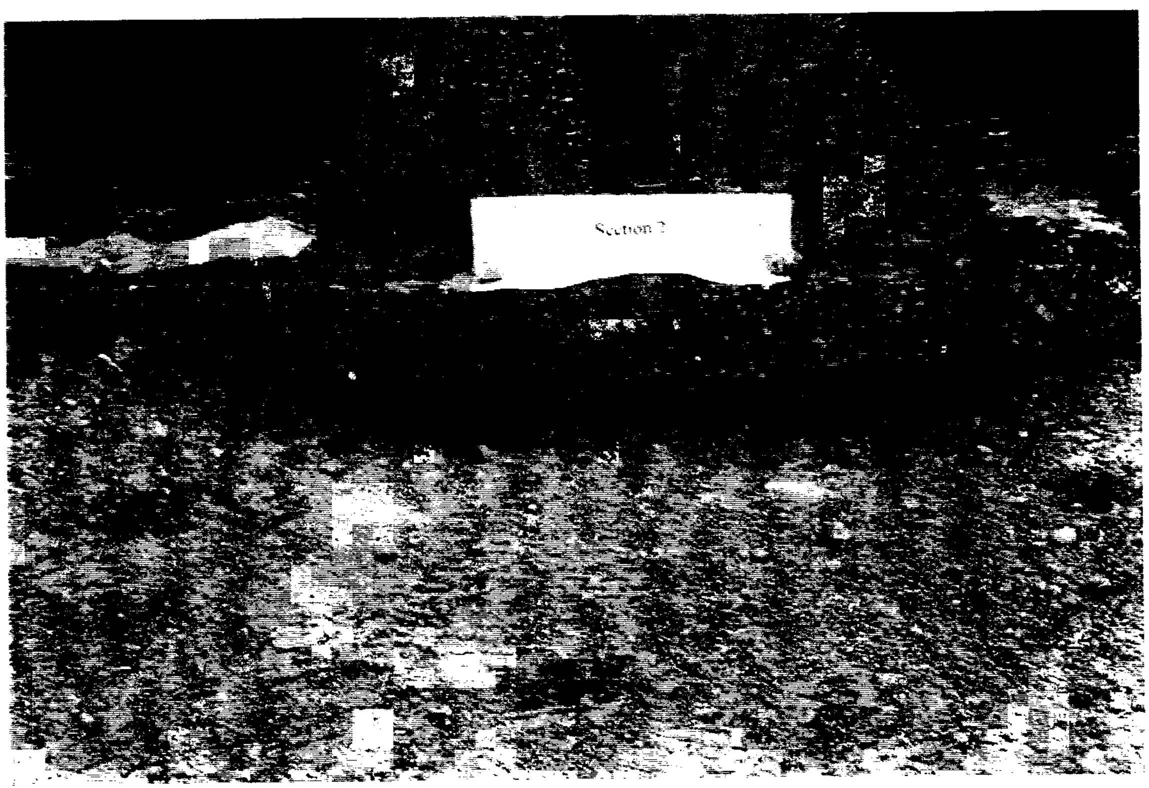
At this point, none of the sections exemplified any signs of distress. The sections did not register fatigue cracks (transverse or longitudinal), nor any permanent deformation rutting along the wheel paths, which suggested that the base materials were still in a stable condition.

To resume testing, the Delcrete wear course and a 50 mm thick layer of asphalt were removed without disturbing the underlying base courses. A new 50 mm (2 in) layer of asphalt was placed and compacted over all four sections by the Orlando Paving Company and testing was resumed.

The accelerated test track proceeded to load the test sections, achieving a total of 133,634 load repetitions (299,340 ESAL). Testing was stopped because the asphalt wear course suffered a uniform 12.5 mm (0.5 in) wearing on all sections. The wearing occurred directly along the wheel path of the testing machine, indicating that it occurred as a consequence of the circular frictional



PHOTOGRAPH 31. Cross Section of Asphaltic Section 1 (254-mm RCA Base Course)



PHOTOGRAPH 32. Cross Section of Asphaltic Section 2 (203-mm Limerock Base Course)

PHOTOGRAPH 33. Cross Section of Asphaltic Section 3 (203-mm RCA Base Course)

PHOTOGRAPH 34. Cross Section of Asphaltic Section 4 (305-mm RCA Base Course)

loading forces imposed by the testing machine's wheels. Visual inspection of cross sections of the asphaltic segments 1 through 4 (see photographs 31 to 34) showed no signs of failure of any of the base sections.

The life expectancy analysis equates that 133,634 (299,340 ESAL) load repetitions on the accelerated test track are equivalent to approximately 9.11 years of loading on a highway with an average daily traffic of 7,500 vehicles, out of which 4% are trucks. The fact that none of the base sections failed under this loading supports the conclusion that even the 203 mm (8 in) recycled concrete aggregate base section is capable of exemplifying a performance which is at least equal to that of the limerock base control section.

Performance Test of Rigid Sections at UCF-CATT

Post-construction tests of the rigid pavement test section included core drilling and the falling weight deflectometer (FWD). One 150 mm (6 in) diameter core was obtained from each slab section by a crew from FDOT. The cores were taken to the FDOT's State Material Office and tested for compressive strength on July 10, 1997, at the age of 120 days. Results of the test are shown in Table 12.2 and in Fig. 12.1. Compressive strengths of cored samples (6000 to 8000 psi) are higher than those of specimens made on the field (5000 to 6000 psi). This may be attributed to better compaction and older age of the cored samples compared to the field-made specimens.

Table 12.2 Compressive strength of concrete specimens from CATT at UCF

MIX TYPE (% of RCA)	COMPRESSIVE STRENGTH		
	Core		Field-made Specimen Psi (% of control)
	psi	% of Control	
(Control) 0	8536	100	6218 (100)
25	7169	84	5726 (92.1)
75	6894	80.8	5522 (88.8)
100	6019	70.5	5073 (81.6)

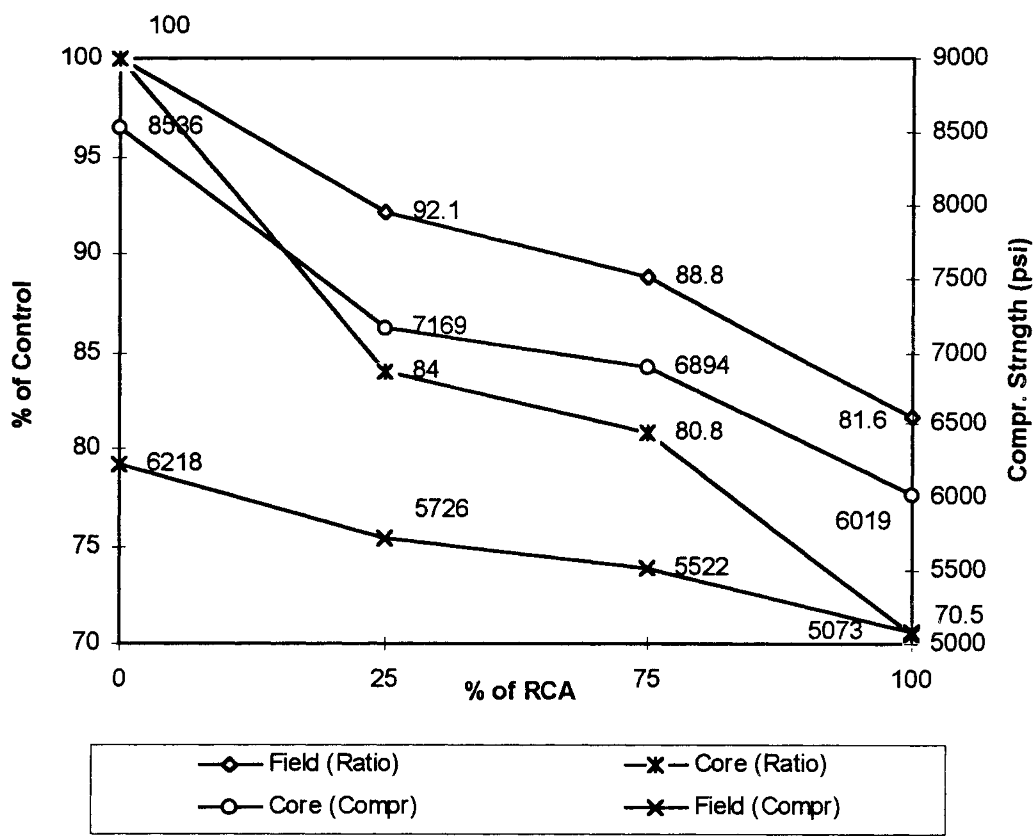


Fig. 12.1 Compressive strength of samples from rigid pavement of the CATT at UCF

The rigid pavement deflection testing (FWD) was also performed by a crew from FDOT Materials Lab. The objective of the FWD testing was to determine the PCC elastic modulus, subgrade modulus of support, load transfer efficiencies across joints, and slab deflections. The details of the test set-up, data collection, and the summary of results are discussed in Chapter 11.

Pavement life expectancy

The loading machine at the CATT is loaded with an equivalent single axle load of 97.8 kN (22 kips) to match the single axle load of Florida truck load. Thus, by substituting 97.8 in Eq. 14, the damage per pass of the CATT wheel (EALF) is 2.23 times that of the 80 kN. $ESAL_D$.

Another modification required to correlate effects of the CATT tests and that of 80 kN $ESAL_D$ is related to the wheel path. At the CATT, the path of the wheel is the same thus applying the load over the same points on the path during each revolution. In the actual highway conditions, however, the probability that a wheel will load the same point for every pass is approximately one third. Therefore the damage effect caused by the CATT load is about three times that of the 80 kN $ESAL_D$. Hence, the number N of loading cycles required at the CATT to simulate one year of highway service is given by

$$N = \left(\frac{AHTT * P}{EALF} \right) \tag{19}$$

where:

AHTT = Average Annual Heavy Truck Traffic

EALF = Equivalent Axle Load Factor (= 2.23)

P = Probability of loading occurrence (= 1/3)

The average annual heavy truck traffic (AHTT) is given by

$$AHTT = (AADT * T_{24} * D_F * L_F * E_{80} * 365) \qquad (20)$$

where all the parameters are as defined in Eq. 1a in chapter 10. Using the same values as used to compute the 80 kN ESALD in Eq. 1a, then

AHTT = 20,000 * 0.065 * 0.5 * 0.81 * 1.95 * 365 = <u>374,740.</u>

Substituting for AHTT in Eq. 19, the number of loading cycles required at the CATT to simulate one year of highway service period is

N = (374,740 * 1/3)/ 2.23 = <u>56,000</u> loading cycles.

With the N-value known, it is now possible to estimate the simulated life expectancy (SLE) of the highway for any given number of loading cycles performed at CATT. Thus

$$SLE = \frac{N_{TOT}}{N} \qquad (21)$$

where N_{TOT} is the cumulative total of all the loading cycles applied at CATT. At the time of writing this report, the recorded N_{TOT} equals 133,634. Substituting this value in Eq. 21, then

SLE = 133 634 /56 000 = 2.39

This means that the CATT has simulated 2.39 years of actual concrete pavement service life. To simulate the design period of the highway (20 years) the CATT has to apply about 1,120,000 loading repetitions which are equivalent to 7,500,000 $ESAL_D$.

<u>Distress survey</u>

The pavement distresses of concern to this study are:

1 Mid-panel cracking
1 D-cracking
2 Faulting of cracks and joints
3 base deformation, and
4 any other visible distress.

D-cracking is a form of pavement distress caused by poor-quality aggregates that deteriorate through freeze-thaw action (durability test). At the time of writing this report no distress of any kind was noticed on the rigid pavement. This was expected because the few number of loading repetitions applied so far. The reason for this low number of loading cycles is the failure of flexible pavement section. Since the loading cycles started in April 14, 1997 the asphalt has failed two times, causing the loading process to stop.

Currently there is a plan to replace the flexible pavement with a rigid pavement in order to continue loading the concrete pavement section to the point where distress can be identified. So the study on the performance of PCC containing RCA is still continuing at the UCF-CATT.

CHAPTER 13

CONCLUSIONS AND RECOMMENDATIONS

Use of RCA in New Concrete

Based on the results obtained from tests in this study, it can be concluded that:

1. the properties of RCA and concrete made with RCA obtained in this study are consistent and within the range of values obtained by other researchers;

2. the properties of RCA used in this study compared very well with those of VA used, and are within limits specified in most SHAs' specifications for concrete aggregates;

3. the mechanical properties of RCA concrete decrease as the ratio of coarse RCA increase in the mix. Compared to VA concrete, the 100% RCA concrete was about 82% in compressive strength, 96% in tensile strength, 81% in flexural strength, and 86% in modulus of elasticity;

4. despite having lower compressive strength than VA concrete, 100% RCA concrete had compressive strength of 5070 psi (average of 6 tests) which is well above the target strength of 3630 psi specified Type II concrete;

5. use of high range water reducer and air entraining admixtures improved workability of RCA mixes even at low w/c ratio;

6. RCA obtained from FDOT's highways can be used to produce quality concrete for construction of new pavements.

Based on information obtained in the literature, and experience gained in conducting this study, the following items should be considered when using RCA as aggregate in new concrete:

1. recycled fines should not be used in producing new concrete;

2. A low w/c ratio should be used, and high range water reducing and air entraining admixtures must be used to achieve the desired workability;

3. Mix design should be based on SSD weight of RCA. Adjustments of mixing water should be made if the moisture content of RCA during mixing is not the same as its moisture content at SSD condition; and

4. since RCA concrete is very susceptible to drying shrinkage, the placed concrete should be properly cured with water to reduce shrinkage cracking.

To evaluate the quality of RCA materials for use in PCCP, the following tests are recommended:

1. For RCA: density, specific gravity, void ratio, water absorption, and LA abrasion.

2. For RCA concrete: compressive strength, modulus of elasticity, flexural strength, and tensile strength.

Use of RCA as Base Course:

Based on the information examined in this project, it is possible to draft the following preliminary recommendations for the use of recycled concrete aggregate as a base course in flexible pavements:

1. Base course aggregate for flexible pavements may include or consist of material processed from Portland Cement Concrete obtained from an approved quality controlled source. The Portland Cement Concrete for recycling shall possess a verifiable uniform and structurally sound original mix design.

2. The recycled concrete aggregate must be free of reinforcing steel, adherent coatings, clay, organic material, brick, asphalt, gypsum, plastics and deleterious substances.

3. Different sizes of recycled concrete aggregate and aggregate from different sources shall be stockpiled separately from each other so that the material will not become intermixed. Any material which segregates so that the grading no longer conforms to that specified shall be rejected for use.

4. The recycled concrete aggregate shall meet the same particle size distribution as that specified for natural aggregates. Sieve analysis testing shall be performed on the recycled concrete aggregate. If the RCA is found to fail the specified grading requirements, adjustments shall be made to the crushing plant or the RCA may be combined with natural aggregates to obtain the desired grading.

5. Recycled concrete aggregate for use in base courses shall be tested for conformance with the following material requirements (the percentages suggested here are based on review of the international and US Department of Transportation standards and are not the direct result of tests performed in this study) :

Los Angeles Abrasion	< 40%
Limerock Bearing Ratio	> 100%
Plasticity Index	< 6%
Thin or Elongated Particles	< 8%

6. The Sodium Sulfate soundness test requirement shall be waived for recycled concrete aggregate.

Recommended Further Studies

1. For the purpose of establishing thresholds of acceptable values for the properties of RCA, it is recommended that more studies be conducted using recycled materials from various sources in FDOT projects. This will determine any variations in properties of reclaimed materials based on the conditions and mix design of the source concrete. It will also establish any relationship (if any) between changes of RCA properties and the resulting properties of RCA concrete. The two sets of data can then be used to specify acceptable range of values of RCA for acceptable qualities of RCA concrete. This study used recycled aggregate from a concrete which had river gravel as coarse aggregate. It is essential to evaluate properties of RCA obtained from a concrete containing limestone, as this is the common material for coarse aggregate in Florida.

2. The performance of RCA base courses needs to be further evaluated. This task can be accomplished by testing experimental pavement sections in roads and in accelerated test tracks. In order to truly compare the performance of recycled concrete aggregate to that of natural aggregate base courses, performance testing should be conducted to the point of failure of one of the base courses.

3. Compilation of a more comprehensive list of concrete recycling plants in Florida may facilitate communication with this industry.

APPENDIX A

Lab Data and Compaction Tests

MODIFIED PROCTOR COMPACTION TEST

Description of soil:		*Meissner Construction Pit Soil Sample*				
Volume of mold:		1/30 ft^3				
No. of blows/layer:		25				
Weight of hammer:		10 lb				
No. of layers:		5				
Test No.	**Wt. of mold W_1 (lb)**	**Wt. of mold + moist soil W_2 (lb)**	**Wt. of moist soil W_2-W_1 (lb)**	**Moist unit Wt. $30(W_2-W_1)$ (lb/ft^3)**	**Moisture Content w (%)**	**Dry Unit Wt. Gdry (lb/ft^3)**
1	9.348	13.054	3.706	111.18	10.36	100.74
2	9.348	13.265	3.917	117.51	12.31	104.63
3	9.348	13.404	4.056	121.68	13.72	107.00
4	9.348	13.338	3.990	119.70	15.83	103.34
5	9.348	13.318	3.970	119.10	16.50	102.23

MOISTURE CONTENT DETERMINATION

Test No.	1	2	3	4	5
Can No.	A	B	C	D	E
Wt. of can (g)	18.1	18.4	18.3	18.2	18.2
Wt. of can + Moist Soil (g)	45.8	48.5	44.0	48.2	53.5
Wt. of can + Dry Soil (g)	43.2	45.2	40.9	44.1	48.5
Moisture content (%)	10.36	12.31	13.72	15.83	16.50

MEISSNER CONSTRUCTION PIT SOIL SAMPLE

Dry Wt. (g)	475				
Sieve #	Wt. retained per sieve (g)	% of Wt. Ret. per sieve	Cumulative % retained	Diameter (mm)	% Finer
4	0.0	0.00	0.00	4.750	100.00
10	0.4	0.08	0.08	2.000	99.92
20	3.0	0.63	0.71	0.850	99.29
40	16.6	3.49	4.20	0.425	95.80
60	39.6	8.34	12.54	0.250	87.46
140	390.1	82.13	94.67	0.106	5.33
200	10.9	2.29	96.96	0.075	3.04
PAN	13.5	*****	*****	*****	*****
TOTAL	474.1				

MODIFIED PROCTOR COMPACTION TEST

Description of soil:		*UCF Soil Sample*				
Volume of mold:		1/30 ft^3				
No. of blows/layer:		25				
Weight of hammer:		10 lb				
No. of layers:		5				
Test No.	**Wt. of mold W_1 (lb)**	**Wt. of mold + moist soil W_2 (lb)**	**Wt. of moist soil W_2-W_1 (lb)**	**Moist unit Wt. $30(W_2-W_1)$ (lb/ft^3)**	**Moisture Content w (%)**	**Dry Unit Wt. Gdry (lb/ft^3)**
1	9.343	12.996	3.653	109.59	6.13	103.26
2	9.343	13.115	3.772	113.16	8.33	104.46
3	9.343	13.272	3.929	117.87	11.39	105.82
4	9.343	13.415	4.072	122.16	14.29	106.89
5	9.343	13.525	4.182	125.46	16.72	107.49
6	9.343	13.558	4.215	126.45	18.68	106.55

MOISTURE CONTENT DETERMINATION

Test No.	**1**	**2**	**3**	**4**	**5**	**6**
Can No.	S34	S2	S14	S32	S43	S5
Wt. of can (g)	18.6	18.1	18.4	18.4	18.5	18.1
Wt. of can + Moist Soil (g)	46.3	49.3	44.8	51.2	57.6	48.6
Wt. of can + Dry Soil (g)	44.7	46.9	42.1	47.1	52.0	43.8
Moisture content (%)	6.13	8.33	11.39	14.29	16.72	18.68

UCF SOIL SAMPLE

Dry Wt. (g)	322.8				
Sieve #	Wt. retained per sieve (g)	% of Wt. Ret. per sieve	Cumulative % retained	Diameter (mm)	% Finer
4	0.0	0.00	0.00	4.750	100.00
10	0.0	0.00	0.00	2.000	100.00
20	0.6	0.19	0.19	0.850	99.81
40	14.7	4.55	4.74	0.425	95.26
60	58.5	18.12	22.86	0.250	77.14
140	238.7	73.95	96.81	0.106	3.19
200	5.2	1.61	98.42	0.075	1.58
PAN	3.0	*****	*****	*****	*****
TOTAL	320.7				

MODIFIED PROCTOR COMPACTION TEST

Description of soil:	*Red Clayey Sandy Soil Sample*	
Volume of mold:	1/30 ft^3	
No. of blows/layer:	25	
Weight of hammer:	10 lb	
No. of layers:	5	

Test No.	Wt. of mold W_1 (lb)	Wt. of mold + moist soil W_2 (lb)	Wt. of moist soil W_2-W_1 (lb)	Moist unit Wt. 30(W_2-W_1) (lb/ft^3)	Moisture Content w (%)	Dry Unit Wt. Gdry (lb/ft^3)
1	9.350	13.450	4.100	123.00	8.44	113.42
2	9.350	13.500	4.150	124.50	9.18	114.03
3	9.350	13.650	4.300	129.00	11.16	116.05
4	9.350	13.750	4.400	132.00	12.31	117.53
5	9.350	13.700	4.350	130.50	13.21	115.27

MOISTURE CONTENT DETERMINATION

Test No.	1	2	3	4	5
Can No.	S32	S23	S18	S43	S35
Wt. of can (g)	18.5	18.2	18.3	18.4	18.5
Wt. of can + Moist Soil (g)	42.9	40.8	44.2	47.6	50.2
Wt. of can + Dry Soil (g)	41.0	38.9	41.6	44.4	46.5
Moisture content (%)	8.44	9.18	11.16	12.31	13.21

RED CLAYEY SANDY SOIL

Dry Wt. (g)	500				
Sieve #	Wt. retained per sieve (g)	% of Wt. Ret. per sieve	Cumulative % retained	Diameter (mm)	% Finer
4	0.0	0.00	0.00	4.750	100.00
10	0.7	0.14	0.14	2.000	99.86
20	27.1	5.42	5.56	0.850	94.44
40	192.8	38.56	44.12	0.425	55.88
60	212.6	42.52	86.64	0.250	13.36
100	57.3	11.46	98.10	0.150	1.90
140	4.2	0.84	98.94	0.106	1.06
200	1.7	0.34	99.28	0.075	0.72
PAN	3.4	*****	*****	*****	*****
TOTAL	499.8				

ARDAMAN & ASSOCIATES, INC.
8008 S. Orange Avenue
Orlando, Florida 32809
(407) 855-3860

FIELD DENSITY TEST REPORT

PROJECT: UCF Test Track

FILE NO 97-6070

PAGE NO.: 1 OF 1

TO: Dr. Kuo - University of Central Florida

DATE: 03-05-97

CC:

TEST NO.	LOCATION	TEST DATE	PR[a]	MAX DRY DENSITY (PCF)	IN-PLACE DRY DENSITY (PCF)	MOISTURE (%)	DEPTH/ ELEVATION[b]	PERCENT COMPACTION
1	SE Section	03-05-97		107.0	103.6	11.3	0/-4"	97
2	West Section	03-05-97		107.0	101.6	10.4	0/-4"	95
3	North Section	03-05-97		107.0	103.7	7.8	0/-6"	97
4	East Section	03-05-97		107.0	101.6	9.6	0/-6"	95
	Proctor Value Supplied by Client							

[a] Hand-cone penetrometer reading.
[b] Referenced from 1st lift subbase
[c] Shaded area indicates the In-Place Density Test or retest (where applicable) does not meet minimum compaction requirement of 95 percent of ASTM D-1557.

JC

ARDAMAN & ASSOCIATES, INC.
8008 S. Orange Avenue
Orlando, Florida 32809
(407) 855-3860

FIELD DENSITY TEST REPORT

PROJECT: UCF Test Track

FILE NO.: 97-6070

PAGE NO.: 1 OF 1

TO: Dr. Kuo - University of Central Florida

DATE: 03-10-97

CC:

TEST NO.	LOCATION	TEST DATE	PR[A]	MAX DRY DENSITY (PCF)	IN-PLACE DRY DENSITY (PCF)	MOISTURE (%)	DEPTH/ ELEVATION[B]	PERCENT COMPACTION
1	E Side S End	03-07-97		117.4	110.1	9.9	+4/+14	94[c]
2	↓	03-07-97		117.4	112.3	9.5	+4/+14	96
3	E Side N End	03-07-97		117.4	106.8	11.2	+4/+14	93[c]
4	↓	03-07-97		117.4	110.3	10.9	+4/+14	94[c]
5	W Side Center	03-07-97		117.4	107.1	9.1	+4/+14	91[c]
	Proctor Value Supplied by Client.							

[A] Hand-cone penetrometer reading.
[B] Referenced from natural ground.
[C] Shaded area indicates the In-Place Density Test or retest (where applicable) does not meet minimum compaction requirement of 95 percent of ASTM D-1557.

RH

APPENDIX A1

HMA Mix Design

LAB

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR BITUMINOUS CONCRETE

SUBMIT TO THE STATE MATERIALS ENGINEER, CENTRAL BITUMINOUS LABORATORY, 2006 NORTHEAST WALDO ROAD., GAINESVILLE, FLA. 32609

F.A.P. No. XU-8868-(11) & XU-8868-(12)

Project No. 77080-3505 & 77080-3565 Type Mix S-I Recycle Date 4 / 15 / 96

Road No. SR-436 County County Seminole District 5

Contractor Name & Plant Location Orlando Paving Co. / Apopka, FL Phone No. (407) 290-9327

Intended Use of Mix Structural Submitted By Orlando Paving Q.A. Tech. F. X. Joy

TYPE MATERIAL	F.D.O.T. CODE	PRODUCER	PIT NO.	DATE SAMPLED
1. Crushed R.A.P.		Orlando Paving Company	Stockpile #96-5	4 / 3 / 96
2. #67-A Stone	41	Florida Rock Industries	08-004	4 / 3 / 96
3. S-1-B Stone	51	G.K.K. Corporation	93-406	4 / 3 / 96
4. Screenings	20	G.K.K. Corporation	93-406	4 / 3 / 96
5. Local Sand		Orlando Paving Company	Apopka	4 / 3 / 96
6.				

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

SIEVE SIZE / Blend	30%	12%	26%	18%	14%	%	JOB MIX	GRADATION
Number	1	2	3	4	5	6	FORMULA	DESIGN RANGE
1"								
3/4"	100	100	100	100	100		100	100
1/2"	99	78	100	100	100		97	88 - 98
3/8"	97	40	98	100	100		91	75 - 93
No. 4	81	8	41	99	100		68	47 - 75
No. 10	63	5	6	78	100		49	31 - 53
No. 40	44	3	4	43	90		35	19 - 35
No. 80	23	2	3	18	20		14	7 - 21
No. 200	10.0	2.0	1.5	3.5	1.0		5.5	2 - 6
Sp. Gr.	2.585	2.325	2.399	2.475	2.620		2.486	

The mix properties of the Job Mix Formula have been verified and the mix design is approved subject to F.D.O.T. specifications.

No. 200 increased due to expected aggregate breakdown during production.

QA 96-7724A (TS-I)

MATERIALS DIVISION USE ONLY

CC: Document Control
Mr. S. B. Wigle
Mr. W. O. Downs
Mr. T. O. Malerk
Orlando Paving Co.
7 Cen Bit Lab
Bit Recycle
Project File

State Materials Engineer

Effective Date 4 / 30 / 96

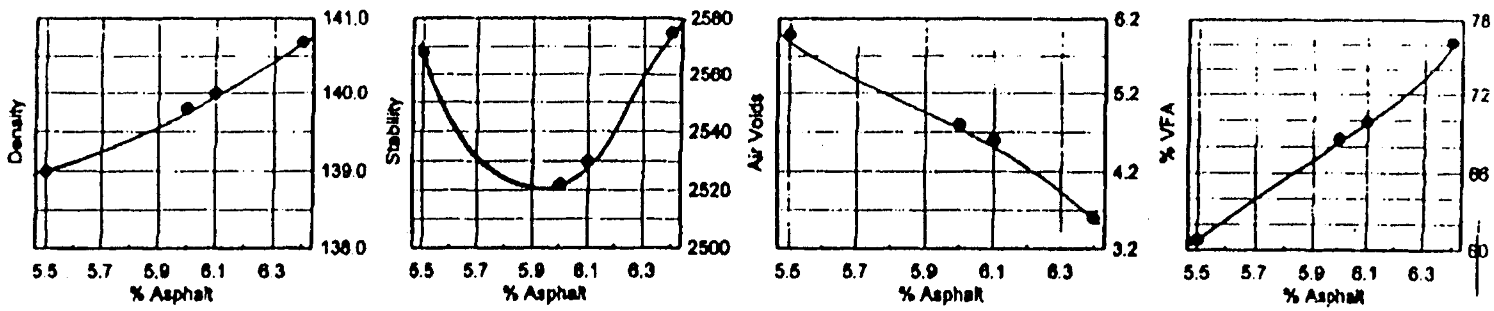
FIGURE 7. Flexible Pavement Mix Design

FIGURE 7. Flexible Pavement Mix Design (Continued)

HOT MIX DESIGN DATA SHEET

QA 96-7724A (TS-I)

Percent A.C. Total Wt. of Mix	Bulk Sp. Gr. of Compacted Mix	Max. Measured Sp. Gr. of Compacted Mix	Air Voids Percent	V.M.A. Percent	Voids Filled Percent	Effective Asphalt Content	Dust to Effective AC Ratio	Adjusted Stability Averaged	Flow Average
5.5	2.227	2.369	6.0	15.3	60.8	4.3	1.3	2568	9.0
6.0	2.240	2.353	4.8	15.3	68.6	4.8	1.1	2522	10.0
6.1	2.243	2.350	4.6	15.3	69.9	4.9	1.1	2530	10.0
6.4	2.255	2.340	3.6	15.1	76.2	5.3	1.0	2575	10.5



Optimum Asphalt 6.1 % V.M.A. 15.3 % Mixing Temperature 285 °F

Lab. Density 140.0 Lbs/Ft.³ Air Voids 4.6 % Additives Antistrip 0.5 %

Stability 2530 Lbs Effective A.C. Content by wt. 4.9 %

Optimum Asphalt	=	6.1%
Asphalt using 30% Milled Material @ 5.3%	=	1.6%
Recycling Agent 2000 poises (AC-20) to be added	=	4.5%

BULK SPECIFIC GRAVITY

TECHNICIAN MIKE BERKOWITZ MIX I.D. U.C.F.

DATE 05/05/97 MIX TYPE TEST TRACK

SPECIMEN I.D.	1	2	3	
WEIGHT IN AIR, g	3023.6	3019.2		
WEIGHT IN WATER, g	1622.4	1584.8		
WEIGHT SURFACE DRY, g	3027.4	3024.3		
WATER TEMPERATURE	77	77	77	AVERAGE
VOLUME, cc	1405	1439.5		1422.25
BULK SPECIFIC GRAVITY, Gmb	2.152	2.097		2.125
RICE SPECIFIC GRAVITY, Gmm	2.376	2.376		2.376
AIR VOIDS, Va	9.4	11.7		10.6

SAMPLE #1 IS FROM FIRST PAVED SECTION NEAR BUILDING

SAMPLE #2 IS FROM SECOND PAVED SECTION AWAY FROM BUILDING

TECHNICIAN MIX I.D.

DATE 05/05/97 MIX TYPE

SPECIMEN I.D.	4	5	6	
WEIGHT IN AIR, g				
WEIGHT IN WATER, g				
WEIGHT SURFACE DRY, g				
WATR TEMPERATURE	77	77	77	AVERAGE
VOLUME, cc				0
BULK SPECIFIC GRAVITY, Gmb				0.000
RICE SPECIFIC GRAVITY, Gmm				ERR
AIR VOIDS, Va	ERR	ERR		ERR

FIGURE 8. Bulk Specific Gravity Test

APPENDIX B

KENLAYER and KENSLABS Computer Output

NUMBER OF PROBLEMS TO BE SOLVED (NPROB) = 1

```
*****************************************************************************************
*                                                                                       *
*     Section 5: 25% RCA + 75% VA Concrete w/11000 lb load on 6 x 12 ft Slab (Corner)   *
*                                                                                       *
*****************************************************************************************
```

TYPE OF FOUNDATION (NFOUND) = 2
TYPE OF DAMAGE ANALYSIS (NDAMA) = 0
NUMBER OF PERIODS PER YEAR (NPY) = 1
NUMBER OF LOAD GROUPS (NLG) = 1
TOTAL NUMBER OF SLABS (NSLAB) = 2
TOTAL NUMBER OF JOINTS (NJOINT) = 1

ARRANGEMENT OF SLABS

SLAB NO.	NO. OF NODES (NX) IN X DIRECTION	NO. OF NODES (NY) IN Y DIRECTION	JOINT NO. AT FOUR SIDES (JONO) LEFT	RIGHT	BOTTOM	TOP
1	6	7	0	1	0	0
2	6	7	1	0	0	0

NUMBER OF LAYERS (NLAYER)--------------------------------------= 1

NODAL NUMBER USED TO CHECK CONVERGENCE (NNCK)------------------= 51

NUMBER OF NODES NOT IN CONTACT (NOTCON)------------------------= 0

NUMBER OF GAPS (NGAP)--= 0

NUMBER OF POINTS FOR PRINTOUT (NPRINT)-------------------------= 0

CODE FOR INPUT OF GAPS OR PRECOMPRESSIONS (INPUT)--------------= 0

BOND BETWEEN TWO LAYERS (NBOND)--------------------------------= 0

CONDITION OF WARPING (NTEMP)-----------------------------------= 0

CODE INDICATING WHETHER SLAB WEIGHT IS CONSIDERED (NWT)--------= 0

MAX NO. OF CYCLES FOR CHECKING CONTACT (NCYCLE)----------------= 1

NUMBER OF ADDITIONAL THICKNESSES TO BE READ IN (NAT)
FOR LAYER 1 --= 0
FOR LAYER 2 --= 0

NUMBER OF POINTS ON X AXIS OF SYMMETRY (NSX)------------------= 0

```
NUMBER OF POINTS ON Y AXIS OF SYMMETRY (NSY)------------------=    0

MORE DETAILED PRINTOUT FOR EACH CONTACT CYCLE (MDPO)----------=    1

DIFFERENCE IN TEMP. BETWEEN TOP AND BOTTOM OF SLAB (TEMP)-----=    .00000

UNIT WEIGHT OF LAYER 1 (GAMA(1))------------------------------=    .00000

UNIT WEIGHT OF LAYER 2 (GAMA(2))------------------------------=    .00000

MODULUS OF RUPTURE OF LAYER 1 (PMR(1))------------------------=    .00000

MODULUS OF RUPTURE OF LAYER 2 (PMR(2))------------------------=    .00000

COEFFICIENT OF THERMAL EXPANSION (CT)-------------------------=  .500E-05

TOLERANCE FOR ITERATIONS (DEL)--------------------------------=  .100E-02

MAXIMUM ALLOWABLE VERTICAL DISPLACEMENT (FMAX)----------------=   1.00000

FOR LAYER 1 FATIGUE COEFFICIENTS:   F1 =      .00000     F2 =      .00000

FOR LAYER 2 FATIGUE COEFFICIENTS:   F1 =      .00000     F2 =      .00000

FOR SLAB NO. 1 :  X=    .00000   5.00000  12.00000  24.00000  72.00000 144.00000
                  Y=    .00000   3.00000   7.87000  12.00000  15.74000  36.00000   72.00000

FOR SLAB NO. 2 :  X=    .00000   5.00000  12.00000  24.00000  72.00000 144.00000
                  Y=    .00000   3.00000   7.87000  12.00000  15.74000  36.00000   72.00000

LAYER    THICKNESS (T)     POISSON'S          YOUNG'S
 NO.                       RATIO (PR)      MODULUS (YM)
  1       10.00000           .15000           .485E+07

NUMBER OF LOADED AREAS (NUDL) FOR EACH LOAD GROUP ARE:
    2

NUMBER OF CONCENTRATED NODAL FORCES (NCNF) FOR EACH LOAD GROUP ARE:
    0

GROUP  1 LOADS ARE APPLIED ON THE SLAB NO.(LS) WITH COORDINATES (XL AND YL) AND INTENSITY(QQ) AS SHOWN:
         2         .00000        8.52000          .00000        5.87000       110.00000
         2         .00000        8.52000         9.87000       15.74000       110.00000


FOUNDATION SEASONAL ADJUSTMENT FACTOR (FSAF) FOR EACH PERIOD ARE
   1.00000

NUMBER OF LAYERS IN BURMISTER FOUNDATION (NL) IS :    3
```

MAXIMUM NO. OF INTEGRATION CYCLES (MAXIC) IS : 30

THICKNESSES OF LAYERS (TH) ARE : 10.00000 24.00000

YOUNG MODULUS OF LAYERS ARE (E) : .320E+05 .270E+05 .250E+05

POISSON RATIOS OF LAYERS (PRBF) ARE : .33000 .40000 .40000

SLAB NO., INITIAL NODAL NUMBER(INITNP), LAST NODAL NUMBER(LASTNP),
INITIAL ELEMENT NO.(INITEN), AND LAST ELEMENT NO.(LASTEN) ARE:
1 1 42 1 30 2 43 84 31 60

JOINT NO. INITIAL STARTING NODAL NO. (ISNN) AND LAST FINAL NODAL NO. (LFNN)
INITIAL STARTING ELEMENT NO.(ISEN) ,LAST FINAL ELEMENT NO.(LFEN) ON BOTH SIDES OF THE JOINT ARE:
1 36 43 42 49 25 31 30 36

NODAL COORDINATES(XN AND YN) OF INDIVIDUAL SLAB ARE:

1	.00000	.00000	2	.00000	3.00000	3	.00000	7.87000	4	.00000	12.00000
5	.00000	15.74000	6	.00000	36.00000	7	.00000	72.00000	8	5.00000	.00000
9	5.00000	3.00000	10	5.00000	7.87000	11	5.00000	12.00000	12	5.00000	15.74000
13	5.00000	36.00000	14	5.00000	72.00000	15	12.00000	.00000	16	12.00000	3.00000
17	12.00000	7.87000	18	12.00000	12.00000	19	12.00000	15.74000	20	12.00000	36.00000
21	12.00000	72.00000	22	24.00000	.00000	23	24.00000	3.00000	24	24.00000	7.87000
25	24.00000	12.00000	26	24.00000	15.74000	27	24.00000	36.00000	28	24.00000	72.00000
29	72.00000	.00000	30	72.00000	3.00000	31	72.00000	7.87000	32	72.00000	12.00000
33	72.00000	15.74000	34	72.00000	36.00000	35	72.00000	72.00000	36	144.00000	.00000
37	144.00000	3.00000	38	144.00000	7.87000	39	144.00000	12.00000	40	144.00000	15.74000
41	144.00000	36.00000	42	144.00000	72.00000	43	.00000	.00000	44	.00000	3.00000
45	.00000	7.87000	46	.00000	12.00000	47	.00000	15.74000	48	.00000	36.00000
49	.00000	72.00000	50	5.00000	.00000	51	5.00000	3.00000	52	5.00000	7.87000
53	5.00000	12.00000	54	5.00000	15.74000	55	5.00000	36.00000	56	5.00000	72.00000
57	12.00000	.00000	58	12.00000	3.00000	59	12.00000	7.87000	60	12.00000	12.00000
61	12.00000	15.74000	62	12.00000	36.00000	63	12.00000	72.00000	64	24.00000	.00000
65	24.00000	3.00000	66	24.00000	7.87000	67	24.00000	12.00000	68	24.00000	15.74000
69	24.00000	36.00000	70	24.00000	72.00000	71	72.00000	.00000	72	72.00000	3.00000
73	72.00000	7.87000	74	72.00000	12.00000	75	72.00000	15.74000	76	72.00000	36.00000
77	72.00000	72.00000	78	144.00000	.00000	79	144.00000	3.00000	80	144.00000	7.87000
81	144.00000	12.00000	82	144.00000	15.74000	83	144.00000	36.00000	84	144.00000	72.00000

LOADS ARE APPLIED ON THE ELEMENT NO.(NL) WITH COORDINATES(XDA AND YDA) AND INTENSITY(Q) AS SHOWN:

31	-1.00000	1.00000	-1.00000	1.00000	110.00000
32	-1.00000	1.00000	-1.00000	.17864	110.00000
37	-1.00000	.00571	-1.00000	1.00000	110.00000
38	-1.00000	.00571	-1.00000	.17864	110.00000
33	-1.00000	1.00000	-.03148	1.00000	110.00000
34	-1.00000	1.00000	-1.00000	1.00000	110.00000
39	-1.00000	.00571	-.03148	1.00000	110.00000
40	-1.00000	.00571	-1.00000	1.00000	110.00000

YOUNG MODULUS OF DOWEL BAR (YMSB) = .290E+08
POISSON RATIO OF DOWEL BAR (PRSB) = .30000

JOINT NO.	SPRING SHEAR (SPCON1)	CONSTANT MOMENT (SPCON2)	MODULUS OF DOWEL SUP. (SCKV)	DOWEL DIAMETER (BD)	DOWEL SPACING (BS)	JOINT WIDTH (WJ)	GAP BETWEEN DOWEL AND CONC. (GDC)	NO. OF NODES ALONG JOINT (NNAJ)
1	.000E+00	.000E+00	.100E+07	1.37500	12.00000	.25000	.00000	0

JOINT NO.	EQUIVALENT SPRING CONSTANT (SPCON)
1	.523E+05

THE GLOBAL COORDINATES (XO AND YO) OF EACH NODE ARE:

1	.00000	.00000	2	.00000	3.00000	3	.00000	7.87000	4	.00000	12.00000
5	.00000	15.74000	6	.00000	36.00000	7	.00000	72.00000	8	5.00000	.00000
9	5.00000	3.00000	10	5.00000	7.87000	11	5.00000	12.00000	12	5.00000	15.74000
13	5.00000	36.00000	14	5.00000	72.00000	15	12.00000	.00000	16	12.00000	3.00000
17	12.00000	7.87000	18	12.00000	12.00000	19	12.00000	15.74000	20	12.00000	36.00000
21	12.00000	72.00000	22	24.00000	.00000	23	24.00000	3.00000	24	24.00000	7.87000
25	24.00000	12.00000	26	24.00000	15.74000	27	24.00000	36.00000	28	24.00000	72.00000
29	72.00000	.00000	30	72.00000	3.00000	31	72.00000	7.87000	32	72.00000	12.00000
33	72.00000	15.74000	34	72.00000	36.00000	35	72.00000	72.00000	36	144.00000	.00000
37	144.00000	3.00000	38	144.00000	7.87000	39	144.00000	12.00000	40	144.00000	15.74000
41	144.00000	36.00000	42	144.00000	72.00000	43	144.00000	.00000	44	144.00000	3.00000
45	144.00000	7.87000	46	144.00000	12.00000	47	144.00000	15.74000	48	144.00000	36.00000
49	144.00000	72.00000	50	149.00000	.00000	51	149.00000	3.00000	52	149.00000	7.87000
53	149.00000	12.00000	54	149.00000	15.74000	55	149.00000	36.00000	56	149.00000	72.00000
57	156.00000	.00000	58	156.00000	3.00000	59	156.00000	7.87000	60	156.00000	12.00000
61	156.00000	15.74000	62	156.00000	36.00000	63	156.00000	72.00000	64	168.00000	.00000
65	168.00000	3.00000	66	168.00000	7.87000	67	168.00000	12.00000	68	168.00000	15.74000
69	168.00000	36.00000	70	168.00000	72.00000	71	216.00000	.00000	72	216.00000	3.00000
73	216.00000	7.87000	74	216.00000	12.00000	75	216.00000	15.74000	76	216.00000	36.00000
77	216.00000	72.00000	78	288.00000	.00000	79	288.00000	3.00000	80	288.00000	7.87000
81	288.00000	12.00000	82	288.00000	15.74000	83	288.00000	36.00000	84	288.00000	72.00000

NODAL NUMBER AND TYPE OF NODES (NDTY) ARE:

1	1	2	1	3	1	4	1	5	1	6	1	7	1	8	1	9	1	10	1
11	1	12	1	13	1	14	1	15	1	16	1	17	1	18	1	19	1	20	1
21	1	22	1	23	1	24	1	25	1	26	1	27	1	28	1	29	1	30	1
31	1	32	1	33	1	34	1	35	1	36	2	37	2	38	2	39	2	40	2
41	2	42	2	43	0	44	0	45	0	46	0	47	0	48	0	49	0	50	1
51	1	52	1	53	1	54	1	55	1	56	1	57	1	58	1	59	1	60	1
61	1	62	1	63	1	64	1	65	1	66	1	67	1	68	1	69	1	70	1
71	1	72	1	73	1	74	1	75	1	76	1	77	1	78	1	79	1	80	1
81	1	82	1	83	1	84	1												

NODAL NUMBERS AND OPPOSITE NODES (NPOP) ARE:

1	0	2	0	3	0	4	0	5	0	6	0	7	0	8	0	9	0	10	0

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 11    0     12    0     13    0     14    0     15    0     16    0     17    0     18    0     19    0     20    0
 21    0     22    0     23    0     24    0     25    0     26    0     27    0     28    0     29    0     30    0
 31    0     32    0     33    0     34    0     35    0     36   43     37   44     38   45     39   46     40   47
 41   48     42   49     43   36     44   37     45   38     46   39     47   40     48   41     49   42     50    0
 51    0     52    0     53    0     54    0     55    0     56    0     57    0     58    0     59    0     60    0
 61    0     62    0     63    0     64    0     65    0     66    0     67    0     68    0     69    0     70    0
 71    0     72    0     73    0     74    0     75    0     76    0     77    0     78    0     79    0     80    0
 81    0     82    0     83    0     84    0

HALF BAND WIDTH (NB) =  123


PERIOD  1  LOAD GROUP  1  AND CYCLE NO. 1
ITERATION NO. (IC) =  1 DIFFERENCE IN DEFLECTION (DF) =   .00882594
ITERATION NO. (IC) =  3 DIFFERENCE IN DEFLECTION (DF) =   .00009750
ITERATION NO. (IC) =  5 DIFFERENCE IN DEFLECTION (DF) =   .00000195

SUM OF APPLIED FORCES (FOSUM)=   11002.7     SUM OF TOTAL REACTIONS (SUBSUM)=   10987.3


DEFLECTIONS OF SLABS (F) ARE: (DOWNWARD POSITIVE)
 1  .6521E-03  2  .6379E-03  3  .6156E-03  4  .5976E-03  5  .5817E-03  6  .5075E-03  7  .3732E-03  8  .7097E-03
 9  .6956E-03 10  .6725E-03 11  .6533E-03 12  .6364E-03 13  .5501E-03 14  .4053E-03 15  .7941E-03 16  .7793E-03
17  .7545E-03 18  .7332E-03 19  .7143E-03 20  .6137E-03 21  .4475E-03 22  .9631E-03 23  .9452E-03 24  .9147E-03
25  .8876E-03 26  .8628E-03 27  .7361E-03 28  .5194E-03 29  .2454E-02 30  .2403E-02 31  .2321E-02 32  .2252E-02
33  .2189E-02 34  .1822E-02 35  .1158E-02 36  .8542E-02 37  .8428E-02 38  .8234E-02 39  .8057E-02 40  .7886E-02
41  .6835E-02 42  .4546E-02 43  .9623E-02 44  .9582E-02 45  .9411E-02 46  .9162E-02 47  .8852E-02 48  .6802E-02
49  .3639E-02 50  .8944E-02 51  .8925E-02 52  .8765E-02 53  .8545E-02 54  .8266E-02 55  .6349E-02 56  .3311E-02
57  .8036E-02 58  .8007E-02 59  .7860E-02 60  .7655E-02 61  .7449E-02 62  .5722E-02 63  .2894E-02 64  .6628E-02
65  .6530E-02 66  .6357E-02 67  .6187E-02 68  .6005E-02 69  .4702E-02 70  .2290E-02 71  .2603E-02 72  .2537E-02
73  .2430E-02 74  .2339E-02 75  .2258E-02 76  .1812E-02 77  .9691E-03 78  .8200E-03 79  .8041E-03 80  .7789E-03
81  .7580E-03 82  .7395E-03 83  .6554E-03 84  .5418E-03

DEFLECTIONS OF SUBGRADE (SUBD) ARE:(DOWNWARD POSITIVE)
 1  .6520E-03  2  .6378E-03  3  .6156E-03  4  .5975E-03  5  .5818E-03  6  .5075E-03  7  .3732E-03  8  .7097E-03
 9  .6955E-03 10  .6725E-03 11  .6533E-03 12  .6365E-03 13  .5501E-03 14  .4053E-03 15  .7941E-03 16  .7793E-03
17  .7545E-03 18  .7332E-03 19  .7143E-03 20  .6137E-03 21  .4475E-03 22  .9631E-03 23  .9452E-03 24  .9147E-03
25  .8876E-03 26  .8628E-03 27  .7361E-03 28  .5194E-03 29  .2454E-02 30  .2403E-02 31  .2321E-02 32  .2252E-02
33  .2189E-02 34  .1822E-02 35  .1158E-02 36  .9083E-02 37  .9005E-02 38  .8822E-02 39  .8609E-02 40  .8369E-02
41  .6818E-02 42  .4092E-02 43  .9083E-02 44  .9005E-02 45  .8822E-02 46  .8609E-02 47  .8369E-02 48  .6818E-02
49  .4092E-02 50  .8944E-02 51  .8925E-02 52  .8765E-02 53  .8545E-02 54  .8266E-02 55  .6349E-02 56  .3311E-02
57  .8036E-02 58  .8007E-02 59  .7860E-02 60  .7655E-02 61  .7449E-02 62  .5722E-02 63  .2894E-02 64  .6628E-02
65  .6530E-02 66  .6357E-02 67  .6187E-02 68  .6005E-02 69  .4702E-02 70  .2290E-02 71  .2603E-02 72  .2537E-02
73  .2430E-02 74  .2339E-02 75  .2258E-02 76  .1812E-02 77  .9691E-03 78  .8200E-03 79  .8041E-03 80  .7789E-03
81  .7580E-03 82  .7395E-03 83  .6554E-03 84  .5418E-03
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SUM OF REACTION FORCE AND PRECOMPRESSION (SUMP) IS : (TENSION IS NEGATIVE)

1	-22.0	2	11.7	3	7.5	4	-43.2	5	33.1	6	-196.3	7	4.1	8	20.4
9	-22.0	10	-17.0	11	42.2	12	-51.2	13	142.8	14	-145.4	15	58.9	16	-55.0
17	-36.8	18	102.0	19	-108.3	20	-3.3	21	73.2	22	6.6	23	12.0	24	-1.3
25	3.1	26	1.9	27	-118.8	28	-260.0	29	-78.4	30	123.6	31	653.1	32	61.6
33	-386.8	34	743.5	35	-113.9	36	1455.6	37	-1363.9	38	722.3	39	-1004.4	40	1080.4
41	-439.7	42	-366.5	43	1640.1	44	-1114.0	45	1047.1	46	-862.4	47	1200.4	48	-407.5
49	-42.3	50	9307.1	51	-9867.2	52	4917.4	53	-4634.4	54	5278.4	55	1687.5	56	1403.7
57	8570.7	58	-8263.5	59	-2734.5	60	9716.7	61	-9523.3	62	948.6	63	-83.3	64	406.0
65	292.2	66	16.3	67	664.1	68	291.5	69	788.5	70	-45.6	71	-14.9	72	126.4
73	414.6	74	53.3	75	-229.1	76	441.5	77	-576.1	78	-17.5	79	5.0	80	71.7
81	-3.7	82	-57.3	83	-101.4	84	-248.8								

ITERATION NO. (IC) = 7 DIFFERENCE IN DEFLECTION (DF) = .00000003

SUM OF APPLIED FORCES (FOSUM)= 11002.7 SUM OF TOTAL REACTIONS (SUBSUM)= 10987.5

DEFLECTIONS OF SLABS (F) ARE: (DOWNWARD POSITIVE)

1	.6521E-03	2	.6380E-03	3	.6157E-03	4	.5976E-03	5	.5818E-03	6	.5076E-03	7	.3732E-03	8	.7098E-03
9	.6956E-03	10	.6725E-03	11	.6533E-03	12	.6365E-03	13	.5501E-03	14	.4053E-03	15	.7942E-03	16	.7794E-03
17	.7546E-03	18	.7333E-03	19	.7143E-03	20	.6138E-03	21	.4476E-03	22	.9631E-03	23	.9453E-03	24	.9147E-03
25	.8877E-03	26	.8628E-03	27	.7361E-03	28	.5194E-03	29	.2454E-02	30	.2403E-02	31	.2321E-02	32	.2252E-02
33	.2189E-02	34	.1822E-02	35	.1158E-02	36	.8542E-02	37	.8428E-02	38	.8234E-02	39	.8057E-02	40	.7886E-02
41	.6835E-02	42	.4546E-02	43	.9623E-02	44	.9582E-02	45	.9411E-02	46	.9162E-02	47	.8853E-02	48	.6802E-02
49	.3639E-02	50	.8944E-02	51	.8925E-02	52	.8765E-02	53	.8545E-02	54	.8266E-02	55	.6349E-02	56	.3311E-02
57	.8036E-02	58	.8007E-02	59	.7860E-02	60	.7656E-02	61	.7450E-02	62	.5722E-02	63	.2894E-02	64	.6628E-02
65	.6530E-02	66	.6357E-02	67	.6187E-02	68	.6005E-02	69	.4702E-02	70	.2290E-02	71	.2603E-02	72	.2538E-02
73	.2430E-02	74	.2339E-02	75	.2258E-02	76	.1812E-02	77	.9692E-03	78	.8200E-03	79	.8041E-03	80	.7789E-03
81	.7580E-03	82	.7396E-03	83	.6554E-03	84	.5419E-03								

DEFLECTIONS OF SUBGRADE (SUBD) ARE:(DOWNWARD POSITIVE)

1	.6520E-03	2	.6379E-03	3	.6157E-03	4	.5976E-03	5	.5818E-03	6	.5076E-03	7	.3732E-03	8	.7097E-03
9	.6956E-03	10	.6725E-03	11	.6533E-03	12	.6365E-03	13	.5501E-03	14	.4053E-03	15	.7942E-03	16	.7794E-03
17	.7546E-03	18	.7333E-03	19	.7143E-03	20	.6138E-03	21	.4476E-03	22	.9631E-03	23	.9453E-03	24	.9147E-03
25	.8877E-03	26	.8628E-03	27	.7361E-03	28	.5194E-03	29	.2454E-02	30	.2403E-02	31	.2321E-02	32	.2252E-02
33	.2189E-02	34	.1822E-02	35	.1158E-02	36	.9083E-02	37	.9005E-02	38	.8822E-02	39	.8609E-02	40	.8369E-02
41	.6819E-02	42	.4092E-02	43	.9083E-02	44	.9005E-02	45	.8822E-02	46	.8609E-02	47	.8369E-02	48	.6819E-02
49	.4092E-02	50	.8944E-02	51	.8925E-02	52	.8765E-02	53	.8545E-02	54	.8266E-02	55	.6349E-02	56	.3311E-02
57	.8036E-02	58	.8007E-02	59	.7860E-02	60	.7655E-02	61	.7449E-02	62	.5722E-02	63	.2894E-02	64	.6628E-02
65	.6530E-02	66	.6357E-02	67	.6187E-02	68	.6005E-02	69	.4702E-02	70	.2290E-02	71	.2603E-02	72	.2538E-02
73	.2430E-02	74	.2339E-02	75	.2258E-02	76	.1812E-02	77	.9692E-03	78	.8200E-03	79	.8041E-03	80	.7790E-03
81	.7580E-03	82	.7396E-03	83	.6554E-03	84	.5419E-03								

SUM OF REACTION FORCE AND PRECOMPRESSION (SUMP) IS : (TENSION IS NEGATIVE)

1	-22.0	2	11.7	3	7.5	4	-43.2	5	33.1	6	-196.3	7	4.1	8	20.4
9	-22.0	10	-17.0	11	42.2	12	-51.2	13	142.8	14	-145.4	15	58.9	16	-55.0
17	-36.8	18	102.0	19	-108.3	20	-3.3	21	73.2	22	6.6	23	12.0	24	-1.3

25	3.1	26	1.9	27	-118.8	28	-260.0	29	-78.4	30	123.6	31	653.2	32	61.6
33	-386.8	34	743.6	35	-113.8	36	1455.6	37	-1363.9	38	722.3	39	-1004.4	40	1080.4
41	-439.7	42	-366.5	43	1640.1	44	-1114.0	45	1047.1	46	-862.4	47	1200.4	48	-407.5
49	-42.3	50	9307.1	51	-9867.2	52	4917.4	53	-4634.5	54	5278.4	55	1687.5	56	1403.7
57	8570.7	58	-8263.5	59	-2734.5	60	9716.7	61	-9523.3	62	948.6	63	-83.3	64	406.0
65	292.2	66	16.3	67	664.1	68	291.5	69	788.5	70	-45.6	71	-14.9	72	126.4
73	414.7	74	53.3	75	-229.2	76	441.5	77	-576.0	78	-17.5	79	5.0	80	71.7
81	-3.7	82	-57.3	83	-101.4	84	-248.8								

FOR JOINT NO. 1 SHEAR (FAJ1) AND MOMENT (FAJ2) AT THE NODES ARE:

36	84.786	.000	37	237.404	.000	38	276.981	.000	39	227.294	.000
40	606.499	.000	41	-48.469	.000	42	-853.889	.000			

FOR JOINT NO. 1 SHEAR IN ONE DOWEL BAR (FAJPD) AT THE NODES IS:

36	678.288	37	723.978	38	738.617	39	693.147	40	606.499	41	-20.677
42	-569.259										

FOR JOINT NO. 1 BEARING STRESS (BEARS) OF CONCRETE AND SHEAR STRESS (SHEARS) OF DOWELS AT THE NODES ARE:

36	535.294	456.791	37	571.352	487.561	38	582.905	497.420	39	547.021	466.798
40	478.640	408.445	41	-16.318	-13.925	42	-449.251	-383.366			

NODAL NUMBER AND REACTIVE PRESSURE (SUBR) ARE: (COMPRESSION POSITIVE)

1	-5.87769	2	1.18685	3	.67032	4	-4.38868	5	1.10388	6	-2.79132	7	.09023	8	2.27087
9	-.93248	10	-.62853	11	1.78610	12	-.71169	13	.84612	14	-1.34639	15	4.13628	16	-1.47196
17	-.86098	18	2.72886	19	-.95002	20	-.01236	21	.42825	22	.14660	23	.10127	24	-.00961
25	.02591	26	.00542	27	-.14075	28	-.48148	29	-.87113	30	.52356	31	2.41912	32	.26098
33	-.53728	34	.44055	35	-.10541	36	26.95608	37	-9.62824	38	4.45891	39	-7.09044	40	2.50091
41	-.43422	42	-.56559	43	437.34960	44	-113.24250	45	93.07157	46	-87.66559	47	40.01211	48	-5.79407
49	-.94010	50	1034.12800	51	-417.92470	52	182.12730	53	-196.29190	54	73.31059	55	9.99835	56	12.99761
57	601.45250	58	-221.05260	59	-63.96391	60	259.92560	61	-83.53793	62	3.54952	63	-.48738	64	9.02268
65	2.47482	66	.12077	67	5.62569	68	.80963	69	.93436	70	-.08444	71	-.16528	72	.53541
73	1.53580	74	.22596	75	-.31828	76	.26161	77	-.53337	78	-.32387	79	.03500	80	.44271
81	-.02644	82	-.13265	83	-.10013	84	-.38392								

NODE	ROTAT.X	ROTAT.Y	NODE	ROTAT.X	ROTAT.Y	NODE	RORAT.X	ROTAT.Y	NODE	ROTAT.X	ROTAT.Y
1	.4734E-05	.1147E-04	2	.4671E-05	.1148E-04	3	.4470E-05	.1135E-04	4	.4320E-05	.1113E-04
5	.4042E-05	.1094E-04	6	.3696E-05	.8414E-05	7	.3636E-05	.6502E-05	8	.4703E-05	.1167E-04
9	.4735E-05	.1163E-04	10	.4713E-05	.1144E-04	11	.4574E-05	.1120E-04	12	.4458E-05	.1096E-04
13	.4107E-05	.8714E-05	14	.3950E-05	.6243E-05	15	.4880E-05	.1261E-04	16	.4996E-05	.1242E-04
17	.5165E-05	.1211E-04	18	.5112E-05	.1176E-04	19	.5060E-05	.1138E-04	20	.4755E-05	.9445E-05
21	.4579E-05	.5985E-05	22	.5866E-05	.1622E-04	23	.6074E-05	.1566E-04	24	.6442E-05	.1488E-04
25	.6637E-05	.1428E-04	26	.6586E-05	.1375E-04	27	.6094E-05	.1114E-04	28	.6068E-05	.5802E-05
29	.1672E-04	.5388E-04	30	.1697E-04	.5310E-04	31	.1679E-04	.5178E-04	32	.1665E-04	.5058E-04
33	.1700E-04	.4941E-04	34	.1833E-04	.4217E-04	35	.1965E-04	.2596E-04	36	.3759E-04	.1002E-03
37	.3848E-04	.9938E-04	38	.4141E-04	.9781E-04	39	.4439E-04	.9625E-04	40	.4684E-04	.9464E-04
41	.5722E-04	.8408E-04	42	.6677E-04	.6003E-04	43	.1011E-04	-.1368E-03	44	.2028E-04	-.1326E-03
45	.4887E-04	-.1301E-03	46	.7301E-04	-.1241E-03	47	.8912E-04	-.1183E-03	48	.1010E-03	-.9050E-04

49	.8441E-04	-.6656E-04	50	.1535E-05	-.1332E-03	51	.1555E-04	-.1316E-03	52	.4483E-04	-.1289E-03
53	.6499E-04	-.1247E-03	54	.8066E-04	-.1162E-03	55	.9627E-04	-.9049E-04	56	.8101E-04	-.6345E-04
57	.6096E-05	-.1254E-03	58	.1606E-04	-.1290E-03	59	.4301E-04	-.1296E-03	60	.5219E-04	-.1267E-03
61	.6225E-04	-.1199E-03	62	.8828E-04	-.8802E-04	63	.7591E-04	-.5599E-04	64	.3251E-04	-.1152E-03
65	.3339E-04	-.1162E-03	66	.3812E-04	-.1165E-03	67	.4499E-04	-.1150E-03	68	.5169E-04	-.1127E-03
69	.7026E-04	-.8220E-04	70	.6582E-04	-.4467E-04	71	.2145E-04	-.5214E-04	72	.2195E-04	-.5160E-04
73	.2209E-04	-.5050E-04	74	.2180E-04	-.4926E-04	75	.2173E-04	-.4791E-04	76	.2246E-04	-.3700E-04
77	.2427E-04	-.1643E-04	78	.5344E-05	-.1272E-04	79	.5240E-05	-.1210E-04	80	.5109E-05	-.1111E-04
81	.5019E-05	-.1032E-04	82	.4813E-05	-.9652E-05	83	.3549E-05	-.6019E-05	84	.3276E-05	.2456E-05

NODE	LAYER	STRESS X	STRESS Y	STRESS XY	MAJOR	MINOR	MAX.SHEAR
1	1	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00
2	1	.000000E+00	-.100270E+01	.000000E+00	-.100270E+01	.000000E+00	.501351E+00
3	1	.000000E+00	-.131324E+01	.000000E+00	-.131324E+01	.000000E+00	.656622E+00
4	1	.000000E+00	-.142799E+00	.000000E+00	-.142799E+00	.000000E+00	.713994E-01
5	1	.000000E+00	-.276027E+01	.000000E+00	-.276027E+01	.000000E+00	.138013E+01
6	1	.000000E+00	.652743E+00	.000000E+00	.000000E+00	.652743E+00	.326371E+00
7	1	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00
8	1	-.186602E+01	.000000E+00	.000000E+00	-.186602E+01	.000000E+00	.933012E+00
9	1	-.150423E+01	.234841E-01	-.475260E+00	-.164001E+01	.159265E+00	.899640E+00
10	1	-.119210E+01	-.561926E+00	-.111033E+01	-.203119E+01	.277162E+00	.115418E+01
11	1	-.104684E+01	-.151672E+01	-.127034E+01	-.257366E+01	.100952E-01	.129188E+01
12	1	-.454620E+00	-.391124E+00	-.175785E+01	-.218101E+01	.133526E+01	.175813E+01
13	1	-.293379E+01	-.639502E+00	-.181880E+01	-.393698E+01	.363695E+00	.215034E+01
14	1	.249144E+01	.000000E+00	.000000E+00	.000000E+00	.249144E+01	.124572E+01
15	1	-.405981E+01	.000000E+00	.000000E+00	-.405981E+01	.000000E+00	.202990E+01
16	1	-.384346E+01	.557454E+00	-.128111E+01	-.418922E+01	.903221E+00	.254622E+01
17	1	-.364322E+01	.273983E-02	-.160709E+01	-.425046E+01	.609982E+00	.243022E+01
18	1	-.343046E+01	-.170312E+01	-.200604E+01	-.475085E+01	-.382731E+00	.218406E+01
19	1	-.249904E+01	-.979940E-01	-.210276E+01	-.371985E+01	.112282E+01	.242133E+01
20	1	-.238096E+01	-.896969E+00	-.201613E+01	-.378730E+01	.509364E+00	.214833E+01
21	1	-.694517E+00	.000000E+00	.000000E+00	-.694517E+00	.000000E+00	.347258E+00
22	1	-.917735E+01	.000000E+00	.000000E+00	-.917735E+01	.000000E+00	.458868E+01
23	1	-.782081E+01	.995203E+00	-.366461E+01	-.914516E+01	.231955E+01	.573235E+01
24	1	-.683905E+01	.498892E+00	-.319177E+01	-.803308E+01	.169292E+01	.486300E+01
25	1	-.659992E+01	-.216030E+00	-.302532E+01	-.780583E+01	.989871E+00	.439785E+01
26	1	-.693259E+01	-.236308E+01	-.280318E+01	-.826418E+01	-.103149E+01	.361634E+01
27	1	-.413798E+01	-.744661E+00	-.293523E+01	-.583164E+01	.948997E+00	.339032E+01
28	1	-.416335E+00	.000000E+00	.000000E+00	-.416335E+00	.000000E+00	.208167E+00
29	1	-.309577E+02	.000000E+00	.000000E+00	-.309577E+02	.000000E+00	.154788E+02
30	1	-.316277E+02	-.521085E+01	-.555183E+01	-.327471E+02	-.409149E+01	.143278E+02
31	1	-.315205E+02	-.615954E+01	-.591937E+01	-.328341E+02	-.484597E+01	.139941E+02
32	1	-.309524E+02	-.484989E+01	-.636597E+01	-.324222E+02	-.338010E+01	.145210E+02
33	1	-.297151E+02	.444350E+00	-.671537E+01	-.311427E+02	.187203E+01	.165074E+02
34	1	-.284670E+02	-.585656E+01	-.845101E+01	-.312766E+02	-.304698E+01	.141148E+02
35	1	-.187819E+02	.000000E+00	.000000E+00	-.187819E+02	.000000E+00	.939095E+01
36	1	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00
37	1	.000000E+00	.144116E+02	-.624361E+01	-.232867E+01	.167403E+02	.953447E+01
38	1	.000000E+00	.153058E+02	-.738727E+01	-.298377E+01	.182895E+02	.106366E+02
39	1	.000000E+00	.203229E+02	-.859089E+01	-.314488E+01	.234678E+02	.133064E+02

40	1	.000000E+00	.116906E+02	-.960388E+01	-.539757E+01	.170882E+02	.112429E+02
41	1	.000000E+00	.133394E+02	-.123755E+02	-.738869E+01	.207281E+02	.140584E+02
42	1	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00
43	1	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00
44	1	.000000E+00	.158297E+03	.197993E+02	-.243887E+01	.160736E+03	.815873E+02
45	1	.000000E+00	.124092E+03	.181228E+02	-.259256E+01	.126685E+03	.646385E+02
46	1	.000000E+00	.163056E+03	.337158E+02	-.669653E+01	.169752E+03	.882245E+02
47	1	.000000E+00	.509170E+02	.357828E+02	-.184567E+02	.693737E+02	.439152E+02
48	1	.000000E+00	-.304270E+02	.201108E+02	-.404305E+02	.100035E+02	.252170E+02
49	1	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00
50	1	-.292298E+02	.000000E+00	.000000E+00	-.292298E+02	.000000E+00	.146149E+02
51	1	.486800E+02	.233850E+03	.108663E+02	.480445E+02	.234486E+03	.932206E+02
52	1	.137756E+02	.659755E+02	.131145E+02	.106660E+02	.690850E+02	.292095E+02
53	1	.627195E+02	.183956E+03	.375692E+02	.520215E+02	.194654E+03	.713165E+02
54	1	-.898056E+01	.442001E+02	.458068E+02	-.353553E+02	.705749E+02	.529651E+02
55	1	-.774413E+01	-.276118E+02	.211923E+02	-.410829E+02	.572702E+01	.234050E+02
56	1	-.290432E+02	.000000E+00	.000000E+00	-.290432E+02	.000000E+00	.145216E+02
57	1	-.474729E+02	.000000E+00	.000000E+00	-.474729E+02	.000000E+00	.237364E+02
58	1	-.721731E+00	.153563E+03	-.169791E+02	-.256818E+01	.155410E+03	.789891E+02
59	1	.192228E+02	.122856E+03	.705266E+01	.187451E+02	.123334E+03	.522943E+02
60	1	-.162178E+02	-.193448E+02	.280867E+02	-.459115E+02	.103489E+02	.281302E+02
61	1	.588715E+02	.134555E+03	.388281E+02	.424951E+02	.150932E+03	.542184E+02
62	1	-.184624E+02	-.343803E+02	.281350E+02	-.556604E+02	.281764E+01	.292390E+02
63	1	-.219421E+02	.000000E+00	.000000E+00	-.219421E+02	.000000E+00	.109711E+02
64	1	-.715352E+01	.000000E+00	.000000E+00	-.715352E+01	.000000E+00	.357676E+01
65	1	-.325221E+02	.634898E+01	-.696002E+01	-.337307E+02	.755762E+01	.206442E+02
66	1	-.415738E+02	.277704E+02	.611972E+01	-.421097E+02	.283063E+02	.352080E+02
67	1	-.345939E+02	.426886E+02	.101919E+02	-.359154E+02	.440101E+02	.399627E+02
68	1	-.463199E+02	.356233E+02	.185166E+02	-.503098E+02	.396132E+02	.449615E+02
69	1	-.169561E+02	-.709822E+01	.294802E+02	-.419166E+02	.178623E+02	.298894E+02
70	1	-.236960E+02	.000000E+00	.000000E+00	-.236960E+02	.000000E+00	.118480E+02
71	1	-.305841E+02	.000000E+00	.000000E+00	-.305841E+02	.000000E+00	.152920E+02
72	1	-.299195E+02	-.132007E+01	.409374E+01	-.304940E+02	-.745628E+00	.148742E+02
73	1	-.295936E+02	-.584651E+01	.551457E+01	-.308117E+02	-.462839E+01	.130916E+02
74	1	-.290831E+02	-.660817E+01	.699720E+01	-.310835E+02	-.460776E+01	.132379E+02
75	1	-.276930E+02	-.326975E+01	.840526E+01	-.303061E+02	-.656657E+00	.148247E+02
76	1	-.233938E+02	-.214767E+01	.127434E+02	-.293612E+02	.381971E+01	.165904E+02
77	1	-.677044E+01	.000000E+00	.000000E+00	-.677044E+01	.000000E+00	.338522E+01
78	1	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00
79	1	.000000E+00	-.691499E+00	.000000E+00	-.691499E+00	.000000E+00	.345749E+00
80	1	.000000E+00	-.881164E-01	.000000E+00	-.881164E-01	.000000E+00	.440582E-01
81	1	.000000E+00	-.142808E-01	.000000E+00	-.142808E-01	.000000E+00	.714038E-02
82	1	.000000E+00	-.162505E+01	.000000E+00	-.162505E+01	.000000E+00	.812526E+00
83	1	.000000E+00	-.121597E+01	.000000E+00	-.121597E+01	.000000E+00	.607984E+00
84	1	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00	.000000E+00

MAXIMUM STRESS (SMAX) IN LAYER 1 IS 234.48570 AND OCCURS AT NODE 51

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NUMBER OF PROBLEMS TO BE SOLVED =    3

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*                                                                                       *
*     Section 1: RCA Base Course 254 mm (10 in) 1                                       *
*                                                                                       *
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MATL = 1 FOR LINEAR ELASTIC LAYERED SYSTEM

NDAMA = 0, SO DAMAGE ANALYSIS WILL NOT BE PERFORMED

NUMBER OF PERIODS PER YEAR (NPY) =    1

NUMBER OF LOAD GROUPS (NLG) =    1

     TOLERANCE FOR INTEGRATION (DEL) -- =     .00100

     NUMBER OF LAYERS (NL)------------- =         5

     NUMBER OF Z COORDINATES (NZ)------ =         1

     LIMIT OF INTEGRATION CYCLES (ICL)- =        80

     COMPUTING CODE (NSTD)------------- =         9

     THICKNESSES OF LAYERS (TH) ARE         :     3.50000    10.00000     6.00000    24.00000

     POISSON'S RATIOS OF LAYERS (PR) ARE    :      .35000      .20000      .33000      .40000      .40000

     VERTICAL COORDINATES OF POINTS (ZC) ARE:      .00000

     CONDITIONS OF INTERFACES (INT) ARE      :  0   0   0   0
     FOR PERIOD NO.  1 ELASTIC MODULI OF LAYERS ARE:    .420000E+06    .750000E+05    .320000E+05    .270000E+05    .250000E+05


     LOAD GROUP NO.  1 HAS 1 CONTACT AREAS
     CONTACT RADIUS (CR)--------------- =   6.00000
     CONTACT PRESSURE (CP)------------- =  79.00000
     RADIAL COORDINATES OF THE 7 POINTS (RC) ARE  :      .00000     8.00000    12.00000    18.00000    24.00000    36.00000
                                                       60.00000

     PERIOD NO.  1  LOAD GROUP NO.  1

  RADIAL     VERTICAL    VERTICAL    VERTICAL     RADIAL    TANGENTIAL    SHEAR     VERTICAL     RADIAL    TANGENTIAL    SHEAR
COORDINATE  COORDINATE    DISP.       STRESS      STRESS      STRESS      STRESS      STRAIN      STRAIN      STRAIN      STRAIN
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.00000	.00000	.1944E-01	.7900E+02	.1996E+03	.1996E+03	.0000E+00	-.1445E-03	.2430E-03	.2430E-03	.0000E+00
8.00000	.00000	.1485E-01	.2448E+02	.6018E+02	.8615E+02	.2958E-06	-.6366E-04	.5109E-04	.1346E-03	.1901E-11
12.00000	.00000	.1214E-01	.1166E+02	.2778E+02	.4429E+02	.8784E-06	-.3229E-04	.1951E-04	.7259E-04	.5647E-11
18.00000	.00000	.9215E-02	.5345E+01	.1103E+02	.1960E+02	.7006E-07	-.1281E-04	.5483E-05	.3303E-04	.4504E-12
24.00000	.00000	.7236E-02	.3039E+01	.5279E+01	.1000E+02	-.1972E-06	-.5499E-05	.1701E-05	.1689E-04	-.1268E-11
36.00000	.00000	.4867E-02	.1361E+01	.1722E+01	.3426E+01	.3102E-06	-.1048E-05	.1095E-06	.5588E-05	.1994E-11
60.00000	.00000	.1746E-02	.4197E-01	-.9814E+00	.8739E-01	.1045E-06	.8449E-06	-.2444E-05	.9909E-06	.6721E-12

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****************************************************************************************
*                                                                                      *
*     Section 1: RCA Base Course 254 mm (10 in) 2                                      *
*                                                                                      *
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MATL = 1 FOR LINEAR ELASTIC LAYERED SYSTEM

NDAMA = 0, SO DAMAGE ANALYSIS WILL NOT BE PERFORMED

NUMBER OF PERIODS PER YEAR (NPY) = 1

NUMBER OF LOAD GROUPS (NLG) = 1

TOLERANCE FOR INTEGRATION (DEL) -- = .00100

NUMBER OF LAYERS (NL)------------- = 5

NUMBER OF Z COORDINATES (NZ)------ = 1

LIMIT OF INTEGRATION CYCLES (ICL)- = 80

COMPUTING CODE (NSTD)------------- = 9

THICKNESSES OF LAYERS (TH) ARE : 3.50000 10.00000 6.00000 24.00000

POISSON'S RATIOS OF LAYERS (PR) ARE : .35000 .20000 .33000 .40000 .40000

VERTICAL COORDINATES OF POINTS (ZC) ARE: .00000

CONDITIONS OF INTERFACES (INT) ARE : 0 0 0 0
FOR PERIOD NO. 1 ELASTIC MODULI OF LAYERS ARE: .420000E+06 .750000E+05 .320000E+05 .270000E+05 .250000E+05

LOAD GROUP NO. 1 HAS 1 CONTACT AREAS
CONTACT RADIUS (CR)--------------- = 6.00000
CONTACT PRESSURE (CP)------------- = 100.00000
RADIAL COORDINATES OF THE 7 POINTS (RC) ARE : .00000 8.00000 12.00000 18.00000 24.00000 36.00000
60.00000

PERIOD NO. 1 LOAD GROUP NO. 1

RADIAL COORDINATE	VERTICAL COORDINATE	VERTICAL DISP.	VERTICAL STRESS	RADIAL STRESS	TANGENTIAL STRESS	SHEAR STRESS	VERTICAL STRAIN	RADIAL STRAIN	TANGENTIAL STRAIN	SHEAR STRAIN
.00000	.00000	.2460E-01	.1000E+03	.2526E+03	.2526E+03	.0000E+00	-.1830E-03	.3077E-03	.3077E-03	.0000E+00
8.00000	.00000	.1880E-01	.3098E+02	.7617E+02	.1091E+03	.3744E-06	-.8059E-04	.6467E-04	.1704E-03	.2407E-11
12.00000	.00000	.1537E-01	.1476E+02	.3516E+02	.5607E+02	.1112E-05	-.4088E-04	.2469E-04	.9189E-04	.7148E-11
18.00000	.00000	.1166E-01	.6766E+01	.1397E+02	.2481E+02	.8868E-07	-.1621E-04	.6940E-05	.4180E-04	.5701E-12
24.00000	.00000	.9160E-02	.3847E+01	.6683E+01	.1266E+02	-.2497E-06	-.6961E-05	.2153E-05	.2137E-04	-.1605E-11
36.00000	.00000	.6160E-02	.1723E+01	.2179E+01	.4337E+01	.3926E-06	-.1327E-05	.1386E-06	.7074E-05	.2524E-11
60.00000	.00000	.2210E-02	.5312E-01	-.1242E+01	.1106E+00	.1323E-06	.1070E-05	-.3094E-05	.1254E-05	.8507E-12

```
*****************************************************************************************
*                                                                                       *
*     Section 1: RCA Base Course 254mm (10in) 3                                         *
*                                                                                       *
*****************************************************************************************
```

MATL = 1 FOR LINEAR ELASTIC LAYERED SYSTEM

NDAMA = 0, SO DAMAGE ANALYSIS WILL NOT BE PERFORMED

NUMBER OF PERIODS PER YEAR (NPY) = 1

NUMBER OF LOAD GROUPS (NLG) = 1

TOLERANCE FOR INTEGRATION (DEL) -- = .00100

NUMBER OF LAYERS (NL)------------- = 5

NUMBER OF Z COORDINATES (NZ)------ = 1

LIMIT OF INTEGRATION CYCLES (ICL)- = 80

COMPUTING CODE (NSTD)------------- = 9

THICKNESSES OF LAYERS (TH) ARE : 3.50000 10.00000 6.00000 24.00000

POISSON'S RATIOS OF LAYERS (PR) ARE : .35000 .20000 .33000 .40000 .40000

VERTICAL COORDINATES OF POINTS (ZC) ARE: .00000

CONDITIONS OF INTERFACES (INT) ARE : 0 0 0 0
FOR PERIOD NO. 1 ELASTIC MODULI OF LAYERS ARE: .420000E+06 .750000E+05 .320000E+05 .270000E+05 .250000E+05

```
LOAD GROUP NO.  1 HAS 1 CONTACT AREAS
CONTACT RADIUS (CR)--------------- =    6.00000
CONTACT PRESSURE (CP)------------- = 134.00000
RADIAL COORDINATES OF THE 7 POINTS (RC) ARE  :       .00000     8.00000    12.00000    18.00000    24.00000    36.00000
                                                   60.00000
```

PERIOD NO. 1 LOAD GROUP NO. 1

RADIAL COORDINATE	VERTICAL COORDINATE	VERTICAL DISP.	VERTICAL STRESS	RADIAL STRESS	TANGENTIAL STRESS	SHEAR STRESS	VERTICAL STRAIN	RADIAL STRAIN	TANGENTIAL STRAIN	SHEAR STRAIN
.00000	.00000	.3297E-01	.1340E+03	.3385E+03	.3385E+03	.0000E+00	-.2452E-03	.4123E-03	.4123E-03	.0000E+00
8.00000	.00000	.2519E-01	.4152E+02	.1021E+03	.1461E+03	.5017E-06	-.1080E-03	.8665E-04	.2283E-03	.3225E-11
12.00000	.00000	.2059E-01	.1978E+02	.4711E+02	.7513E+02	.1490E-05	-.5478E-04	.3309E-04	.1231E-03	.9579E-11
18.00000	.00000	.1563E-01	.9067E+01	.1872E+02	.3325E+02	.1188E-06	-.2172E-04	.9300E-05	.5602E-04	.7639E-12
24.00000	.00000	.1227E-01	.5156E+01	.8955E+01	.1697E+02	-.3346E-06	-.9327E-05	.2885E-05	.2864E-04	-.2151E-11
36.00000	.00000	.8255E-02	.2309E+01	.2920E+01	.5811E+01	.5261E-06	-.1778E-05	.1857E-06	.9479E-05	.3382E-11
60.00000	.00000	.2962E-02	.7119E-01	-.1665E+01	.1482E+00	.1773E-06	.1433E-05	-.4146E-05	.1681E-05	.1140E-11

APPENDIX C

Concrete Recycling Companies

Anderson Columbia Co., Inc.
PO Box 490
Bagdad, FL 32530
Tel: (904) 938-2002
Contact: Ken Murphy, Brian Yerby

Central Florida Crusher
9800 Recycled Center Rd. Suite A
Orlando, FL 32824
Tel: (407) 240-1664
Contact: Lloyd Glover

Continental Waste Industries
CWI of Florida
11273 Rocket Blvd.
Orlando, FL 32824
Tel: (407) 240-6895
Contact: Kerry Bazinet

Dade Recycling Center, Inc.
15490 NW 97th Av.
Miami, FL 33016
Tel: (305) 826-0707
Contact: Alex Gomez

Dixie Septic Tank
PO Box 740557
Orange City, FL 32774
Tel: (904) 775-3051
Contact: Gene and Todd Evans

Glasbrenner, Sonny, Inc.
6409 N. 123rd Av.
Largo, FL 34642
Tel: (813) 536-6607
Contact: Sonny Glasbrenner

Homestead Landfill & Recycling Co.
PO Box 901840
Homestead, FL 33090
Tel: (305) 230-1111
Contact: Elvis Mason

D.S. Eakins Construction Co.
PO Box 9818
Riviera Beach, FL 33419
Tel: (407) 842-0001
Contact: Doug Eakins

Florida Concrete Recycling, Inc.
730 SW 3rd St.
Gainesville, FL 32601
Tel: (352) 372-1237
Contact: Tim Renfroe

Frontier Recycling
1755 SE 20th Av.
Largo, FL 33771
Tel: (813) 581-1544
Contact: Robert Gomes

Gator Asphalt
PO Box 20309
Brandenton, FL 34202
Tel: (941) 355-9306
Contact: John Jackson

GeoTech Industries
PO Box 490300
Leesburg, FL 34749
Tel: (352) 787-0608
Contact: Randy Thompson

Realco Recycling
8707 Somers Rd.
Jacksonville, FL 32226
Tel: (904) 751-1556
Contact: Jean Baker

Woodruff & Sons
PO Box 10127
Brandenton, FL 34282
Tel: (813) 756-1871
Contact: Roy Woodruff

J&A Transfer
2241 NW 15th Ct.
Pompano, FL 33069
Tel: (954) 968-6268
Contact: Frank Leon

Kimmins Contracting Corp.
1501 E. 2nd Av.
Tampa, FL 33605
Tel: (813) 248-3878

Mulliniks
5937 Soutel Dr.
Jacksonville, FL 32219
Tel: (904) 764-3644
Contact: Lynne Mulliniks

Independent Excavating Company
730 Roosevelt Plaza
Tampa Port Authority
Tampa, FL 33605
Tel: (813) 247-4114
Contact: Leonard Burd

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