This is to certify that the

thesis entitled

The Effects of Mix Design on the Design of the Pavement Structure when Utilizing Recycled Portland Cement Concrete as Aggregate

presented by

James S. Fergus

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Civil Engineering

Major professor

Date May 8, 1980

THE EFFECTS OF MIX DESIGN ON THE DESIGN OF THE PAVEMENT STRUCTURE WHEN UTILIZING RECYCLED PORTLAND CEMENT CONCRETE AS AGGREGATE

by

James Stanley Fergus, P.E.

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Civil Engineering

1980

ABSTRACT

THE EFFECTS OF MIX DESIGN ON THE DESIGN OF THE PAVEMENT STRUCTURE WHEN UTILIZING RECYCLED PORTLAND CEMENT CONCRETE AS AGGREGATE

by

James Stanley Fergus, P.E.

The principal purpose of this research was to investigate the feasibility of crushing an existing Portland cement concrete pavement and using the resulting aggregate in the concrete mixture required for replacement of the structure. In addition, the research included initial experiments to determine the effects of incorporating bituminous overlay materials as a proportion of the aggregate.

Many areas in this country are experiencing difficulty obtaining quality aggregates for paving and other construction. Since there are a number of crushing operations engaged in crushing concrete for non-structural construction purposes, a few researchers have attempted to determine the value of this waste material for use as concrete aggregate. Each investigator predicted lower concrete strengths and, therefore, more expense when using recycled Portland cement concrete for the aggregate in a concrete mixture. Because these experiments were limited in scope, it was suggested

that further research would be necessary before a valid determination could be made.

The experimental procedures used for this research attempted to incorporate the complete range of variables found in crushing and utilizing recycled concrete including determinations of crushing properties, aggregate properties, and concrete properties with varying mix proportions. Research results were applied to the economic, environmental, and design factors related to Portland cement concrete pavement construction.

The basic research procedure was to obtain sufficient amounts of concrete from an existing pavement to perform comprehensive experiments. Material for the standard experiments was obtained from pavement slab sections which had been removed from a highway during a reconstruction project. The slab material was crushed at a commercial crushing plant with further processing at the laboratory. In addition, pavement cores were obtained from various highway locations for correlation experiments.

Seventy experimental tests related to the determination of aggregate properties were completed. Three hundred-eighty tests were completed for the determination of concrete properties. All laboratory tests were accomplished according to current ASTM standards or procedures used by the Michigan Department of Transportation. Pavement design was based on procedures suggested by the AASHO Interim Guide for the Design of Pavement Structures.

The major finding of this study was that crushing existing Portland cement concrete pavements will provide an aggregate that can be used on a design basis equal to a concrete design utilizing conventional aggregates. In addition, the utilization of recycled Portland cement concrete aggregates in new concrete provides an economically and environmentally sound resource for the reconstruction of roadways.

To my wife Joan, and to my children, Carol, Deborah, Barbara, James, Christopher, Susan, David, Paul, Elizabeth, Alexander, and Laura.

ACKNOWLEDGMENTS

In appreciation to my guidance committee, Dr. G. C. Blomquist, Dr. J. D. Brogan, Mr. W. J. MacCreery, Dr. F. X. McKelvey, and Dr. W. C. Taylor.

In special gratitude to my colleagues at the Michigan Department of Transportation for their help and encouragement throughout the period of this research.

This research was made possible through the sponsorship of the Michigan Department of Transportation and a fellowship from the National Highway Institute, Federal Highway Administration.

TABLE OF CONTENTS

	Page
LIST OF TABLES	vii
LIST OF FIGURES	xii
Chapter	
I. INTRODUCTION.	1
II. LITERATURE REVIEW	4
2.1 Physical Properties of Recycled PCC Aggregates	5
2.1.1 Gradation	5
2.1.2 Absorption and Specific Gravity	8
2.1.3 Durability Factor	11
2.2 Physical Properties of Concrete Made with Recycled PCC Aggregate	14
2.2.1 Flexural Strength	14
2.2.2 Compressive Strength.	14
2.2.3 Other Physical Properties of Hardened Concrete	17
2.3 Economics of Crushing PCC for New Pavements	22
2.3.1 Previous Economic Evaluations . . .	22
2.4 Concrete Mix Design.	28
2.4.1 Portland Cement Association Method.	28
2.4.2 American Concrete Institute Method.	32
2.4.3 Michigan Department of Transportation (Mortar Voids) Method.	40
2.4.4 Mix Design Utilizing Recycled PCC Aggregate	43
2.5 Rigid Pavement Design.	45
2.5.1 Theoretical Stress Analysis	45
2.5.2 Portland Cement Association Method.	48
2.5.3 AASHO Interim Guide Method.	48

Chapter			Page
III.	RESEARCH MATERIALS AND MIX DESIGN		55
	3.1 Component Materials.		55
		3.1.1 Materials for Recycling	55
		3.1.2 Bituminous Material	64
		3.1.3 Fine Aggregate.	65
		3.1.4 Coarse Control Aggregate.	65
		3.1.5 Cement.	66
	3.2 Concrete Mix Design Used for Research. . .		66
		3.2.1 Mix Design Procedure.	67
IV.	AGGREGATE PROPERTIES.		69
	4.1 Material Preparation and Gradation		70
		4.1.1 Field Crushed PCC Slab Sections . .	70
		4.1.2 PCC Pavement Cores.	77
		4.1.3 Laboratory PCC Test Beams	78
		4.1.4 Other Research Aggregates	78
	4.2 Physical Properties of Research Aggregates		85
		4.2.1 Deleterious Particles in Coarse Aggregate	85
		4.2.2 Bulk Specific Gravity and Percent Absorption of Coarse Aggregate. . .	89
		4.2.3 Salt Content (NaCl) of Portland Cement Concrete	91
		4.2.4 Experimental Results for Aggregate Properties.	91
V.	CONCRETE PROPERTIES		97
	5.1 Aggregate Proportions for Experimental Mixes.		98
		5.1.1 Recycled PCC Aggregate.	98
		5.1.2 Recycled PCC in Combination with Bituminous Concrete	99
	5.2 Laboratory Procedures for Test Batches . .		102
		5.2.1 Material Weighing and Preparation .	102
		5.2.2 Research Mix Design	103
		5.2.3 Mixing Experimental Batches	104

Chapter | Page

5.3 Properties of Fresh Concrete 104

5.3.1 Workability 104
5.3.2 Test Results for Fresh Concrete . . 106

5.4 Properties of Hardened Concrete. 106

5.4.1 Curing Test Specimens 106
5.4.2 Compressive (f'_c) and Flexural (MR) Strengths. 111
5.4.3 Sonic Testing 116

VI. APPLICATION OF EXPERIMENTAL RESULTS 122

6.1 Economic Evaluation. 122

6.1.1 Crushing PCC for Aggregate. 123
6.1.2 Cost Comparisons. 123

6.2 Environmental Considerations 126

6.2.1 Energy Requirements 129
6.2.2 Natural Resources 129

6.3 Pavement Design. 131

6.3.1 Concrete Properties Related to Pavement Design 131
6.3.2 Thickness Design Criteria 131
6.3.3 Alternate Working Stress (f_t) Determination 132

VII SUMMARY AND CONCLUSIONS. 135

7.1 Discussion of Experimental Results. . 135

7.2 Conclusions 137

LIST OF REFERENCES. 139

APPENDICES:

Appendix A Values Used for Economic and Energy Comparisons. 143

Appendix B Sample Calculations 146

Appendix C Sample Worksheets for Experimental Tests. 150

LIST OF TABLES

Table		Page
2-1.	Iowa Gradation Test Results for Recycled Aggregate	7
2-2.	Recalculated Iowa Gradation Test Results for Recycled Aggregate	9
2-3.	Specific Gravities and Absorptions of Aggregates	10
2-4.	Specific Gravities of Recycled Concrete From the Iowa Project	10
2-5.	Durability Factor for Concrete Beams in Accelerated Freezing and Thawing	12
2-6.	Selected Physical Properties of the Five Concrete Mixtures Tested	12
2-7.	Iowa Durability Factors	13
2-8.	Iowa Project Mix Proportions	15
2-9.	28-Day Flexural Strength Test Results from the Iowa Experimental Project	16
2-10.	Average Compressive Strengths of the Five Concrete Mixtures Tested	18
2-11.	Relationship Between Water-Cement Ratio and Compressive Strength. Cement: Portland Cement Type III; Fine Aggregate: Ottawa Sand. Tested at 8 Days	19
2-12.	Relationship Between Water-Cement Ratio and Compressive Strength. Cement: Portland Cement Type I; Fine Aggregate: Granite Sand. Tested at 15 Days	19
2-13.	28-Day Compressive Strength Test Results form the Iowa Experimental Project	20

Table		Page

2-14.	Compared Compressive Strengths from Three Studies	20
2-15.	Linear Coefficient of Thermal Expansion of the Five Concrete Mixtures Tested. . . .	21
2-16.	Length Changes of Concrete Specimens Stored at Constant Moisture and Temperature. . . .	23
2-17.	Energy Requirements for Recycled PCC Aggregate Compared to Conventional Aggregate.	27
2-18.	Recommended Slumps for Various Types of Construction.	33
2-19.	Approximate Mixing Water and Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregates	34
2-20.	Relationships Between Water-Cement Ratio and Compressive Strength of Concrete. . . .	35
2-21.	Maximum Permissible Water-Cement Ratios for Concrete in Severe Exposures.	36
2-22.	Volume of Coarse Aggregate Per Unit of Volume of Concrete.	37
2-23.	First Estimate of Weight of Fresh Concrete . .	38
2-24.	Concrete Proportioning Data for Slipform Pavement.	44
2-25.	Stress Ratios and Allowable Load Repetitions .	51
3-1.	Gradation Requirements for Coarse Aggregates Used in Source Material for Recycling . . .	60
3-2.	Gradation Requirements for Coarse Aggregates Used in Source Material for Recycling . . .	60
3-3.	Histories of Source Materials From Michigan Department of Transportation Road Logs	61
4-1.	Crusher Run Gradations for Recycled I-96 Slab Sections	71
4-2.	Coarse Fraction Gradation Test Results for Three Samples of Recycled PCC Aggregate A - Cumulative Percent Passing.	74

Table		Page

4-3. Fine Fraction Gradation Test Results for Three Samples of Recycled PCC Aggregate A - Cumulative Percent Passing. 75

4-4. Average Compressive Strengths of PCC Pavement Cores from Various Locations . . . 77

4-5. Gradations of Coarse Recycled PCC Aggregates - Cumulative Percent Passing. 79

4-6. Gradations of Fine Recycled PCC Aggregates - Cumulative Percent Passing. 80

4-7. Gradations of Various Coarse Aggregates Used for Research - Cumulative Percent Passing . 83

4-8. Gradations of Various Fine Aggregates Used for Research - Cumulative Percent Passing . . . 84

4-9. Michigan Gradation Limits for Coarse Aggregates Used in PCC Mixes for Pavement - Cumulative Percent Passing 86

4-10. Michigan Gradation Limits for Fine Aggregates Used in Mixes for PCC Pavements - Cumulative Percent Passing 87

4-11. Coding and Source Information for Research Aggregates. 88

4-12. Weighted Bulk Specific Gravity (G_b) and Percent Absorption (A_b) of Recycled PCC Coarse Aggregate A. 90

4-13. Salt Content (NaCl) of Recycled PCC Aggregate 92

4-14. Deleterious Particles in Coarse Aggregates Used for Research Compared to Michigan Department of Transportation Specifications 93

4-15. Various Properties of Coarse Aggregates Used for Research. 94

4-16. Various Properties of Fine Aggregates Used for Research. 95

5-1. Combinations of Aggregates Used for Recycled PCC Mix Design. 100

Table		Page

5-2. Combinations of Aggregate Used for Recycled PCC Mix Design Including Bituminous Concrete. 101

5-3. Average Percent Retained on Each Sieve Size For Aggregate A 103

5-4. Properties of Fresh Concrete Made with Recycled PCC Aggregate. 107

5-5. Properties of Fresh Concrete Made with Combinations of Recycled PCC and Crushed Bituminous Concrete 108

5-6. Air Contents of Concrete Made with Proportions of Recycled PCC and Bituminous Concrete . . 109

5-7. Number of Test Specimens Made for Each Experimental Batch. 109

5-8. Compressive and Flexural Strengths of Concrete Made with Recycled PCC and Control Aggregate 112

5-9. Compressive and Flexural Strengths of Concrete Made with a Combination of Recycled PCC and Bituminous Concrete. . . . 113

5-10. Durability Factors (DF)* for Research Mixes. . 119

5-11. Dynamic Young's Modulus of Elasticity (E) and Poisson's Ratio (μ) for Selected Research Test Specimens 121

6-1. Estimated Hourly Costs for a Recycled PCC Crushing Operation. 125

6-2. Aggregate Proportions Using Recycled PCC or Natural Aggregate for One Cubic Yard of Concrete - Based on Replacing an Equal Section 127

6-3. Cost Comparisons for Aggregate Alternatives for a Ten Mile Dual PCC Pavement Removal and Replacement Project - Based on 1979 Michigan Prices 128

6-4. Energy Requirements for Aggregate Alternatives for a Ten Mile Dual PCC Pavement Removal and Replacement Project 130

Table		Page

6-5. Pavement Thickness Design Based on Standard Research Mix Designs 133

6-6. Alternate Determinations of Working Stress for Research Mixes 134

LIST OF FIGURES

Figure		Page
2-1.	Relationship Between Water-Cement Ratio and Modulus of Elasticity. Cement: Portland Cement Type III; Fine Aggregate: Ottawa Sand.	24
2-2.	Relationship Between Water-Cement Ratio and Modulus of Elasticity. Cement: Portland Cement Type I; Fine Aggregate: Granite Sand.	24
2-3.	Schematic Flow Chart of Recycling Plant. . . .	26
2-4.	Typical Trial Mix Strength Curves.	30
2-5.	Typical Relationship Between Percentage of Fine Aggregate and Cement Content for a Given Water-Cement Ratio and Slump.	31
2-6.	Typical Curve Showing the Relationship Between the Water Content of Mortars and the Volume of Mortar	41
2-7.	Typical Relationship Between Compressive Strength and Cement-Space Ratio	42
2-8.	Westergaard's Case for Corner Loading.	46
2-9.	Design Chart for Single-Axle Truck Loads . . .	49
2-10.	Design Chart for Tandem-Axle Truck Loads . . .	50
2-11.	Design Chart for Rigid Pavements, P_t = 2.5 . .	52
2-12.	Design Chart for Rigid Pavements, P_t = 2.0 . .	53
3-1.	Typical Transverse Joint Failure	57
3-2.	Removal of Slab Sections for Joint Repair. . .	57
3-3.	Disposal Site for Waste Pavement Sections. . .	58
3-4.	Breaking Pavement Slabs for Research Material.	58
3-5.	Coring Pavement Slabs.	59

Figure		Page

3-6. Charging Apron Feeder at Michigan Crushed Concrete, Inc.. 63

3-7. Hand-Picking Steel and Other Material from Crusher Belt at Michigan Crushed Concrete Inc. 63

3-8. Removal of Steel from Crusher Belt by Magnet at Michigan Crushed Concrete, Inc.. 64

4-1. Gilson Mechanical Grader 73

4-2. Denver Jaw Crusher 73

4-3. Particle Size Distribution of Coarse and Fine Fractions of Aggragate A 76

4-4. Particle Size Distribution of Coarse and Fine Fractions of Recycled PCC Aggregates . 81

5-1. Laboratory Pan Mixer 105

5-2. Roll-A-Meter for Volumetric Air Tests. 105

5-3. Air Contents of Concrete, Containing Proportions of Crushed Bituminous Concrete for Aggregate with the Addition of Various Amounts of Air Entraining Admixture 110

5-4. The Effects of the Percent of Recycled PCC Fine Aggregate, in Total Fine Aggregate, on Compressive Strength 114

5-5. The Effects of the Percent of Recycled PCC Fine Aggregate, in Total Fine Aggregate, on Flexural Strength. 115

5-6. Soiltest CT 366C Sonometer 117

5-7. Freeze-Thaw Chamber. 117

6-1. Schematic of a Portable Recycled PCC Crushing Operation. 124

CHAPTER I

INTRODUCTION

Due to the extensive road building and other construction programs carried on in the United States since the 1950's, the availability of quality aggregates for construction purposes has become critical in many geographical areas. This shortage of aggregates has led to a variety of experimental projects using "waste" or recycled materials for all or part of the components of roadway structures. To date, most work involving recycled materials for highways has concentrated on using these materials in bituminous concrete mixtures and for base course materials.

Until the early 1970's, most Portland cement concrete waste materials were disposed of in landfills, but problems with meeting the requirements of new environmental restrictions is making this procedure more difficult. In addition, it is not unusual to have to haul great distances to suitable landfill sites when this waste material is generated in urban areas. Therefore, economic factors have led to the establishment of major waste Portland cement concrete crushing operations in many metropolitan areas which have proven to be both environmentally and economically feasible.

Most of the material resulting from these crushing operations is used as subbase for road and parking lot surfacing, aggregate driveways, and various fill purposes. An investigation of crushing operations in the Detroit, Michigan metropolitan area indicated that appropriate screening could produce an aggregate with a gradation suitable for concrete mixtures at a cost which would be competitive with other natural or manufactured aggregate.

Many of the highway systems started in the late 1950's using Portland cement concrete for the surface structure are now in the need of repair. This is normally accomplished by some bituminous overlayment procedure. An investigation of highway systems in Michigan resulted in a determination that these overlays normally have a useful service life of about eight years. Therefore, it would seem desirable to completely rebuild the surface structure for a service life of twenty years or more if reduced periods of traffic control and maintenance are a consideration. In addition, a limited amount of overlays can be placed on existing roadways due to the necessity of maintaining overhead clearance at structures. Furthermore, complete removal of an existing pavement for the purpose of recycling the materials into a new pavement would allow for correction of subgrade failures, deficiencies in geometrics, and drainage problems.

Before a roadway has been selected for recycling into a new pavement structure, it would be preferable to have some knowledge of the physical properties of the final mixture with regard to design. The limited data available, to date, indicated the possibility of having to design thicker pavements with recycled concrete materials, in addition to other construction and material problems. A determination that it may not be possible to use all of the material available in the existing pavement for the new concrete mixture on an equivalent design basis would be very important from an economical and processing standpoint.

The main emphasis of this research was to investigate the variables connected with completely recycling existing Portland cement concrete pavement materials and to apply the results to the design of Portland cement concrete pavement. Although theoretical concepts with respect to pavement design will be discussed, the final application of research results will be based on empirical determinations.

CHAPTER II

LITERATURE REVIEW

Although the use of building rubble as aggregate for concrete construction purposes was reported in Europe immediately following World War II (4,13), technical data was somewhat limited. Reported construction projects in the United States which utilized recycled concrete as an aggregate substitute for new Portland cement concrete are restricted to a few airfield reconstruction projects (18,24, 25) and an experimental paving project in Iowa (3). Since the concrete mixtures for the airfields were actually "lean mixes" used as subbase for conventional concrete surfacing, the results are not pertinent to this study. The technical report concerning the Iowa project offered valuable background information for pavement and concrete mix design. However, conclusions resulting from this project, in addition to other studies (4,12) indicated a need for further research. This was particularly true in the design of the thickness of the surfacing structure, the utilization of bituminous overlayment materials, and the incorporation of crusher fines in a concrete mixture.

In addition, previously reported research did not thoroughly investigate the physical properties of materials resulting from concrete crushing operations with respect to gradation characteristics, structural integrity, and mix design incorporating the number of variables which result from crushing operations. Furthermore, a review of existing literature did not produce a valid analysis of the economic and environmental factors applicable to the utilization of aggregates produced by crushing existing Portland cement concrete (PCC) pavements and using this material in concrete produced for the replacement structure.

2.1 Physical Properties of Recycled PCC Aggregates

There exists a traditional theory which states that the final concrete product is no better than the aggregates used in the mix. Therefore, this section will concentrate on previous research related to the basic qualities of recycled PCC aggregates.

2.1.1 Gradation

The gradation or grain size distribution of aggregates is an important property affecting the strength and proportions of a concrete mixture (42). Most conventional aggregates such as gravel and crushed stone are produced through a crushing and/or screening process that assures a gradation falling within certain specified limits. However, the assurance of a consistant gradation is the most important factor from a concrete mix design standpoint.

The Iowa report (3) was the only study that offered an indication of the overall crushing characteristics of recycled PCC under field conditions. In this case, an existing PCC pavement, resurfaced with three inches of asphalt concrete, was selected for an experimental project. The asphalt was removed as a separate operation prior to pavement breaking and removal. The asphalt and Portland cement concrete materials were independently crushed in a primary jaw crusher to a minus six inch size and stockpiled. The materials were then processed through a secondary crusher to 100 percent passing the 1-1/2 inch size screen opening. Since it was intended to use a combination of asphalt and Portland cement concrete in part of the project, a portion of the six inch top size material was passed through the secondary crusher in approximately the same proportions existing in the original pavement.

A laboratory analysis of gradations of the crushed PCC alone and the combination of materials (Table 2-1) indicated a fairly well-graded material. The analysis did not indicate whether the asphalt concrete crushed linearly with the PCC concrete when the materials were crushed together. Information of this nature would have been of significant value for design purposes.

Reported field observations on the Iowa (3) project were that there was a high degree of segregation of aggregate particle sizes when stockpiling the material from the

Table 2-1. Iowa Gradation Test Results for Recycled Aggregate. (Source: Bergren and Britson)(3)

	Crushed PCC		Crushed PCC and AC	
Sieve	% Retained	% Passing	% Retained	% Passing
1"	10.1	89.9	15.0	85.0
3/4"	18.6	71.3	17.0	68.0
1/2"	23.4	47.9	21.7	46.3
3/8"	8.6	39.3	8.5	37.8
#4	16.0	23.3	15.9	21.9
#8	7.6	15.7	7.8	14.1
#16	4.4	11.3	4.2	9.9
#30	3.7	7.6	3.7	6.2
#50	3.5	4.1	3.0	3.2
#100	1.9	2.2	1.4	1.8
#200	1.0	1.2	0.8	1.0
Pan	1.2		1.0	
	100.0		100.0	

secondary crusher. This generated abnormal batching difficulties when the materials were used. Therefore, final recommendations resulting from research experience on this project were that the crushed materials should have been separated by appropriate screening into fine and coarse fractions and stockpiled separately. This can be accomplished through a simplified crushing operation as indicated by previous work in Florida (23,25). The gradations shown in Table 2-1 were recalculated to provide information concerning the fine and coarse aggregate particle sizes using material retained on the #4 sieve as the size split (Table 2-2).

2.1.2 Absorption and Specific Gravity

A determination of the absorptions and specific gravities of component materials is necessary for concrete mix design purposes. Buck (4), in his work at the United States Army Engineer Waterways Experiment Station reported values listed in Table 2-3. The first values listed were for crushed material from a driveway containing siliceous aggregate (chert gravel and natural sand) in the PCC mix. The second material was from a laboratory beam containing calcareous coarse aggregate (limestone) and a siliceous natural sand. Test results for control aggregates are also included.

Specific gravity results, only, were furnished in the Iowa(3) report (Table 2-4). The original concrete used for recycling was made with natural gravel coarse aggregate

Table 2-2. Recalculated Iowa Gradation Test Results for Recycled Aggregate. (Based on Bergren and Britson)(3)

	Crushed PCC		Crushed PCC and AC	
Sieve	% Retained	% Passing	% Retained	% Passing
	Coarse Fraction			
1"	13.2	86.8	19.3	80.7
3/4"	24.2	62.6	21.9	58.8
1/2"	30.5	32.1	27.9	30.9
3/8"	11.2	10.9	10.9	10.0
#4	20.9	Min.	20.0	Min.
	100.0		100.0	
	Fine Fraction			
#4	0.0	100.0	0.0	100.0
#8	32.6	67.4	35.6	54.4
#16	18.9	48.5	19.2	35.2
#30	15.9	32.6	16.9	28.3
#50	15.0	17.6	13.7	14.6
#100	8.1	9.5	6.4	8.2
#200	4.3	5.2	3.6	4.6
Pan	5.2		4.6	
	100.0		100.0	

Table 2-3. Specific Gravities and Absorptions of Aggregates. (Source: Buck)(4)

Aggregate	Bulk Specific Gravity Saturated Surface - Dry	Percent Absorption
Crushed Siliceous Concrete Coarse	2.43	4.0
	2.44	4.3
Fine	2.34	7.6
	----	9.0
Crushed Calcareous		
Concrete (Coarse	2.52	3.9
Chert Gravel	2.52	2.6
Limestone	2.67	0.8
Natural Sand	2.63	0.4

Table 2-4. Specific Gravities of Recycled Concrete From the Iowa Project. (Source: Bergren and Britson)(3)

Material	Specific Gravity
Crushed PCC	2.457
Crushed PCC and Asphalt Concrete Combined	2.445

and natural sand. Specific gravities for both the plain PCC and the combination of materials are in close agreement with those reported by Buck (4) for materials with the same basic composition.

2.1.3 Durability Factor

The durability factor is an indicator of the resistance of concrete to rapid freezing and thawing and is a test used to compare aggregates on the basis of standard mix design. On a range from 0 to 100, a higher numerical value would indicate greater resistance. Buck's (4) test results were extremely low (Table 2-5). However, when compared to control aggregates, the resistance to freezing and thawing was significantly improved for the aggregate produced by crushing chert concrete and essentially comparable when aggregate was made from limestone concrete. Mix designs for all tests were approximately equal (Table 2-6).

Laboratory data (Table 2-7) from the Iowa (3) tests indicated higher values with the factor given for the mix containing asphalt concrete as part of the aggregate considered of doubtful durability. This comparison may not be valid since different designs were used for each mix. Such related information as values for the water-cement ratios and air contents of the laboratory mixes were not reported.

Table 2-5. Durability Factor for Concrete Beams in Accelerated Freezing and Thawing. (Based on Buck)(4)

	Durability Factor			
Mixture	1	2	3	Combined
1	4	4	2	3
2	28	22	19	23
3	30	28	25	28
4	62	--	--	--
5	45	--	--	--

Table 2-6. Selected Physical Properties of the Five Concrete Mixtures Tested. (Based on Buck)(4)

Mix	Round	Slump (in.)	Air (%)	Cement Content (lb/yd)	Aggregate Coarse	Aggregate Fine
1	1	2-1/4	6.0	461		
	2	2-1/2	6.3	461	Chert Gravel	Sand
	3	2-1/2	6.3	461		
2	1	2-1/2	5.7	461		
	2	2-1/2	5.8	461	Chert PCC	Sand
	3	2-1/2	6.0	461		
3	1	2	6.3	498		
	2	2	6.0	508	Chert PCC	Chert PCC
	3	2	5.9	508		
4	-	2-3/4	6.0	508	Limestone	Sand
5	-	2-1/2	6.1	489	Limestone PCC	Sand

Table 2-7. Iowa Durability Factors. (Source: Bergren and Britson)(3)

Mix	Cement (lb.)	Aggregate Type	Percent Aggregate Proportion	Sand Added	Durability Factor
1	564	Cr. PC	60 C.A. - 40 F.A.	633	88
2	564	Cr. PC	50 C.A. - 50 F.A.	1043	94
3	470	Cr. ACPC	66 C.A. - 34 F.A.	486	79

2.2 Physical Properties of Concrete Made with Recycled PCC Aggregate

There are a number of parameters involving the application of the properties of Portland cement concrete to engineering design with those related to strength considered most important.

2.2.1 Flexural Strength

The flexural or bending strength of concrete is used for the determination of pavement design in all contemporary methods. An average 28-day test value of 650 psi is often considered as a standard design strength for pavements (46).

Of the four mixes used on the Iowa (3) project (Table 2-8), mixes A and B containing crushed PCC indicated higher than normal flexural strengths (Table 2-9). This agreed with previous conclusions by Gluzhge (13) that flexural strengths will be higher compared to compressive strengths. The mixes C and C-3 containing crushed asphalt concrete were significantly lower.

2.2.2 Compressive Strength

Compressive strengths of concrete are normally used for determining design of buildings and bridge structures. In addition, compressive strengths are often used to compare concrete mixes made with different proportions of cement, aggregates, and other variables.

Table 2-8. Iowa Project Mix Proportions. (Based on Bergren and Britson)(3)

	Basic Absolute Volume	Quantities Cubic Yard
Mix "A": 35% C.A. - 65% F.A.		
Cement	.106611	564 lb.
Water	.181030	305 lb.
Air	.060000	
Agg. (Crushed PCC)	.300429	1244 lb.
F. Agg. (Sand)	.351930	1589 lb.
w/c = 0.54 lb./lb.	Max. w/c = 0.613 lb./lb.	
	Project Average - 0.514	
Mix "B": 50% C.A. - 50% F.A.		
Cement	.106611	564 lb.
Water	.164411	277 lb.
Air	.060000	
Agg. (Crushed PCC)	.440117	1822 lb.
Agg. (Sand)	.228861	1033 lb.
w/c = 0.49 lb./lb.	Max. w/c = 0.556 lb./lb.	
	Project Average - 0.456	
Mix "C": Crushed A.C. & P.C. (Note: Approximately 80% C.A. and 20% F.A.)		
Cement	.088842	470 lb.
Water	.150760	254 lb.
Air	.060000	
Aggregate	.700398	885 lb.
w/c = 0.54 lb./lb.	Max. w/c = 0.613 lb./lb.	
	Project Average - 0.550	
Mix "C3": 85% A.C. & P.C. - 15% Sand (Note: Approximately 65% C.A. and 35% F.A.)		
Cement	.088842	470 lb.
Water	.150760	254 lb.
Air	.060000	
Crushed A.C. P.C.	.595338	2452 lb.
Aggregate (Sand)	.105060	474 lb.
w/c = 0.54 lb./lb.	Max. w/c = 0.613 lb./lb.	
	Project Average - 0.500	

Table 2-9. 28-Day Flexural Strength Test Results from the Iowa Experimental Project. (Source: Bergren and Britson)(3)

Mix	Average Flexural Strength (psi)	Water-Cement Ratio
A	799	0.51
B	811	0.46
C	586	0.55
C-3	560	0.50

Buck (4) offered the most comprehensive study concerning compressive strengths of concrete made with recycled PCC. The results of his tests (Table 2-10) indicated concrete mixes with crushed concrete aggregate produced lower compressive strengths than control mixes. Frondistou-Yannas (12), who also reported the differences between concretes made with crushed PCC and control aggregates at various water-cement ratios (Tables 2-11 and 2-12), drew the same conclusion. Results of average field tests for the Iowa (3) experimental project indicated more than adequate strengths (7) for concrete made with recycled PCC aggregate (Table 2-13).

The Frondistou-Yannas (12) tests were made on concrete with an abnormally high water-cement ratio and tested at an early age. However, the results of tests for the concrete using regular cement and recycled PCC aggregate were extrapolated and compared to the other studies with respect to mixes having approximately the same water-cement ratio (Table 2-14). It was assumed that 15-day tests were 80 percent of 28 day values.

2.2.3 Other Physical Properties of Hardened Concrete

Buck (4) also performed tests to investigate two other parameters to provide information for comparing the physical properties of concrete made with recycled PCC to concrete made with conventional aggregate. These were determinations of the linear coefficient of expansion (Table 2-15)

Table 2-10. Average Compressive Strengths of the Five Concrete Mixtures Tested. (Source: Buck)(4)

Mixture Number	Round	Compressive Strength (psi) 7 Days	28 Days	58 Days	90 Days	180 Days
1	1	2,800	4,420	5,160	5,230	5,660
	2	2,360	3,840	4,400	4,890	5,120
	3	2,520	4,160	4,530	5,070	5,050
	Combined	2,590	4,140	4,700	5,060	5,280
2	1	1,910	2,880	3,480	3,900	3,850
	2	1,990	3,210	3,620	3,840	4,090
	3	2,030	3,050	3,650	3,900	4,140
	Combined	1,980	3,050	3,580	3,880	4,030
3	1	2,440	3,210	3,780	4,270	4,570
	2	2,210	3,570	3,930	4,440	4,640
	3	2,240	3,430	3,700	4,120	4,340
	Combined	2,300	3,400	3,810	4,280	4,520
4	---	3,180	4,510	4,790	5,320	5,530
5	---	2,580	4,150	4,000	4,660	4,840

Table 2-11. Relationship Between Water-Cement Ratio and Compressive Strength. Cement: Portland Cement Type III; Fine Aggregate: Ottawa Sand. Tested at 8 Days. (Based on Frondistou-Yannas)(12)

Compressive Strength (psi)		Water-Cement Ratio
Recycled PCC Concrete	Granite Gravel Concrete	
3400	3700	0.55
2100	2150	0.65
1300	1600	0.75

Table 2-12. Relationship Between Water-Cement Ratio and Compressive Strength. Cement: Portland Cement Type I; Fine Aggregate: Granite Sand. Tested at 15 Days. (Based on Frondistou-Yannas)(12)

Compressive Strength (psi)		Water-Cement Ratio
Recycled PCC Concrete	Granite Gravel Concrete	
2600	3500	0.55
2200	2500	0.65
1700	1500	0.75

Table 2-13. 28-Day Compressive Strength Test Results from the Iowa Experimental Project. (Source: Bergren and Britson)(3)

Mix	Average Compressive Strength (psi)	Water-Cement Ratio
A	4413	0.51
B	4292	0.46
C	2250	0.55
C-3	2290	0.50

Table 2-14. Compared Compressive Strengths from Three Studies

Information Source	Water-Cement Ratio	Compressive Strength (psi)
Bergren and Britson (3)	0.51	4413
Buck (4)	0.49	3050
	0.49	3400
	0.49	4150
Frondistou-Yannas (12)	0.50*	3500*

*Extrapolated values

Table 2-15. Linear Coefficient of Thermal Expansion of the Five Concrete Mixtures Tested. (Based on Buck)(4)

Mixture Number	Linear Coefficient of Expansion		
	1	2	Combined
1	6.3	---	---
2	6.1	---	---
3	5.6	5.7	5.6
4	3.6	---	---
5	4.7	---	---

and the length change of concrete specimens stored at constant moisture and temperature (Table 2-16). The results correlated exceptionally well and were well within the acceptable range of 2.5 to 8.0 and maximum of 0.025 percent respectively (40,42). Because of the apparently tight controls used in these experiments, it can be assumed that concrete made with recycled PCC aggregate will react normally with respect to these properties.

Tests by Frondistou-Yannas (12) to determine the relationship of modulus of elasticity to various water-cement ratios (Figures 2-1 and 2-2) were made with concrete not representative of mixes normally used for construction (7). Therefore, the results were not considered conclusive.

2.3 Economics of Crushing PCC for New Pavements

Intuition demands that, if an existing PCC pavement surface must be removed because of structural deficiencies, it would have to be more economical to re-use the resulting waste material as aggregate rather than haul the material to a dump site and haul in new aggregate for replacement construction. This, of course, would be dependent upon the expense of crushing operations, haul distances, and the quality of the recycled aggregate.

2.3.1 Previous Economic Evaluations

There were no reported studies dealing specifically with the economics of recycling old PCC pavements for new,

Table 2-16. Length Changes of Concrete Specimens Stored at Constant Moisture and Temperature. (Based on Buck)(4)

			Length Increase (percent)	
Mix	Round	Specimen	28 Days	90 Days
1	1	1	0.013	0.019
	2	5	0.016	0.018
	3	9	0.010	0.008
		Average	0.013	0.015
2	1	1	0.014	0.023
	2	5	0.010	0.011
	3	9	0.012	0.014
		Average	0.012	0.016
3	1	1	0.017	0.036
	2	5	0.007	0.009
	3	9	0.007	0.011
		Average	0.010	0.019
4	1	1	0.003	0.001
	2	5	-----	-----
	3	9	-----	-----
		Average	0.003	0.001
5	1	1	0.003	0.002
	2	5	-----	-----
	3	9	-----	-----
		Average	0.003	0.002

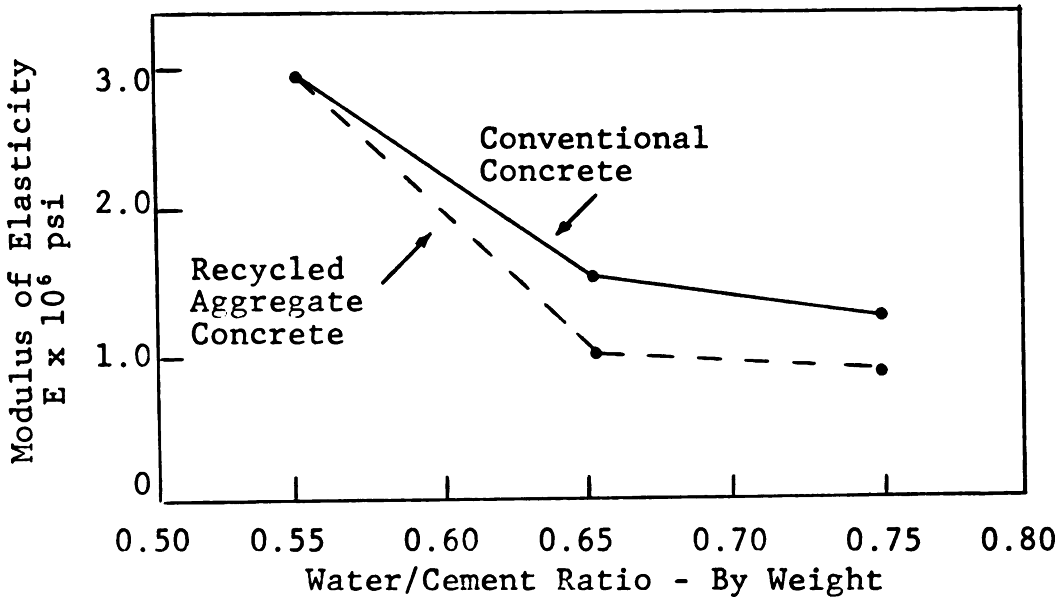

Figure 2-1. Relationship Between Water-Cement Ratio and Modulus of Elasticity. Cement: Portland Cement Type III; Fine Aggregate: Ottawa Sand. (Based on Frondistou-Yannas)(12)

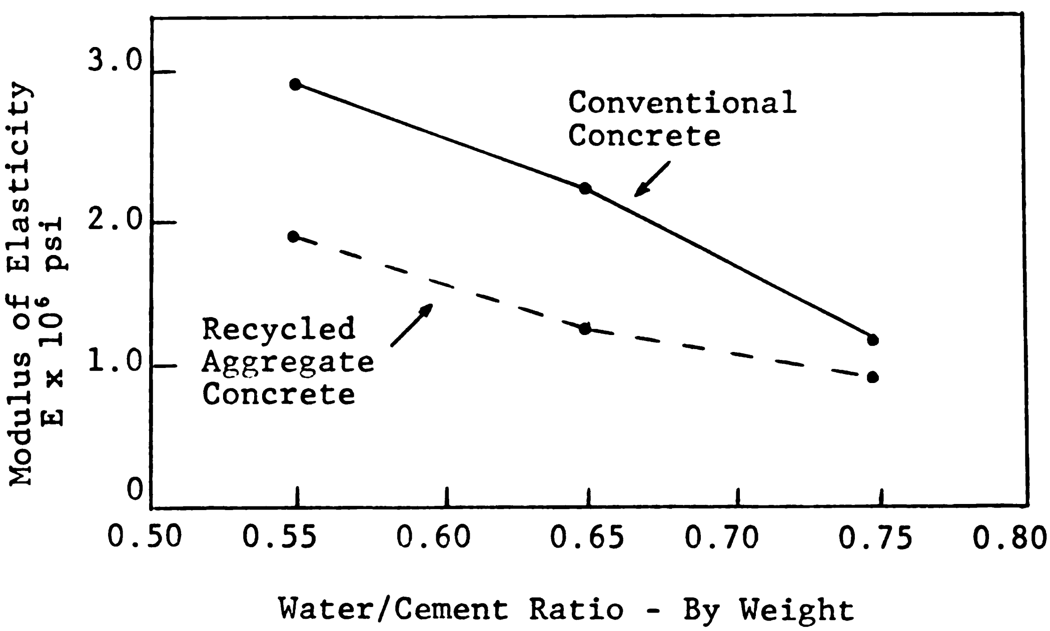

Figure 2-2. Relationship Between Water-Cement Ratio and Modulus of Elasticity. Cement: Portland Cement Type I; Fine Aggregate: Granite Sand. (Based on Frondistou-Yannas)(12)

although some background information was available. Two researchers at the Massachusetts Institute of Technology (11) made a comprehensive study of average equipment and production costs related to crushing PCC demolition debris. Theorizing this debris would be contaminated with other materials, they designed a crushing operation with facilities for removing any undesirable products (Figure 2-3). Based on these factors, they estimated the plant price of recycled PCC aggregate to be 67 percent of the plant price of conventional aggregate.

Since previous research resulted in a determination of reduced strength and stiffness in concrete made with recycled concrete, the researchers predicted that concrete members produced with recycled PCC aggregate would require 20 percent more volume than members produced with conventional aggregate. This canceled the cost advantage unless the source of conventional aggregates were at least 15 miles farther than the source of recycled aggregates.

Ray and Halm (21) reported a preliminary study of energy requirements to produce one mile of pavement (10 inches thick and 24 feet wide, or 3911 cubic yards) comparing the use of conventional aggregate, crushing the existing pavement, and hauling aggregate from a commercial recycling plant for the concrete mix (Table 2-17). It was evident that the energy requirements for breaking the old pavement were included in the calculations and should be

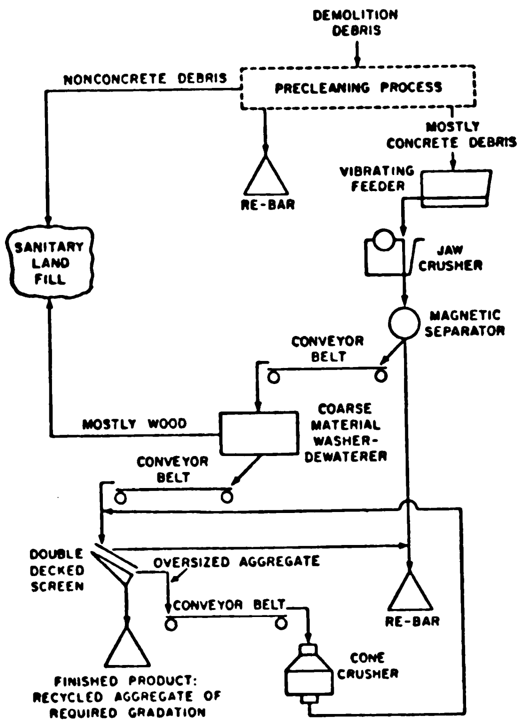

Figure 2-3. Schematic Flow Chart of Recycling Plant. (Source: Frondistou-Yannas and Itoh)(11)

deleted if this operation must be accomplished in the regular progress of a project. However, their conclusion was that, when the hauling distances for conventional aggregates exceeds 50 miles, recycled pavement becomes a desirable alternative.

Table 2-17. Energy Requirements for Recycled PCC Aggregate Compared to Conventional Aggregate. (Based on Ray and Halm)(21)

Aggregate Haul Distance (Miles)	Energy Used (BTU X 10^6)*
Natural Aggregates	
10	7931
20	7977
50	8115
100	8346
Recycled Pavement	
On the Job Plant	8148
Recycled Concrete	
10	7829

*Calculated on the basis of aggregate required for one mile of pavement.

Loken (18) reported an estimated savings of one-hundred thousand dollars by the Iowa Department of Transportation on an unreported 17 mile pavement project using recycled PCC for aggregate. Personal communication with this agency revealed the particulars of the project were not available at this time.

2.4 Concrete Mix Design

The basic components of a Portland cement concrete mixture are cement, fine aggregate, course aggregate and water. Determinations of the relative proportions of these components range from the, now largely outmoded, 1:2:3 volumetric method requiring one part cement, two parts sand, and three parts coarse aggregate with sufficient water added to provide a workable mix (42) to theoretical methods based on laboratory analysis. Most contemporary methods of mix design have been derived from work done by Abrams in 1918 (2, 7,38) and Talbot and Richart in 1922 (2,36,38). Abram's major contribution was the concept of the relationship of water-cement ratio to strength. Talbot and Richart investigated the application of the voids-cement ratio to mix design which contributed the concept of the absolute volumes of component materials.

2.4.1 Portland Cement Association Method

The Portland Cement Association method utilizes Abrams' water-cement ratio theory, compressive strength requirements, and observed mixture qualities in a series of trial mixes to determine the relative proportions of materials (7). The following general steps are used in the mix design process:

Step 1. A compressive strength requirement is determined by specification or other criteria.

Step 2. Select the required water-cement ratio (W/C) from Figure 2-4 where:

$$W/C = \frac{W_w}{W_c} \qquad (2\text{-}1)$$

where:

W_w = Weight of water;

W_c = Weight of cement.

Step 3. From the weight of the cement selected for a trial batch, determine the weight of the water required from:

$$W_w = W_c \cdot W/C \qquad (2\text{-}2)$$

Step 4. Saturated, surface dry, fine and coarse aggregates are weighed and mixed with the cement and water in proportions required to bring the mixture to desired consistency and workability.

Step 5. Aggregate not used in the trial mix is weighed and subtracted from original weights, the unit weight of the mixture is determined, and the weights of component materials per unit volume are determined through appropriate calculations.

A series of trial mixes are made by varying the amount of fine aggregate and holding the other materials constant.

The results are plotted and the most economical mix, with respect to ratios of cement and sand (Figure 2-5), is selected holding the water-cement ratio constant.

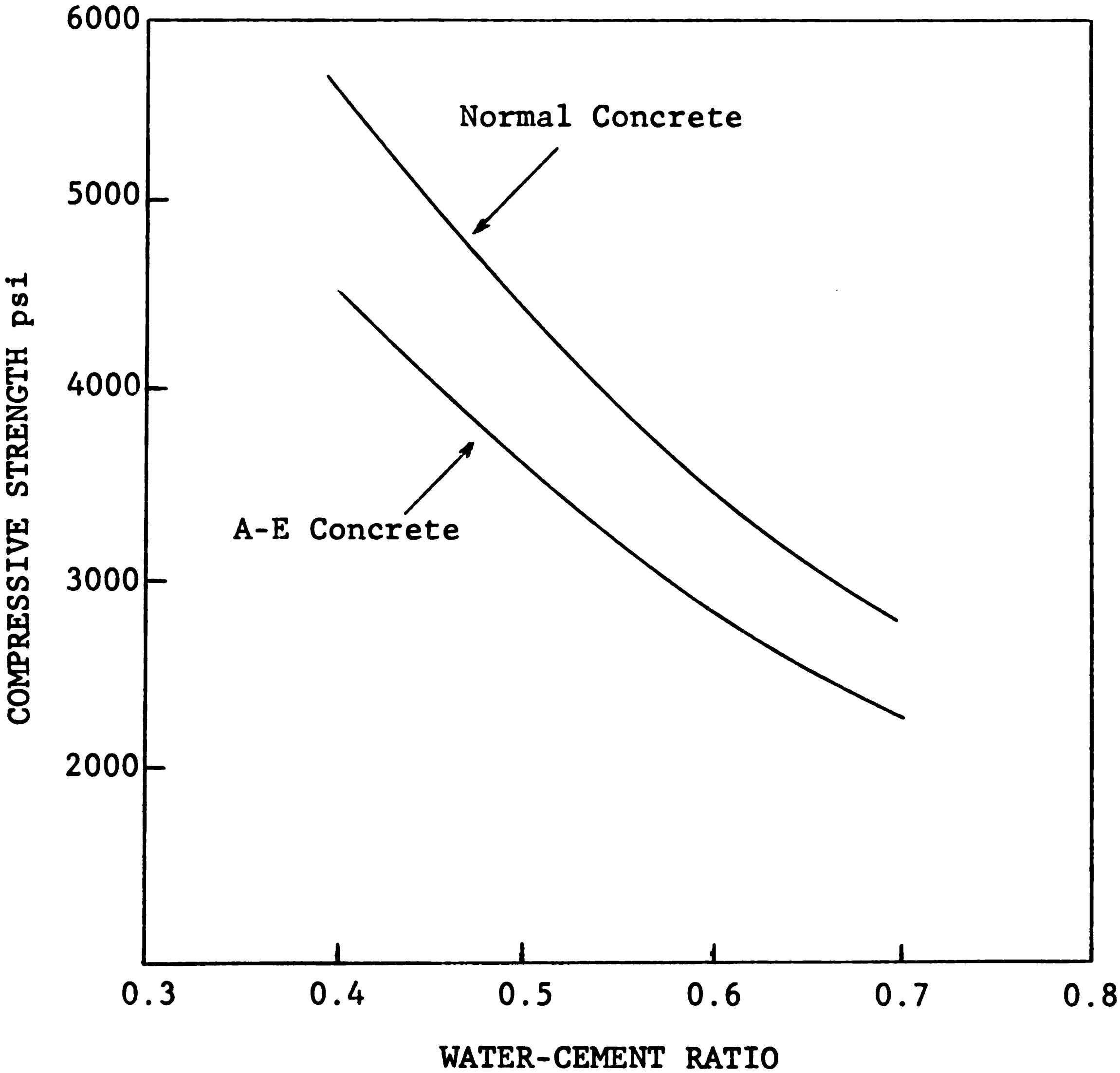

Figure 2-4. Typical Trial Mix Strength Curves. (Based on Portland Cement Association)(7)

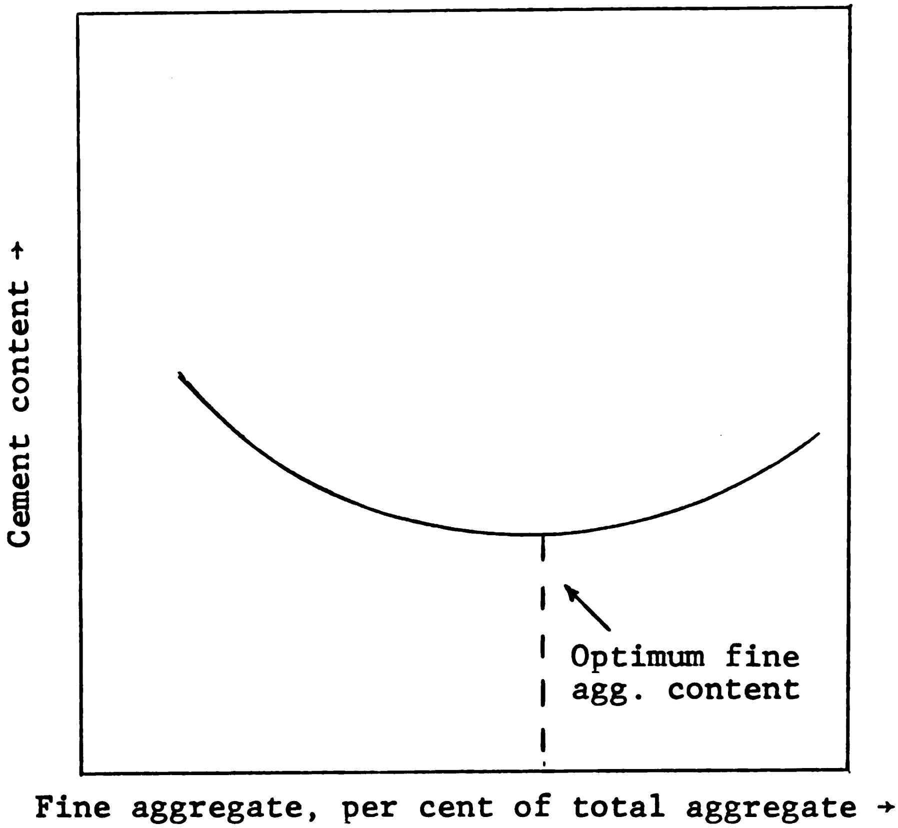

Figure 2-5. Typical relationship between percentage of fine aggregate and cement content for a given water-cement ratio and slump. (Based on Portland Cement Association)(7)

2.4.2 American Concrete Institute Methods

Two methods of mix design are offered by the American Concrete Institute (24). Each incorporates a comprehensive set of empirical criteria to aid in selecting design proportions (Tables 2-18 through 2-23).

Weight Method

The weight method is basically the same as that previously described for the Portland Cement Association method except that determinations of the unit weight of the coarse aggregate and the gradations of both the fine and coarse aggregates are required to determine factors or proportions from the tables. Steps utilized in formulating a mix design for one cubic yard of concrete are:

Step 1. Select the appropriate weight of water from Table 2-19.

Step 2. Calculate the weight of cement from the water-cement ratio related to the required compressive strength in Table 2-20. The water-cement ratio is subject to constraints in Table 2-21.

Step 3. Multiply the selected workability factor in Table 2-22 times the unit weight of coarse aggregate times 27.

Step 4. Subtract the total weight of the materials in Steps 1 through 3 from the estimated weight of fresh concrete in Table 2-23 to determine the weight of the fine aggregate.

The trial batch is then tested for desired qualities and adjustments are made as necessary.

Table 2-18. Recommended Slumps for Various Types of Construction. (Source: American Concrete Institute)(24)

Types of Construction	Slump, in.	
	Maximum	Minimum
Reinforced foundation walls and footings	3	1
Plain footings, caissons, and substructure walls	3	1
Beams and reinforced walls	4	1
Building columns	4	1
Pavements and slabs	3	1
Mass Concrete	2	1

Table 2-19. Approximate Mixing Water and Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregates. (Source: American Concrete Institute)(24)

Slump, in.	Water, lb per cu yd of concrete for indicated nominal maximum sizes of aggregate							
	3/8 in.	1/2 in.	3/4 in.	1 in.	1-1/2 in.	2 in.	3 in.	6 in.
Non-air-entrained concrete								
1 to 2	350	335	315	300	275	260	240	210
3 to 4	385	365	340	325	300	285	265	230
6 to 7	410	385	360	340	315	300	285	---
Approximate amount of entrapped air	3	2.5	2	1.5	1	0.5	0.3	0.2
Air-entrained concrete								
1 to 2	305	295	280	270	250	240	225	200
3 to 4	340	325	305	295	275	265	250	220
6 to 7	365	345	325	310	290	280	270	---
Recommended percent air content:								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Extreme exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

Table 2-20. Relationships Between Water-Cement Ratio and Compressive Strength of Concrete. (Source: American Concrete Institute)(24)

Compressive strength at 28 days (psi)	Water-cement ratio, by weight	
	Non-air-entrained concrete	Air-entrained concrete
6000	0.41	---
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

Table 2-21. Maximum Permissible Water-Cement Ratios for Concrete in Severe Exposures. (Source: American Concrete Institute)(24)

Type of structure	Structure wet continuously or frequently and exposed to freezing and thawing	Structure exposed to sea water or sulfates
Thin sections (railings, curbs, sills, ledges, ornamental work) and sections with less than 1 in. cover over steel	0.45	0.40
All other structures	0.50	0.45

Table 2-22. Volume of Coarse Aggregate Per Unit of Volume of Concrete. (Source: American Concrete Institute)(24)

Maximum size of aggregate, in.	Volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of sand			
	2.40	2.60	2.80	3.00
3/8	0.50	0.48	0.46	0.44
1/2	0.59	0.57	0.55	0.53
3/4	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1-1/2	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76
6	0.87	0.85	0.83	0.81

Table 2-23. First Estimate of Weight of Fresh Concrete. (Source: American Concrete Institute)(24)

Maximum size of aggregate, in.	First estimate of concrete weight, lb per cu yd	
	Non-air-entrained concrete	Air-entrained concrete
3/8	3840	3690
1/2	3890	3760
3/4	3960	3840
1	4010	3900
1-1/2	4070	3960
2	4120	4000
3	4160	4040
6	4230	4120

Absolute Volume Method

Although a detailed laboratory analysis of the physical properties of component materials is required before applying the absolute volume method, it is the most exact means of designing concrete mixtures of those commonly used. In this case, the total volume displaced by water, air, cement, and coarse aggregate, as determined from the tables or specifications, is subtracted from the unit volume of concrete to obtain the required volume of fine aggregate. For the purposes of this research, this procedure was converted to formula form using the following notations:

W_a, W_b, W_c, W_w = Weights of fine aggregate, coarse aggregate, cement, and mixing water respectively.

G_a, G_b, G_c= Specific gravities of fine aggregates, coarse aggregate, and cement respectively.

V = Unit volume of fresh concrete.

V_a, V_b, V_c, V_w, V_λ = The absolute volume of fine aggregate solids, coarse aggregate solids, cement solids, mixing water, and entrained or entrapped air in the unit volume.

γ_w = Weight per unit volume of water.

λ = Percent of entrained or entrapped air.

After determining known quantities from the tables:

$$V_b = \frac{W_b}{G_b \gamma_w} \qquad (2\text{-}3)$$

$$V_c = \frac{W_c}{G_c \gamma_w} \qquad (2\text{-}4)$$

$$V_w = \frac{W_w}{\gamma_w} \qquad (2\text{-}5)$$

$$V_\lambda = \lambda V \qquad (2\text{-}6)$$

$$V_a = V - V_b - V_c - V_w - V_\lambda \qquad (2\text{-}7)$$

$$W_a = V_a \cdot G_a \cdot \gamma_w \qquad (2\text{-}8)$$

In addition to this basic design, allowances are made for the absorption of the fine and coarse aggregates to calculate the total quantity of water required for the mix.

2.4.3 Michigan Department of Transportation (Mortar Voids) Method.

The theory proposed by Talbot and Richart (36) that there is a definite relationship between concrete strength and the ratio of the volume of cement to the volume of voids in the mortar (water and air) formed the basis for Michigan mix design. This relationship is true provided there is enough mortar to fill the spaces between the coarse particles of aggregate (31).

In the mortar voids method, tests are performed to determine the amount of water required to provide the most dense mortar with a selected ratio of dry mortar materials which, therefore, establishes a basic water content (Figure 2-6). A factor termed relative water content (R.W.C.) derived by empirical methods for various uses, is then applied to determine the actual amount of mixing water required. Relationships between the various parameters are illustrated in Figure 2-7. Coarse aggregate requirements are determined by applying a workability factor (b/b_o),

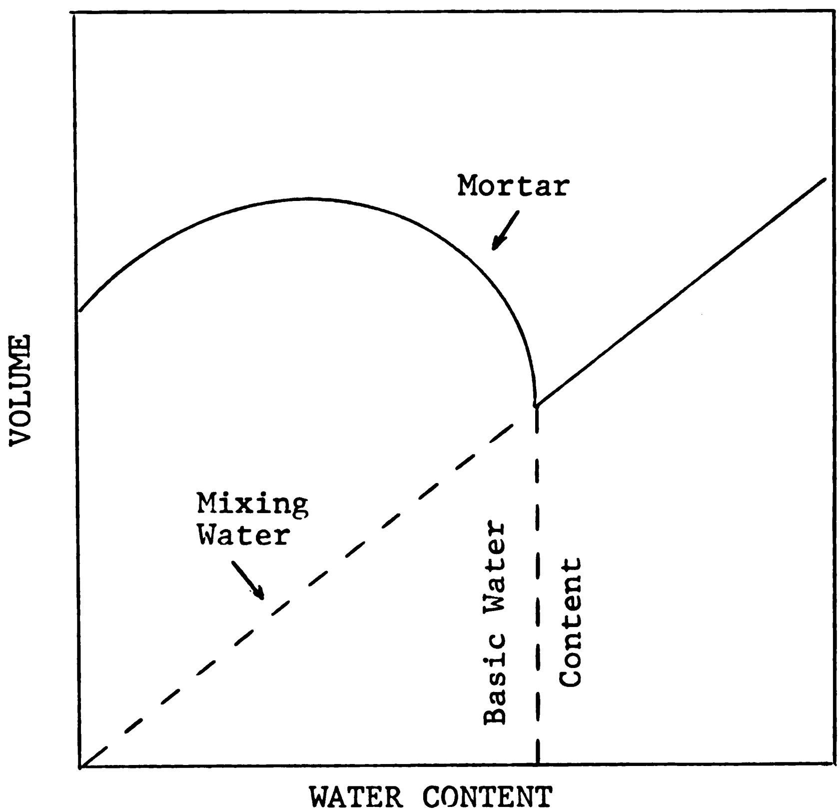

Figure 2-6. Typical Curve Showing the Relationship Between the Water Content of Mortars and the Volume of Mortar. (Source: Bauer)(2)

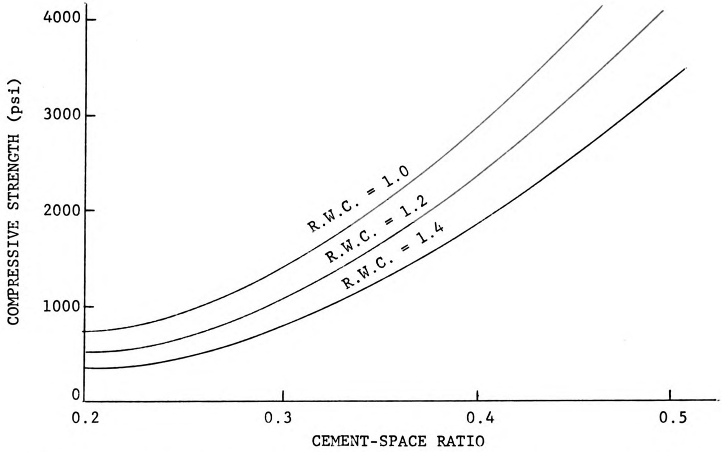

Figure 2-7. Typical Relationship Between Compressive Strength and Cement-Space Ratio. (Source: Bauer)(2)

defined by Talbot and Richart (36) but determined by field experience, to the weight of the unit volume of loose, bone dry aggregate. This factor is synonymous with those offered previously in Table 2-22 for the American Concrete Institute method (24).

In actual application, Michigan uses interpolated or extrapolated average values from mortar void tests, performed previously over a number of years, to determine water requirements for various proportions of materials. These average values are considered adequate due to the uniformity of component materials as required by specification, variables associated with actual field application, and the fact that actual cement contents are specified (Table 2-24). On a practical basis, the procedures outlined for the method incorporating absolute volumes are essentially comparable.

2.4.4 Mix Design Utilizing Recycled PCC Aggregate

Previous investigators used a variety of mix designs in their work with recycled PCC aggregate. Frondistou-Yannas (12) used the 1:2:3 volumetric method. Buck's (4) mix design was based on water-cement ratio as the controlling factor varying the amount of cement to provide a standard consistancy. An absolute volume method was used for the experimental project in Iowa (3) although there were insufficient fines to provide a desirable degree of density for the C and C-3 mixes.

Table 2-24. Concrete Proportioning Data for Slipform Pavement. (Source: Michigan Department of Transportation Testing and Research Laboratory)

1830 (8/78)

CONCRETE PROPORTIONING DATA

Control Section Identification	General
Plant No.	M-27
Laboratory No.	79C-2132
Date	November 16, 1979
Mix Design No.	79-990

Intended Use of Concrete: PAVEMENT (Slipform Method)

Grade of Concrete: 35P Modified

Specification: 1979 Std Specs

CONCRETE MATERIALS

MATERIAL	SOURCE	PIT NUMBER	CLASS	LABORATORY NUMBER	SPECIFIC GRAVITY	ABSORPTION PERCENT
Cement	SEE REMARKS		IA		3.11	
Fine Agg.	Western Materials #1	63-7	2NS	79A-775	2.58	1.81
Coarse Agg.	France Stone Company	58-1	6AA	79A-492	2.63	2.49

Cement Content, lb/cu yd 564 (sk/cu yd 6.0)

b/b_o 0.72

R.W.C. 1.05

Air Content (Design), 5.5 %; (Specified) 6.5 %

Specification Tolerance, ± 1.5 %

Weight of Coarse Aggregate (Dry, Loose) lb per cu ft	AGGREGATE & WATER PROPORTIONS QUANTITIES, LB/CU YD OF CONCRETE		
	Fine Agg. (Oven Dry)	Coarse Agg. (Oven Dry)	Total Water
78	1555	1516	297
79	1539	1536	297
80	1522	1555	296
81	1505	1575	295
82	1488	1594	294
83	1471	1614	294
84	1455	1633	293
85	1438	1652	292
86	1422	1672	291
87	1405	1691	291

MATERIAL PROPERTIES

Fine Aggregate:

Fineness Modulus 2.84

Soundness Loss, percent

Laboratory No.

Coarse Aggregate:

Soundness Loss, percent

Laboratory No.

Abrasion, percent of wear 32

Laboratory No. 79A-492

REMARKS:

This chart for use with cements, of the class shown above, from the following sources:

Aetna	Peerless	General-Paulding, Ohio
Dundee	Penn-Dixie	Medusa - All Plants
Huron	Wyandotte	

Typical unit weight (dry loose) of coarse aggregate as described above is 82 lb/cu ft.

2.5 Rigid Pavement Design

The predominate method used in the design of rigid highway pavements in the United States is based on empirical determinations of the effect of the magnitude and repetitions of loads and environmental factors peculiar to the various geographical locations (46). Therefore, most states use a standard cross section for the surface structure with provisions for correcting deficiencies in the subgrade.

Inasmuch as this research is primarily interested in thickness requirements for the pavement surface structure using recycled PCC for aggregate in the concrete mixture, factors leading to the development of contempory pavement design were investigated.

2.5.1 Theoretical Stress Analysis

In 1926, Westergaard (43) published the results of an analytical study defining stresses in concrete pavements due to loading. His assumptions were that:

1. The pavement slab acts as a homogeneous, elastic solid in equilibrium.

2. The reactions of the subgrade are vertical and proportional to the deflections in the slab.

Although three cases for determining maximum stress were presented, the stress formula for corner loading of the slab (Figure 2-8) was considered most critical.

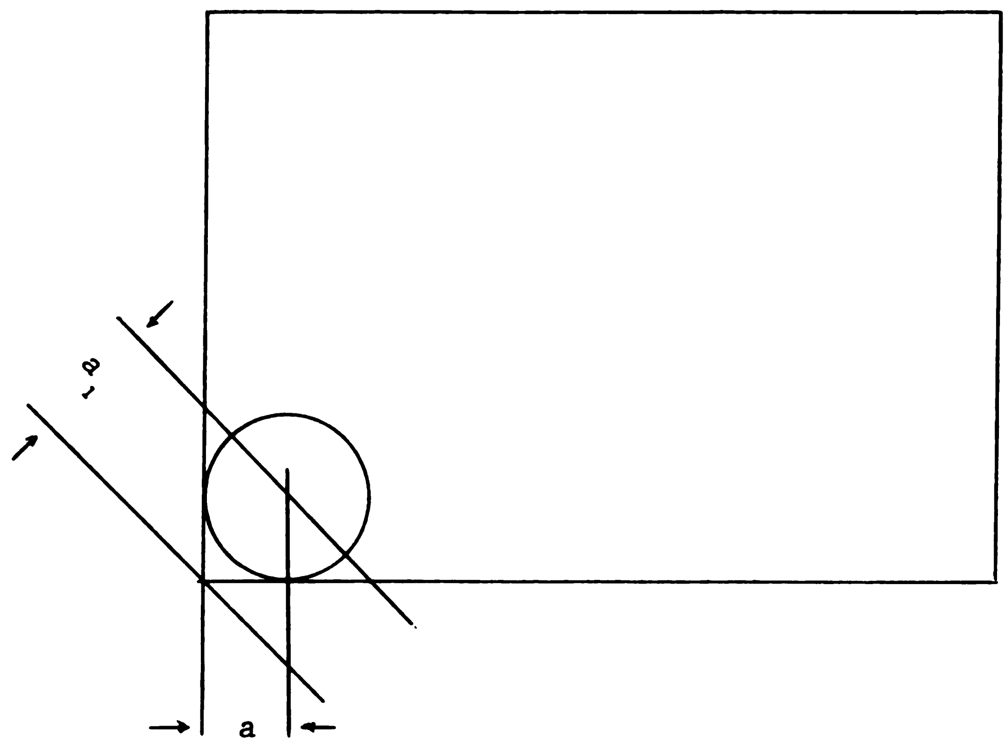

Figure 2-8. Westergaard's Case for Corner Loading.
(Source: Westergaard)(43)

Westergaard (43) defined two identities necessary in deriving his formula as the modulus of subgrade reaction (k) and the radius of relative stiffness (l) where:

$$k = \frac{P}{z} \qquad (2\text{-}9)$$

where:

P = Reaction of the subgrade per unit area;

z = Deflection of a point.

and:

$$l = \sqrt[4]{\frac{Eh^3}{12(1-\mu^2)k}} \qquad (2\text{-}10)$$

where:

E = Modulus of elasticity of the concrete;

h = Thickness of the slab;

μ = Poisson's ratio for concrete.

The equation for maximum tensile stress (σ_c) at a corner is:

$$\sigma_c = \frac{3P}{h^2}\left[1 - \left(\frac{Eh^3}{12(1-\mu^2)k}\right)^{-0.15} a_1^{0.6}\right] \qquad (2\text{-}11)$$

where:

P = Point load;

a_1 = Defined in Figure 2-8.

Simplified:

$$\sigma_c = \frac{3P}{h^2}\left[1 - \left(\frac{a_1}{l}\right)^{0.6}\right] \qquad (2\text{-}12)$$

2.5.2 Portland Cement Association Method

This method modifies Westergaard's static stress analysis to allow for repeated load applications (46) and offers a simplified means of determining stress in the pavement under various axle loads (Figure 2-9 and 2-10). The ratio of this stress to the modulus of rupture (flexural strength) of the concrete is compared to the allowed repetitions in Table 2-25. The projected number of repetitions for each class of axle loadings over the design life of the pavement are then weighted as a percentage of the allowable repetitions. General theories pertinent to this method are that:

1. If the stress ratio is less than 0.51, the concrete will sustain an unlimited number of stress repetitions without failure.

2. The design is corrected if the sum of percentages used by repeated loadings over the design life is under 100 percent.

2.5.3 AASHO Interim Guide Method

The results of AASHO Road Tests studied from 1958 to 1960 provided the basis for this method of pavement design and is the method used by most states for actual design or to verify standards (37). Basic design procedure incorporates the use of nomographs (Figure 2-11 and 2-12) which represent the equation developed from strain measurements and condition determinations during the study period (1).

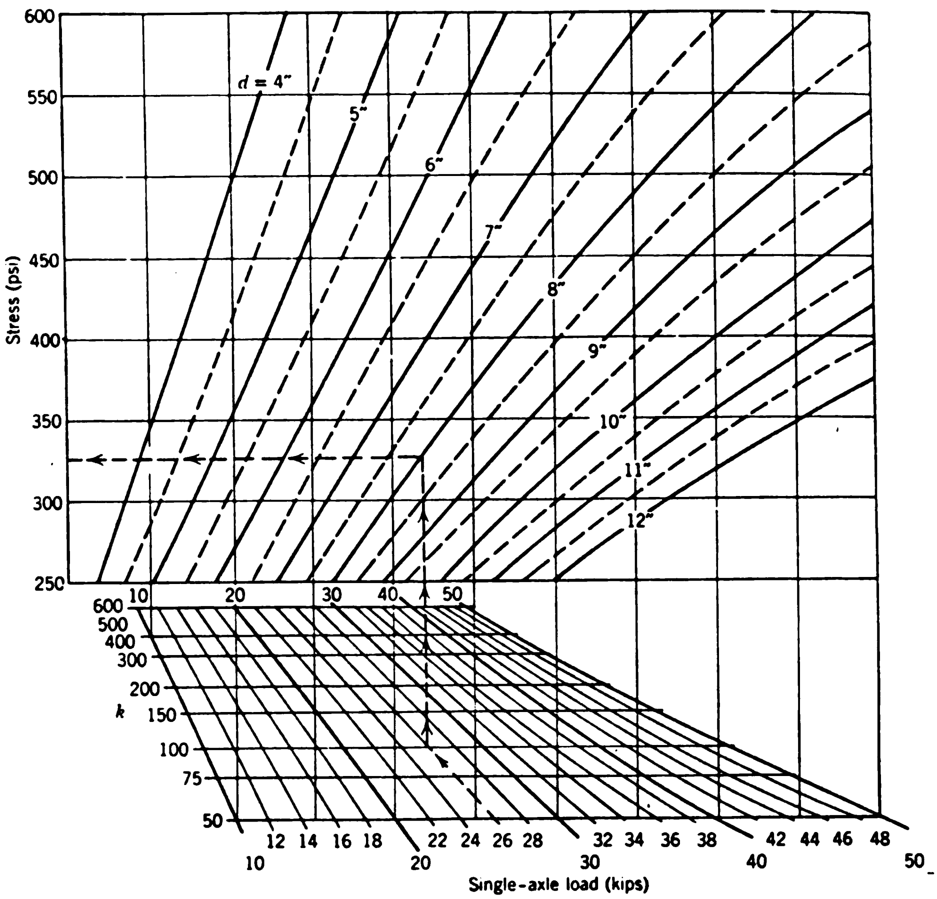

Figure 2-9. Design Chart for Single-Axle Truck Loads. (Source: Portland Cement Association)(7)

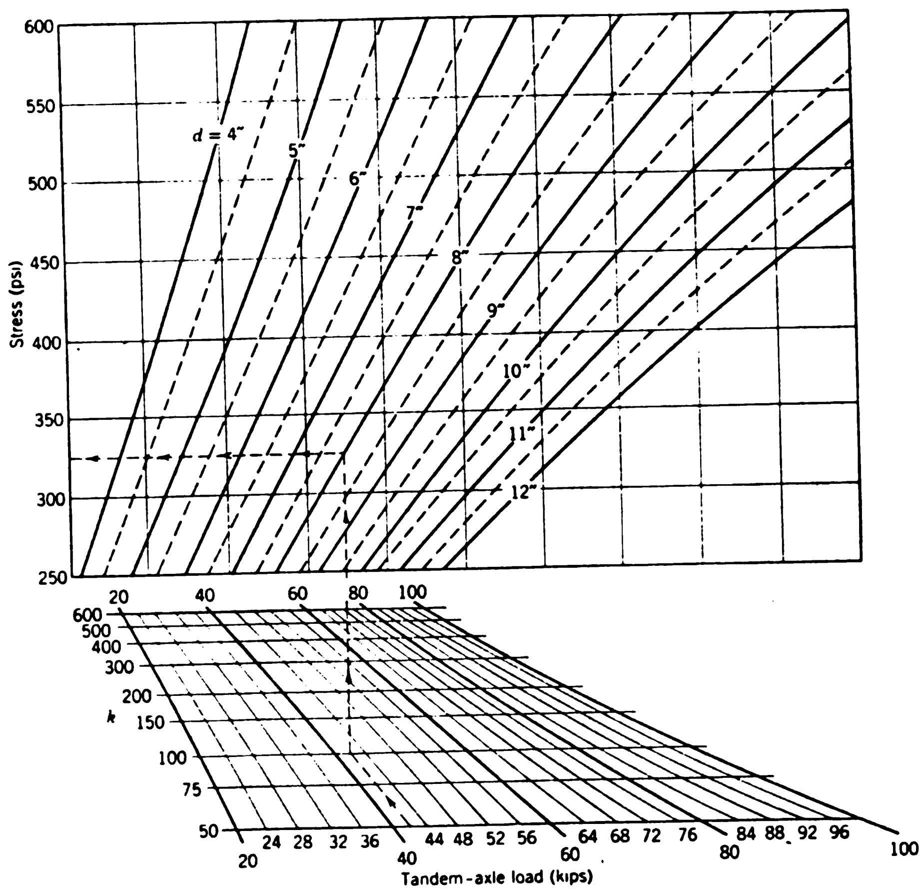

Figure 2-10. Design Chart for Tandem-Axle Truck Loads. (Source: Portland Cement Association)(7)

Table 2-25. Stress Ratios and Allowable Load Repetitions. (Source: Portland Cement Association)(7)

Stress Ratio	Allowable Repetition	Stress Ratio	Allowable Repetition
0.51	400,000	0.69	2,500
0.52	300,000	0.70	2,000
0.53	240,000	0.71	1,500
0.54	180,000	0.72	1,100
0.55	130,000	0.73	850
0.56	100,000	0.74	650
0.57	75,000	0.75	490
0.58	57,000	0.76	360
0.59	42,000	0.77	270
0.60	32,000	0.78	210
0.61	24,000	0.79	160
0.62	18,000	0.80	120
0.63	14,000	0.81	90
0.64	11,000	0.82	70
0.65	8,000	0.83	50
0.66	6,000	0.84	40
0.67	4,500	0.85	30
0.68	3,500	----	--

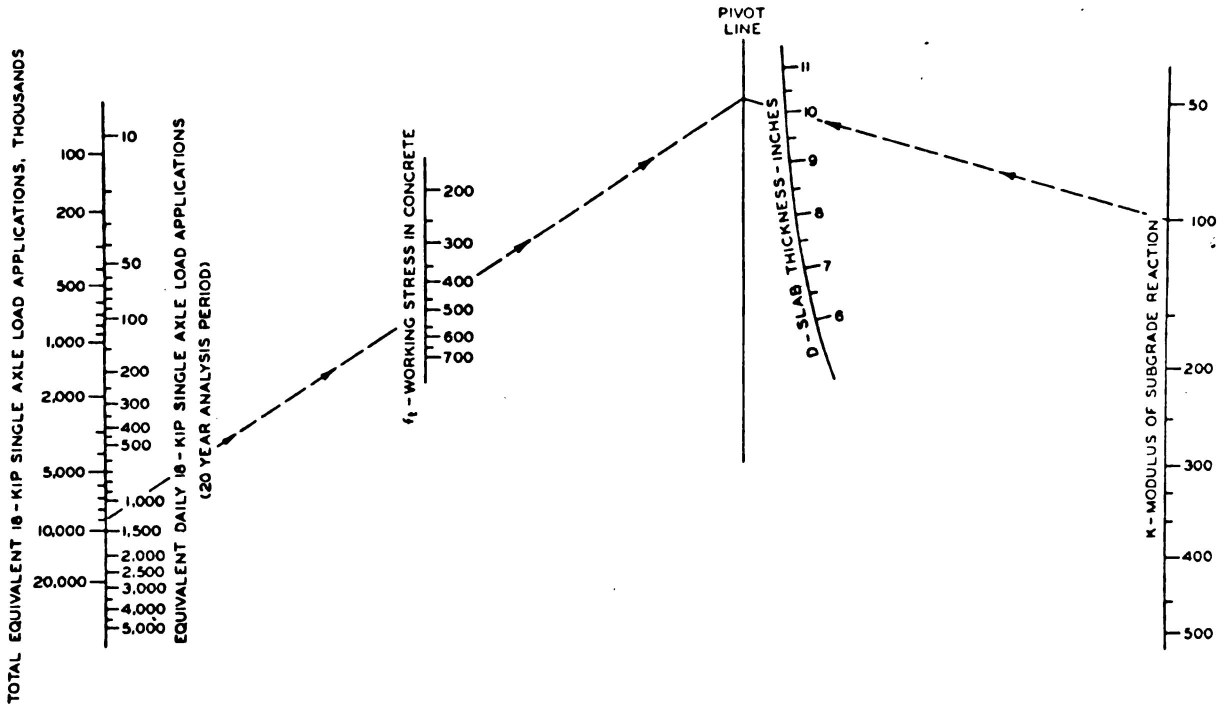

Figure 2-11. Design Chart for Rigid Pavements, P_t = 2.5. (Source: AASHO Interim Guide)(1)

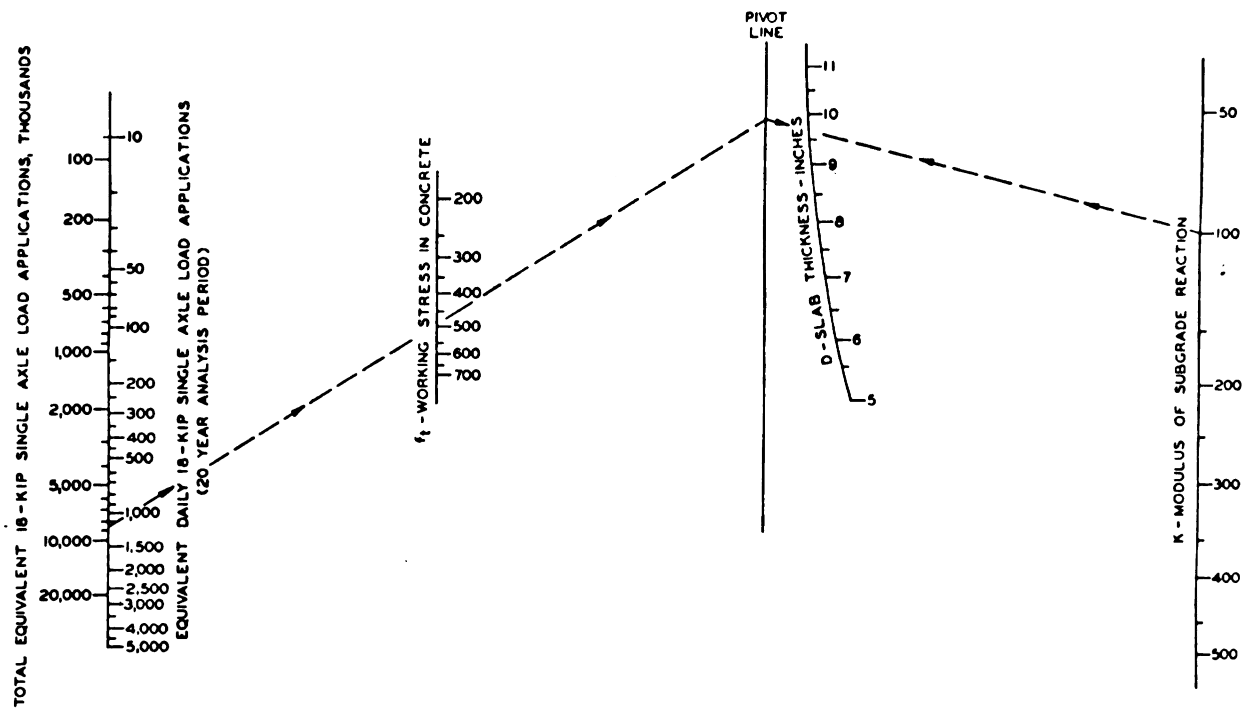

Figure 2-12. Design Chart for Rigid Pavements $P_t = 2.0$. (Source: AASHO Interim Guide)(1)

Use of the nomographs requires an evaluation of the following parameters:

1. Expected terminal serviceability index (P_t).

2. Equivalent 18-kip single-axle loads over the design life of the pavement.

3. Modulus of subgrade reaction (k) as previously defined.

4. The working stress (f_t) in the concrete. An empirical f_t value of 0.75 times the modulus of rupture of the concrete was established from road test results.

CHAPTER III

RESEARCH MATERIALS AND MIX DESIGN

The materials obtained for research were strictly related to recycling an existing PCC highway pavement for the purpose of using the material in the mix for the new pavement surface. Mix design procedure followed, as closely as possible, Michigan Department of Transportation methods (31).

3.1 Component Materials

In order to provide a valid correlation in research data, it was considered necessary to collect a sufficient quantity of materials required to complete all phases of the research process. Background information relative to the materials used was also considered necessary.

3.1.1 Materials for Recycling

One of the main purposes of this research was to provide a basis for determining, as closely as possible, the characteristics of recycled aggregates under field conditions. In addition, another purpose was to devise a method of predetermining material properties for design purposes.

PCC Material

The Michigan Department of Transportation has been involved in a major pavement joint repair program in recent years. In this process, pavement sections surrounding transverse joints experiencing mechanical failure (Figure 3-1) are removed (Figure 3-2) and replaced with a quick-set concrete patch. Waste materials are normally hauled to a fill site. A project of this type was completed in 1979 on a section of I-96 between Novi and New Hudson in Michigan. The waste concrete was disposed of in a nearby abandoned gravel pit area where a pond was being filled (Figure 3-3). Three slab sections of this material were selected for research.

In order to simulate procedures normal to those required to completely remove an existing pavement, the sections were broken into maximum three-foot square pieces (Figure 3-4). It was observed that most of the temperature reinforcement present in the slabs broke along the lines of fracture in the concrete. The material was then loaded and hauled to a crushing operation in Detroit. Prior to the breaking operation, two representative six-inch cores were drilled from each slab (Figure 3-5). Material from this source was designated as A for the broken material and A-1 for the cores.

Six cores were also taken from a section of I-94 Business Loop near Battle Creek, Michigan to provide correlation. These were designated material B. In addition, twelve cores were obtained from a section of I-94 near Jackson, Michigan. This pavement had a nominal three-inch

Figure 3-1. Typical Transverse Joint Failure

Figure 3-2. Removal of Slab Sections for Joint Repair.

Figure 3-3. Disposal Site for Waste Pavement Sections.

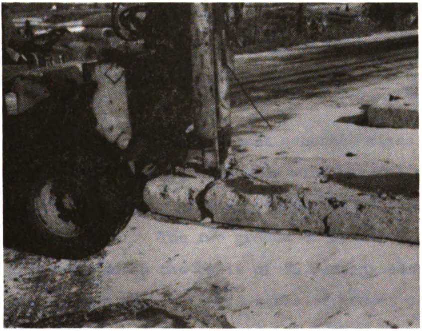

Figure 3-4. Breaking Pavement Slabs for Research Material.

Figure 3-5. Coring Pavement Slabs.

bituminous concrete overlay. Since it was intended to utilize bituminous concrete material as part of this research, six of the cores with the overlay removed were designated aggregate material C and those with the overlay as C-1.

The original Portland cement concrete mixes for all of the indicated sources were made with natural gravel and sand conforming to the grading requirements listed in Tables 3-1 and 3-2. The two grades of coarse aggregate were proportioned on the basis of 50 percent each by weight. Basic mix design was for 5-1/2 sacks of cement per cubic yard with air entrainment (31,32,33). Background histories for each source are given in Table 3-3.

Table 3-1. Gradation Requirements for Coarse Aggregates Used in Source Material for Recycling. (Source: 1942 and 1950 Standard Specifications for Road and Bridge Construction, Michigan State Highway Department)

Sieve	Michigan Grade 4A % Passing	Michigan Grade 10A % Passing
2-1/4"	100	
2"	95-100	
1-1/2"	65-90	100
1"	10-40	95-100
1/2"		35-65
3/8"	0-5	
#4		0-8

Table 3-2. Gradation Requirements for Fine Aggregate Used in Source Material for Recycling. (Source: 1942 and 1950 Standard Specifications for Road and Bridge Construction, Michigan State Highway Department)

Sieve	Michigan Grade 2NS % Passing
3/8"	100
#4	95-100
#8	65-95
#16	35-75
#30	20-55
#50	10-30
#100	0-10
L.B.W.	3 maximum

Table 3-3. Histories of Source Materials From Michigan Department of Transportation Road Logs.

Material Code	Source	Construction Dates
A and A-1	I-96 New Hudson	9" PCC Pavement - 1957
B	I-94 Business Loop	9" PCC Pavement - 1943 Bituminous Concrete Overlay - 1965
C and C-1	I-94 Jackson	9" PCC Pavement - 1949 Bituminous Concrete Overlay - 1972

Field Crushing

Facilities at Michigan Crushed Concrete, Inc. were used to crush the broken concrete material from the I-96 location. Normal operations at this company are to crush concrete debris and sell the resulting material for various uses. Operational steps are:

Step 1. Material is dumped into an apron feeder (Figure 3-6) leading to a Hewitt-Robins 22 X 48 primary jaw crusher which reduces the material to a 5-inch maximum size.

Step 2. Unwanted material such as wood and steel (Figure 3-7) is hand picked. Pieces of steel getting by this point are removed by a magnet (Figure 3-8) from the top of the belt taking the crushed product to a double deck screen.

Step 3. Material in excess of 2-1/2 inches is scalped and fed into a Hewitt-Robins 12 X 48 secondary jaw crusher. All material passing the 2-1/2 inch screen is separated into the minus 1-1/2 inch and 1-1/2 to 2-1/2 inch sizes on a set of the double deck screens. Material from the secondary crusher is returned to the screening process.

Step 4. The two sizes are independently stockpiled by radial stackers.

Inasmuch as the debris normally crushed at this facility contains topsoil and other objectionable materials, equipment was thoroughly cleaned before crushing the research material. Economics did not provide for changing

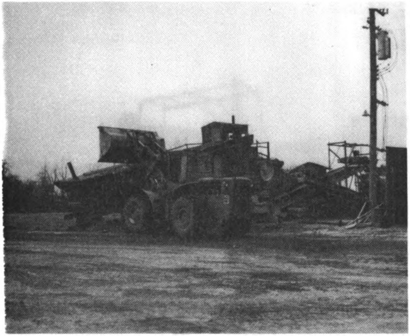

Figure 3-6. Charging Apron Feeder at Michigan Crushed Concrete, Inc.

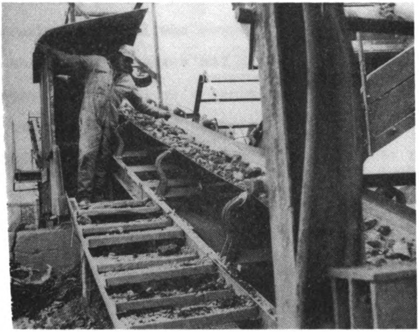

Figure 3-7. Hand-Picking Steel and Other Material from Crusher Belt at Michigan Crushed Concrete, Inc.

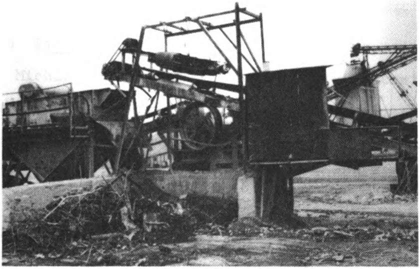

Figure 3-8. Removal of Steel from Crusher Belt by Magnet at Michigan Crushed Concrete, Inc.

the screening process to provide a more suitable grading. All crushed material was caught at the point of discharge from the radial stackers and placed in a hauling unit for transport to the writer's residence. Here, sufficient material was bagged for transport to the laboratory. Approximately four cubic yards of material for research resulted from this procedure.

3.1.2 Bituminous Material

Bituminous concrete overlay materials which had been roto-milled from a project on U.S. 12 near Inkster, Michigan, and stockpiled at an asphalt plant, provided the materials required for this project. The overlays were placed in successive layers in 1953 and 1972 and were, therefore, considered appropriate. This material was designated as Code E.

3.1.3 Fine Aggregate

Michigan 2NS natural sand was used extensively for this research project. Forty bags (approximately 3000 pounds) were gathered at the Morgan Sand and Gravel Company near Brighton, Michigan to insure a sufficient quantity for uniformity of test results. This type of sand results from the disintegration of rocks as part of the erosion and weathering process and is the material used for, virtually, all concrete construction purposes in the State. The material was considered similar to those used in the mixes for the original concrete used for recycling.

3.1.4 Control Coarse Aggregate

Since it was desirable to use a coarse aggregate similar to those used in the mixes for concrete to be recycled, natural gravel meeting the requirements of Michigan specifications 6A was selected for the control mix. These gravels are, largely, metamorphic in nature, and contain a variety of base materials. The aggregate gradings used in the original mix were no longer available. The source of coarse aggregate used for this research was the L.W. Hall Pit near St. Johns, Michigan. Sufficient quantities were obtainable at the Michigan Department of Transportation laboratory to make the necessary batches.

3.1.5 Cement

Cement used for this project was Peerless Portland Cement Type I-A meeting the requirements of Michigan specifications which state this material must meet ASTM Standards C150 and C359. Type I-A cement is designed to provide air-entrainment for concrete, but normally requires the addition of an air-entrainment agent to provide satisfactory levels.

Arrangements were made with the Peerless Cement Company in Detroit, Michigan to provide twenty bags (1880 pounds) of cement from a single manufacturing batch. Representative samples were obtained from these bags and tested for uniformity and specification requirements by the company. The cement was stored in plastic bags for the period of research to avoid the possibility of premature hydration.

3.2 Concrete Mix Design Used for Research

As previously discussed, the Michigan Department of Transportation uses a variation of the mortar-void method for the design concrete mixtures which is closely related to the absolute volume method (31). Since this work was also related to practices in Michigan, it was decided to use the absolute volume method adjusted for empirical factors relevant to current practices in Michigan.

Most major paving projects in Michigan are accomplished with the use of slipform pavers. Assuming a recycling project would be considered major, the concrete mix was designed accordingly.

3.2.1 Mix Design Procedure

Review of previous mix designs for slipform paving in Michigan resulted in a determination that the average water-cement ratio used was approximately 0.43. In addition, the cement factor is specified as 6 sacks per cubic yard (564 lb.), the workability factor (b/b_o) as 0.72, and air content as 5.5% ± 1.5%. Design is based on the bone-dry weights of aggregates and on one yard of concrete (31).

Using this information, put into formula form, the mix design for this research was:

$$W_b = b/b_o \cdot V\gamma_b \qquad (3\text{-}1)$$

where:

γ_b = Weight per cubic foot of the coarse aggregate in a loose, bone-dry condition.

$$V_b = \frac{W_b}{G_b \gamma_w} \qquad (2\text{-}3)$$

$$V_c = \frac{W_c}{G_c \gamma_w} \qquad (2\text{-}4)$$

$$W_w = W/C \cdot W_c \qquad (3\text{-}2)$$

$$V_w = \frac{W_w}{\gamma_w} \qquad (2\text{-}5)$$

$$V_\lambda = \lambda V \qquad (2\text{-}6)$$

$$V_a = V - V_b - V_c - V_w - V_\lambda \qquad (2\text{-}7)$$

$$W_a = V_a \cdot G_a \cdot \gamma_w \qquad (2\text{-}8)$$

The total water (W_{wt}) required for the mix was determined by the absorption of the aggregates from :

$$W_{wt} = W_w + A_a W_a + A_b W_b \qquad (3\text{-}3)$$

where :

A_a = The percent absorption of the fine aggregate;

A_b = The percent absorption of the coarse aggregate.

CHAPTER IV

AGGREGATE PROPERTIES

Research test methods were in accordance with ASTM standard procedures (5). Certain modifications to these procedures, as applied by the Michigan Department of Transportation, were considered appropriate. Recycled aggregates were treated in the same manner as conventional aggregates for all experiments. Procedures are enumerated in the following standards or discussed as required:

1. Bulk Specific Gravity (G_a) and Percent Absorption (A_a) of Fine Aggregate - ASTM C 128-73 Modified.

2. Bulk Specific Gravity (G_b) and Percent Absorption (A_b) of Coarse Aggregate - ASTM C 127-77 Modified.

3. Deleterious Particles in Coarse Aggregate - Michigan Methods.

4. Fineness Modulus (FM) of Fine Aggregate - ASTM C 125-76.

5. Materials Finer Than Number 200 Sieve by Washing (LBW) - ASTM C 117-76.

6. Organic Impurities in Sand For Concrete - ASTM C 40-73.

7. Salt (NaCl) Content in Portland Cement Concrete - Michigan Methods.

8. Sieve or Screen Analysis of Fine and Coarse Aggregate - ASTM C 136-76.

9. Soundness of Aggregates by Use of Magnesium Sulfate - ASTM C 88-76.

10. Unit Weight of Coarse Aggregate (γ_b) - ASTM C 29-78.

Inasmuch as specifications relative to aggregate properties vary from state to state, and because the basic research materials are peculiar to the State of Michigan, experimental results are compared to Michigan Department of Transportation specifications (35).

4.1 Material Preparation and Gradation

The preparation of recycled aggregates for use in experimental concrete mixes, and for test samples, approximated field crushing operations as closely as possible.

4.1.1 Field Crushed PCC Slab Sections

Three samples representing the crushed slab sections (Aggregate material Code A) were reduced to a workable size using a standard sample splitter. The reduced samples were then tested for gradation using standard sieves. Results (Table 4-1) indicate a degree of uniformity between samples. Since the larger aggregate particles were considered too large for use in normal pavement concrete, it was necessary to recrush these particles in the laboratory.

A procedure was devised to simulate a field crushing operation where material exceeding a nominal one inch

Table 4-1. Crusher Run Gradations for Recycled I-96 Slab Sections - Cumulative Percent Passing.

Sieve	Sample Number 1	2	3	Average
2-1/2"	100	100	100	100
1-1/2"	97	97	96	97
1"	67	63	74	68
3/4"	51	47	60	53
1/2"	30	30	40	34
3/8"	24	22	30	26
#4	12	12	15	13

maximum size is scalped after primary crushing and recrushed in a secondary crusher. Individual steps in this procedure are:

Step 1. Recycled aggregate is graded through a Gilson mechanical grader (Figure 4-1).

Step 2. All material retained on the one inch screen is removed and recrushed in a Denver 5 X 6 inch laboratory jaw crusher (Figure 4-2).

Step 3. The recrushed material is then returned to the Gilson grader and processed with the rest of the sample.

For the three samples used in the initial analysis, weights retained on each screen size were used to determine gradations. Material passing the number four (#4) sieve size was separated as fine aggregate and was, therefore, not included in the calculations for the coarse fraction. Gradation test results (Tables 4-2 and 4-3) for both the coarse and fine fractions resulting from this procedure show that the material maintained the same degree of uniformity as the original sample.

Graphing cumulative percents passing on special graph paper should produce a straight line for a perfectly well-graded aggregate. For this material, the coarse and fine fractions were fairly well graded (Figure 4-3).

Approximately 4000 pounds of the crushed slab material was processed in exactly the same manner. Each sieve size was bagged separately to provide material for controlled proportioning of the various sizes. The procedures

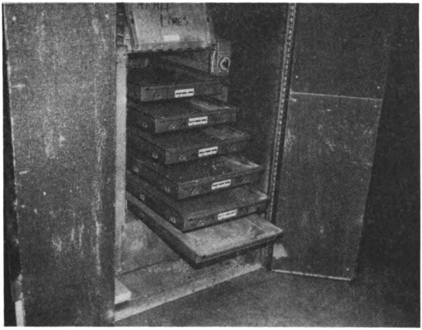

Figure 4-1. Gilson Mechanical Grader

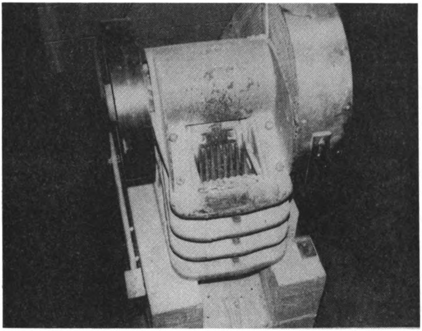

Figure 4-2. Denver Jaw Crusher

Table 4-2. Coarse Fraction Cradation Test Results for Three Samples of Recycled PCC Aggregate A - Cumulative Percent Passing.

Sieve	Sample Number 1	2	3	Average
1-1/2"	100	100	100	100
1"	99	96	98	98
3/4"	75	73	80	76
1/2"	41	42	46	43
3/8"	24	24	25	25
#4	Min.	Min.	Min.	Min.
LBW	---	---	---	0.5*
Passing #4**	18	20	20	19

* Average for materials from each sample.
**Aggregates were split at the #4 sieve and not included in the calculations for the coarse fraction.

Table 4-3. Fine Fraction Gradation Test Results for Three Samples of Recycled PCC Aggregate A - Cumulative Percent Passing.

Sieve	Sample Number 1	2	3	Average
3/8"	100	100	100	100
#4	100	99	99	99
#8	63	62	60	61
#16	42	40	38	40
#30	30	28	27	28
#50	20	18	18	19
#100	12	12	12	12
LBW	6.3	6.7	6.9	6.6
FM	3.34	3.42	3.47	3.41

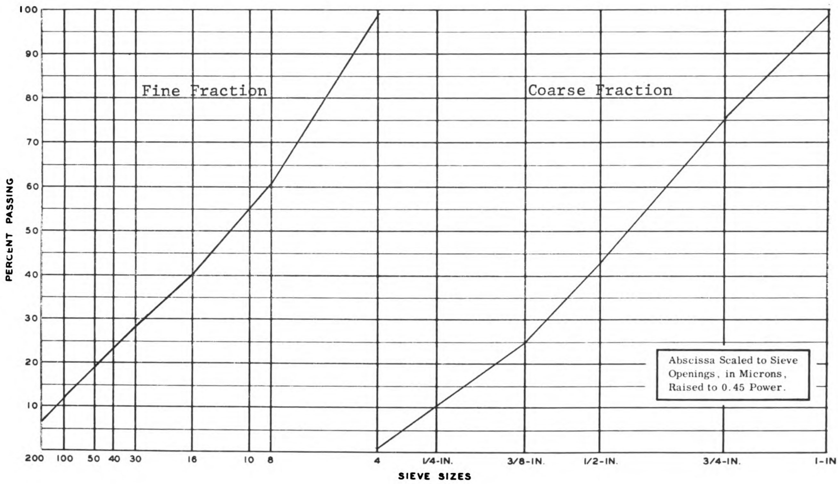

Figure 4-3. Particle Size Distribution of Coarse and Fine Fractions of Aggregate A.

described in this section were established as a standard for the preparation of all recycled materials used for research experiments. Nine pieces of temperature steel ranging in length from three to nine inches were found in the entire grading process. In addition, visual observations during grading were that there were random particles of asphalt joint patching material present in the samples.

4.1.2 PCC Pavement Cores

PCC pavement cores (Aggregate material codes A-1, B, and C) obtained from previously described locations were first tested for compressive strength (Table 4-4). The resulting core fragments were then crushed in the Denver jaw crusher simulating primary field crushing. After this initial crushing, exactly the same procedures as those used for the crushed slab sections were followed.

Table 4-4. Average Compressive Strengths of PCC Pavement Cores from Various Locations.

Aggregate Code	Compressive Strength, psi
A-1	5990
B	6500
C	5860

4.1.3 Laboratory PCC Test Beams

In order to investigate a case where aggregates are produced from concrete originally made with recycled aggregates, in other words a "re-recycled" aggregate, twelve laboratory test beams, cast from concrete containing Aggregate A for the coarse aggregate and varying proportions of PCC and natural fines, were crushed using the established procedure. This material was coded as Aggregate D.

The beams had experienced 350 cycles in the freeze-thaw chamber used for durability tests and were, therefore, considered a valid approximation of concrete exposed to extreme temperature differentials. The crushed particles exhibited the same shape characteristics as the other recycled PCC aggregate, although it was difficult to identify the natural aggregates used in the original concrete.

Gradations for all of the aforementioned crushed PCC aggregates are shown in Table 4-5 and 4-6. Graphs of the fine and coarse fractions indicated nearly identical crushing characteristics (Figure 4-4).

4.1.4 Other Research Aggregates

Other aggregate materials of a recycled nature were processed in the same manner as PCC materials. Conventional sampling and test methods were used to determine the properties of the natural gravel and sand used for the experiments.

Table 4-5. Gradations of Coarse Recycled PCC Aggregates - Cumulative Percent Passing.

Sieve	Aggregate Code				
	A*	A-1	B	C	D
1-1/2"	100	100	100	100	100
1"	98	98	98	97	100
3/4"	76	74	76	77	80
1/2"	74	36	36	36	40
3/8"	25	19	21	20	23
#4	Min.	Min.	Min.	Min.	Min.
LBW	0.5	0.4	0.5	0.4	0.3
Passing #4**	20	15	16	17	21

* Average of three samples.
**Aggregates were split at the #4 sieve and not included in the calculations for the coarse fraction.

Table 4-6. Gradations of Fine Recycled PCC Aggregates - Cumulative Percent Passing.

Sieve	Aggregate Code				
	A*	A-1	B	C	D
3/8"	100	100	100	100	100
#4	99	99	99	99	100
#8	61	62	68	72	71
#16	40	38	46	48	48
#30	28	26	32	32	33
#50	19	17	19	20	22
#100	12	10	10	12	15
LBW	6.6	5.6	4.1	5.8	9.1
FM	3.41	3.48	3.25	3.16	3.11

*Average of three samples.

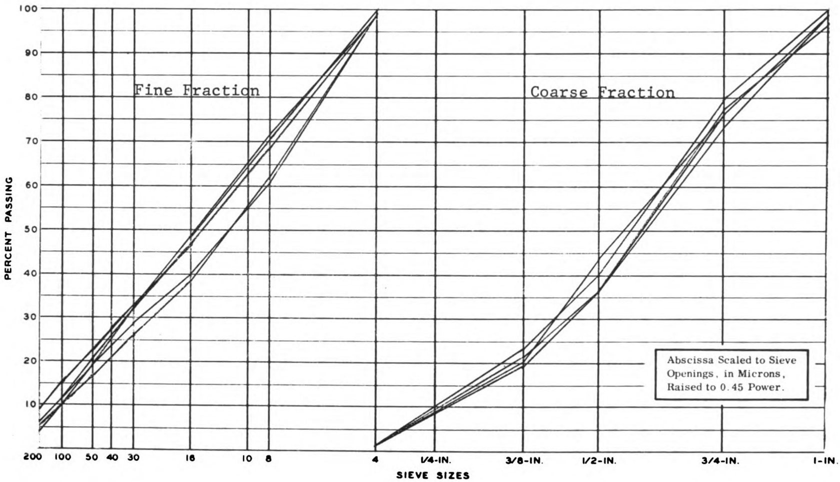

Figure 4-4. Particle Size Distribution of Coarse and Fine Fractions of Recycled PCC Aggregates.

PCC Pavement Cores with Bituminous Overlay

PCC Pavement cores with a nominal three inches of bituminous concrete overlay (Aggregate material code C-1) were crushed to determine the resulting proportions of each material in the coarse and fine aggregate fractions.

The bituminous concrete was approximately 25 percent of the total core volume. Only 17 percent of the total crushed material on and above the #4 sieve contained bituminous concrete particles of which a major proportion were natural aggregate particles with thin coatings of bitumen.

Crushed Bituminous Concrete

The crushed bituminous concrete (Aggregate material code E) exhibited the same characteristics as the overlay material crushed with the pavement cores in that more material passed the #4 sieve than the plain crushed PCC. In addition, much of the coarse fraction materials were natural aggregates with minimal coatings of bitumen. All materials passing the #4 sieve were thoroughly coated.

Natural Aggregates

A representative sample of the natural sand (Aggregate code 2NS) from the lot used for this research was tested and considered a constant. The coarse gravel (Aggregate code 6A) was tested for physical properties, only, since mix proportioning was based on a standard gradation.

Gradations for aggregate materials discussed in this section are shown in Tables 4-7 and 4-8. Current Michigan Department of Transportation gradation limits (35) for fine

Table 4-7. Gradations of Various Coarse Aggregates Used for Research - Cumulative Percent Passing.

Sieve	Aggregate Code C-1	E
1-1/2"	100	100
1"	99	100
3/4"	80	90
1/2"	39	67
3/8"	23	44
#4	Min.	Min.
LBW	---	---
Passing #4*	18	31

*Aggregates were split at the #4 sieve and not included in the calculations for the coarse fraction.

Table 4-8. Gradations of Various Fine Aggregates Used for Research - Cumulative Percent Passing.

Sieve	Aggregate Code C-1	E	2NS
3/8"	100	100	100
#4	100	100	99
#8	69	57	84
#16	42	32	60
#30	24	19	38
#50	13	9	13
#100	7	3	3
LBW	2.5	----	0.6
FM	3.44	3.80	3.02

and coarse aggregates used in concrete mixtures for pavements are shown in Tables 4-9 and 4-10.

4.2 Physical Properties of Research Aggregates.

In order to simplify the identification of the research aggregates, a recapitulation of aggregate material codings and sources is offered in Table 4-11. Experimental procedures not covered by ASTM standards (5) or those of special interest are discussed in the following sections.

4.2.1 Deleterious Particles in Coarse Aggregate.

Michigan Department of Transportation methods (35) were used to evaluate the percentage of aggregate particles considered detrimental to concrete quality and durability. In this method, all aggregate particles retained on and above the 3/8 inch sieve during gradation testing are visually inspected for a determination of aggregate type. Percentages of deleterious particles are based on the fractional weight of total aggregates used in the analysis.

Using this method for recycled PCC aggregate, the total weight of crushed PCC particles containing any evidence of an exposed deleterious aggregate was included in the calculated percentages.

The major concentrations of deleterious substances in Michigan natural aggregates are chert and soft particles including friable sandstone, siltstone, shale, ochre, and clay ironstone.

Table 4-9. Michigan Gradation Limits for Coarse Aggregates Used in PCC Mixes for Pavement - Cumulative Percent Passing. (Source: 1979 Standard Specifications for Construction - Michigan Department of Transportation)

Michigan Series	Class	Sieve 1-1/2"	1"	1/2"	#4	LBW
6	A	100	95-100	30-60	0-8	1.0 max.*

*Loss by washing of 2.0 percent permitted for material produced entirely by crushing rock, boulders, cobbles, or slag.

Table 4-10. Michigan Gradation Limits for Fine Aggregates Used in Mixes for PCC Pavements - Cumulative Percent Passing. (Source: 1979 Standard Specifications for Construction - Michigan Department of Transportation)

Aggregate Number	3/8"	#4	#8	#16	#30	#50	#100	LBW	FM
2NS	100	95-100	65-95	35-75	20-55	10-30	0-10	0-3	2.50 to 3.5

Table 4-11. Coding and Source Information for Research Aggregates.

Aggregate Code	Description	Source
A	Crushed slab sections	I-96 New Hudson
A-1	Crushed cores	I-96 New Hudson
B	Crushed cores	I-94 BL Battle Creek
C	Crushed cores	I-94 Jackson
C-1	Crushed cores with 3" overlay	I-94 Jackson
D	Crushed beams	Laboratory - Freeze-Thaw test on concrete made with aggregate A
E	Crushed bituminous concrete	US-12 Inkster
6A	Natural gravel	Morgan Sand and Gravel Company
2NS	Natural sand	Hall Sand and Gravel Company

4.2.2 Bulk Specific Gravity and Percent Absorption of Coarse Aggregate.

In order to provide a comprehensive investigation of these properties in recycled PCC, tests were made on each size fraction of Coarse Aggregate A. Test results were weighted on the basis of average percentage retained on each sieve size using the following formulae (5):

$$G_b = \frac{1}{\frac{P_1}{100G_1} + \frac{P_2}{100G_2} + + + \frac{P_n}{100G_n}} \qquad (4\text{-}1)$$

where:

G_1, G_2, ... G_n = Appropriate specific gravity values for each size fraction;

P_1, P_2, ... P_n = Weight percentages of each size fraction present in the original sample.

and:

$$A_b = \frac{P_1A_1}{100} + \frac{P_2A_2}{100} + + + \frac{P_nA_n}{100} \qquad (4\text{-}2)$$

where:

A_1, A_2, ... A_n = Absorption percentages of each size fraction in the original sample.

Test results for each size fraction are shown in Table 4-12. A visual examination of the aggregates at each sieve size resulted in a determination that the top-size material contained a larger proportion of unbonded and crushed natural aggregate than the material retained on the smaller sizes.

Table 4-12. Weighted Bulk Specific Gravity (G_b) and Percent Absorption (A_b) of Recycled PCC Coarse Aggregate A.

Sieve	Percent Retained	G_b	A_b
1"	2	2.52	2.54
3/4"	22	2.36	3.98
1/2"	33	2.34	4.50
3/8"	18	2.29	5.34
#4	25	2.23	6.50
Weighted Average		2.31	5.00

The aggregates retained on the #4 sieve were mostly crushed mortar particles.

4.2.3 Salt Content (NaCl) of Portland Cement Concrete.

Because the Michigan Department of Transportation uses large amounts of rock salt as a deicing agent for highways, there was a concern that detrimental amounts of sodium chloride may have infiltrated the PCC material used for recycling.

Test methods used by the Michigan Department of Transportation (20) to determine damaging amounts of salt, in pounds per cubic yard, in bridge deck concrete were considered appropriate for this research.

Michigan specifies that when the salt content of bridge deck concrete exceeds four pounds per cubic yard, the concrete should be removed and replaced with new concrete. Inasmuch as test results (Table 4-13) for the recycled PCC used in this research were well under the specified amount, this factor was not considered significant. This is especially true considering that the transverse joints in the pavement slabs (Aggregate A) would contain the highest concentrations of salt.

4.2.4 Experimental Results for Aggregate Properties.

The results of various experimental rests for all research aggregates are shown in Tables 4-14 through 4-16. Test results are compared to Michigan Department of Transportation specifications where applicable.

Table 4-13. Salt Content (NaCl) of Recycled PCC Aggregates.

Aggregate Code	NaCl, lb./yd^3
A*	1.89
A-1	1.72
B	1.72
C	1.72
D	1.03

*Average of three samples.

Table 4-14. Deleterious Particles in Coarse Aggregates Used for Research Compared to Michigan Department of Transportation Specifications.

Aggregate Code	Percent Soft Particles	Percent Chert	Sum
A*	0.7	0.5	1.2
A-1	0.6	0.5	1.1
B	1.5	1.0	2.5
C	1.3	2.9	4.2
C-1	0.9	0.8	1.7
D	Negligible	Negligible	---
E	Negligible	Negligible	---
6A	2.4	4.3	6.7
MDOT Specifications	2.5 max.	---	9.0 max.

*Average of three tests.

Table 4-15. Various Properties of Coarse Aggregates Used for Research.

Aggregate Code	Percent Soundness Loss	Percent Absorption (A_b)	Bulk Specific Gravity (G_b)	Unit Weight (γ_b), lb./ft^3
A	0.9	5.00	2.31	76
A-1	1.4	4.48	2.33	---
B	2.0	4.28	2.39	---
C	0.9	3.43	2.38	---
C-1	---	2.78	2.40	---
D	0.4	8.36	2.11	68
E	---	1.44	2.38	---
6A	3.9	1.02	2.67	104
MDOT Specifications	12.0 max*	----	----	---

*Prior to 1973 - Not specified in current specifications.

Table 4-16. Various Properties of Fine Aggregates Used for Research.

Aggregate Code	Percent Soundness Loss	Percent Absorption (A_b)	Bulk Specific Gravity (G_b)	Organic Plate Number
A	8.3	8.31	2.16	1*
A-1	6.8	7.78	2.18	1*
B	8.8	7.17	2.23	1*
C	7.0	7.53	2.15	1*
C-1	---	5.17	2.23	--
D	5.7	11.79	2.00	1*
E	---	2.40	2.29	--
2NS	7.1	1.38	2.60	2
MDOT Specifications	16.0 max**	-----	----	3 max.

* Tests for organic impurities were well under the number one standard reference plate.
**Prior to 1973 - Not specified in current specifications.

Coarse aggregates produced by crushing Portland cement concrete were superior to the control natural gravel in those tests designed to evaluate the possible effect of aggregate properties with respect to the durability of concrete. Recycled PCC fine aggregate properties were essentially comparable to the durability properties of the control natural sand.

The extremely high absorptions and low specific gravities of Aggregate D are assumed to result from the fact that the aggregate particles were, mainly, crushed mortar containing progressively higher percentages of entrained air.

CHAPTER V

CONCRETE PROPERTIES

Experimental procedures to determine the properties of fresh and hardened recycled aggregate concrete, as well as for control mixes, were accomplished according to the following standards:

1. Air Content of Freshly Mixed Concrete by the Volumetric Method - ASTM C 173-78.
2. Capping Cylindrical Concrete Specimens - ASTM C 617-76.
3. Compressive Strength of Cylindrical Concrete Specimens - ASTM C 39-72.
4. Concrete Test Specimens, Making and Curing in the Laboratory - ASTM C 192-76.
5. Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading) - ASTM C 293-68.
6. Fundamental Transverse and Torsional Frequencies of Concrete Specimens - ASTM C 215-60.
7. Resistance of Concrete to Rapid Freezing and Thawing - ASTM C 666-77.
8. Slump of Portland Cement Concrete - ASTM C 143-74.
9. Unit Weight and Yield of Concrete - ASTM C 138-77.

5.1 Aggregate Proportions for Experimental Mixes

The main emphasis of this research was to determine the effects of using the various components of recycled aggregates, resulting from crushing surfacing concrete found in existing pavements, on the properties of concrete and pavement design. In this respect, research aggregates were proportioned on the basis of crushing pavement concrete peculiar to actual field conditions.

5.1.1 Recycled PCC Aggregate

As a result of determining the proportions of fine and coarse aggregates required for mix design compared to the percentages of these aggregates resulting from the crushing process, it was determined that approximately 30 to 35 percent of the fine aggregate, necessary to utilize all of the coarse aggregate produced, would be available in the crusher fines. Therefore, additional fines in the form of conventional aggregate would have to be provided.

Since it was previously determined that the coarse and fine fractions of recycled PCC aggregate should be split and stockpiled separately to avoid segregation problems, a number of options concerning the ratios of recycled and natural fines used in mix proportioning were considered. These options could range from using all crushed PCC fines to all natural fines in combination with 100 percent crushed PCC coarse aggregate if concrete quality permitted.

Recycled Aggregate A from the crushed slab sections was used, extensively, as a standard for experiments to determine concrete properties related to varying the proportions of recycled PCC crusher fines with conventional fines.

Crushed Pavement Cores and Test Beams

Individual concrete batches made with aggregate resulting from crushing PCC pavement cores were used as a check against the standard mix. Concrete made with aggregate from the crushed laboratory beams provided an initial investigation to determine if concrete made with recycled aggregates could be recycled again in the future.

Percentages of the volumes of coarse and fine aggregates used in the recycled PCC concrete mixtures are identified by batch series and aggregate code in Table 5-1.

5.1.2 Recycled PCC in Combination with Bituminous Concrete

Because of conflicting reports concerning the detrimental effects of overlayment materials on concrete quality (3) and the entrainment of air in fresh concrete (3,19), mixes were designed incorporating various amounts of crushed bituminous concrete.

Bituminous concrete overlays in Michigan are normally 1-1/2, 2-1/2, and 4 inches in depth. Calculated on the basis of these overlay depths on a nine inch PCC pavement, volume percentages are 14.3, 21.7, and 30.8 percent respectively. Volume percentages of aggregates used in concrete batches made with combinations of crushed bituminous and PCC materials are shown in Table 5-2.

Table 5-1. Combinations of Aggregates Used for Recycled PCC Mix Design

Batch Series	Coarse Aggregate		Fine Aggregate			
	Aggregate Code	Percent Volume	Aggregate Code	Percent Volume	Aggregate Code	Percent Volume
1	A	100	A	100	---	---
2	A	100	A	75	2NS	25
3	A	100	A	50	2NS	50
4	A	100	A	25	2NS	75
5	A	100	--	---	2NS	100
6	A-1	100	A-1	25	2NS	75
7	B	100	--	---	2NS	100
8	C	100	--	---	2NS	100
9	D	100	--	---	2NS	100
10 - Control Mix	6A	100	--	---	2NS	100

Table 5-2. Combinations of Aggregate Used for Recycled PCC Mix Design Including Bituminous Concrete.

Batch Series	Coarse Aggregate				Fine Aggregate			
	Agg. Code	Percent Volume	Agg. Code	Percent Volume	Agg. Code	Percent Volume	Agg. Code	Percent Volume
11	A	85.7	E	14.3	E	14.3	2NS	85.7
12	A	78.3	E	21.7	E	21.7	2NS	78.3
13	A	85.7	E	14.3	--	-----	2NS	100
14	A	78.3	E	21.7	--	-----	2NS	100
15	A	69.2	E	30.8	--	-----	2NS	100
16	A	69.2	E	30.8	E	30.8	*	69.2
17	C-1**	100	--	----	--	-----	2NS	100
18	E	100	--	----	E	100	---	-----

* Combination of A, B and C.
**Approximately 17 percent bituminous concrete determined from gradation test.

Batch series 11 and 12 were designed to test the effect of bituminous materials on air entrainment, therefore, bituminous fines were combined with natural fines, only, so that the possible effects of PCC fine aggregate on air entrainment are deleted. This combination would not be present under normal field conditions. Batch series 18 using 100 percent crushed bituminous concrete was designed for informational purposes only.

The concrete mix designs discussed in this section provided the basis of an initial investigation of the properties of concrete containing the stated proportions of aggregates and were not intended as part of a comprehensive study.

5.2 Laboratory Procedures for Test Batches.

The procedures to prepare, proportion, weigh, and mix materials for concrete test batches closely followed those outlined in ASTM C 192-76.

5.2.1 Material Weighing and Preparation.

Coarse aggregates were proportioned on the basis of the average percent retained on the various sieve sizes from gradation tests for Aggregate A (Table 5-3). Weights for each size fraction were corrected for moisture content and weighed cumulatively. In order to assure complete absorption, the individual aggregate sizes were recombined in tared containers and immersed in water for a minimum of 24 hours. Prior to use in a mix, excess water was decanted, the aggregate reweighed, and appropriate corrections made for mixing water.

Table 5-3. Average Percent Retained on Each Sieve Size For Aggregate A.

Sieve	1"	3/4"	1/2"	3/8"	#4
Percent Retained	2	22	33	18	25

Fine aggregates were proportioned in their original gradations. After weighing, enough water was added to the material to allow for absorption. The same procedure as that used for the coarse aggregate was followed before using the material in a concrete mixture.

Both the cement and mixing water were proportioned by weight.

5.2.2 Research Mix Design

The basic concrete mix design used for all experiments is outlined in Chapter III. The following factors were held constant:

1. Water-Cement Ratio (W/C) = 0.43
2. Cement Factor, per cubic yard = 6 sacks (564 lb.)
3. Coarse Aggregate Workability Factor (b/b_o) = 0.72
4. Percent Entrained Air (λ) = 5.5 ± 1.5

A standard laboratory batch size of 1.4 cubic feet was sufficient for fresh concrete tests and for making the necessary test specimens. This batch size provided for 15 percent extra volume for uniformity in sampling and waste. Concrete used for slump and unit weight determinations was remixed with the batch and used for test specimens.

5.2.3 Mixing Experimental Batches

Concrete batches were mixed in a laboratory pan mixer (Figure 5-1) large enough to mix an entire batch. The pan and mixing blades were "buttered" before the introduction of batch material to allow for the loss of any mortar adhering to the mixer. The sequences stated in the standards (5) for the introduction of materials and mixing times were followed as closely as possible.

5.3 Properties of Fresh Concrete.

Tests to determine slump, air content, yield, and temperature were made for each experimental batch upon completion of mixing. A Soiltest Roll-a-meter (Figure 5-2) was used for determining air contents because of the relatively high absorptions of the recycled PCC aggregates.

5.3.1 Workability

Although the workability of fresh concrete is difficult to define unless this factor is determined under the field conditions in which the concrete is to be used, an attempt was made to identify the finishing and consolidation properties of recycled aggregate laboratory mixtures. Inasmuch as the equipment used in a normal paving operation would include combinations of multiple vibrators, floats, and screeds capable of consolidating and finishing harsh concrete mixes, laboratory observations are of minimal value.

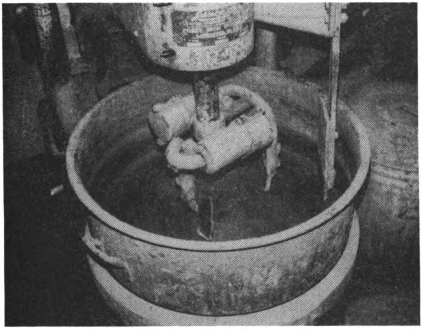

Figure 5-1. Laboratory Pan Mixer

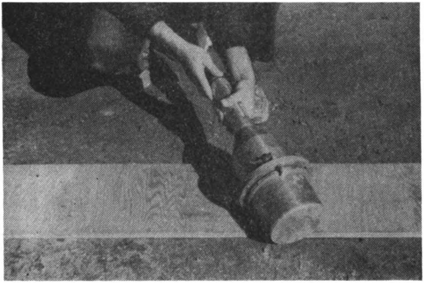

Figure 5-2. Roll-A-Meter for Volumetric Air Tests

5.3.2 Test Results for Fresh Concrete

Average test results and observations related to the properties of fresh concrete made with recycled PCC and control aggregates are shown in Table 5-4. The properties of mixes containing proportions of crushed bituminous concrete are shown in Table 5-5.

Table 5-6 shows the relationship of the percentage of entrained air to varying amounts of air entraining admixture added to concrete mixes containing bituminous material. It was determined that concrete containing the stated materials will react normally to the addition of air entraining admixtures as indicated in Figure 5-3.

5.4 Properties of Hardened Concrete

Test specimens to determine the properties of hardened concrete were made from each experimental batch in the quantities shown in Table 5-7. A total of 380 individual tests were completed to provide comprehensive research data.

5.4.1 Curing Test Specimens

Test specimens were removed from the molds the day following mixing the concrete and stored in saturated-lime water for seven days. Specimens not subject to 7-day testing were stored in an approved moist room (5) until tested.

Table 5-4. Properties of Fresh Concrete Made with Recycled PCC Aggregate.

Batch Ident.	Slump Inches	% Air Content	Temp. ^{0}F	Unit Wgt. lb.	Yield* %	Observed Workability Finishing	Consolidation
Field Crushed Slab Sections							
1A-B-C-D	1.0	5.0	70	132.8	+0.9	Harsh	Good
1E**	1.5	5.0	73	133.3	-0.5	Harsh	Good
2A-B-C	1.5	4.9	71	-----	---	Harsh	Good
3A-B-C	1.0	4.3	72	-----	---	Harsh	Good
4A-B-C	1.75	5.3	72	138.3	+0.5	Good	Good
5A-B-C	2.0	6.6	70	137.2	+0.2	Good	Good
Laboratory Crushed Cores							
6A***	5.0	8.6	71	132.1	+1.2	Good	Good
7A	1.25	6.7	68	140.1	-0.9	Good	Good
8A	1.0	5.3	68	141.4	-0.8	Good	Good
Laboratory Freeze-Thaw Beams (Recycled Concrete)							
9A	1.5	5.7	72	135.9	-0.1	Good	Good
Control Mix-Gravel							
10A-B	3.25	5.8	72	146.2	-0.6	Good	Good

* Corrected for air content.

**W/C = 0.46 and b/b_o = 0.70 for a check on workability.

***Batching error - W/C = 0.49 - Included for information.

Table 5-5. Properties of Fresh Concrete Made with Combinations of Recycled PCC and Crushed Bituminous Concrete.

Batch Ident.	Slump Inches	% Air Content	Temp. °F	Unit Wgt. lb.	Yield* %	Observed Workability Finishing	Consolidation
Field Crushed Slabs, Natural Sand, and Crushed Bituminous Concrete - To Determine the Effect of Overlay Materials on Air Content.							
11A-B-C	2.5	6.6	73	137.6	-0.6	Good	Good
12A	2.5	7.7	71	135.7	-0.7	Good	Good
Field Crushed Slabs and Bituminous Concrete							
13A	1.75	5.0	72	138.5	+0.1	Good	Good
14A	2.5	6.5	73	137.8	-0.1	Good	Good
15A	1.0	5.5	74	140.4	-0.4	Good	Good
16A	1.5	4.9	74	136.6	-1.0	Harsh	Good
Laboratory Crushed Cores with Bituminous Overlay.							
17A	1.0	4.8	69	140.2	-0.3	Good	Good
Crushed Bituminous Concrete - Test for Information							
18A	0.25	5.8	72	133.2	+0.5	Harsh	Fair

*Corrected for air content.

Table 5-6. Air Contents of Concrete Made with Proportions of Recycled PCC and Bituminous Concrete.

Batch Identification	Vinsol* Resin	Air Content
11A	30	8.2
11B	10	4.8
11C	15	6.8
12A	20	7.7

*In cubic centimeters per 1.4 cubic foot batch.

Table 5-7. Number of Test Specimens Made for Each Experimental Batch.

Quantity	Type	Purpose
5	3 X 4 X 16 inch beams	For flexural strength tests, freeze-thaw tests, and the determination of dynamic moduli.
6	4 X 8 inch cylinders	For compressive strength test.

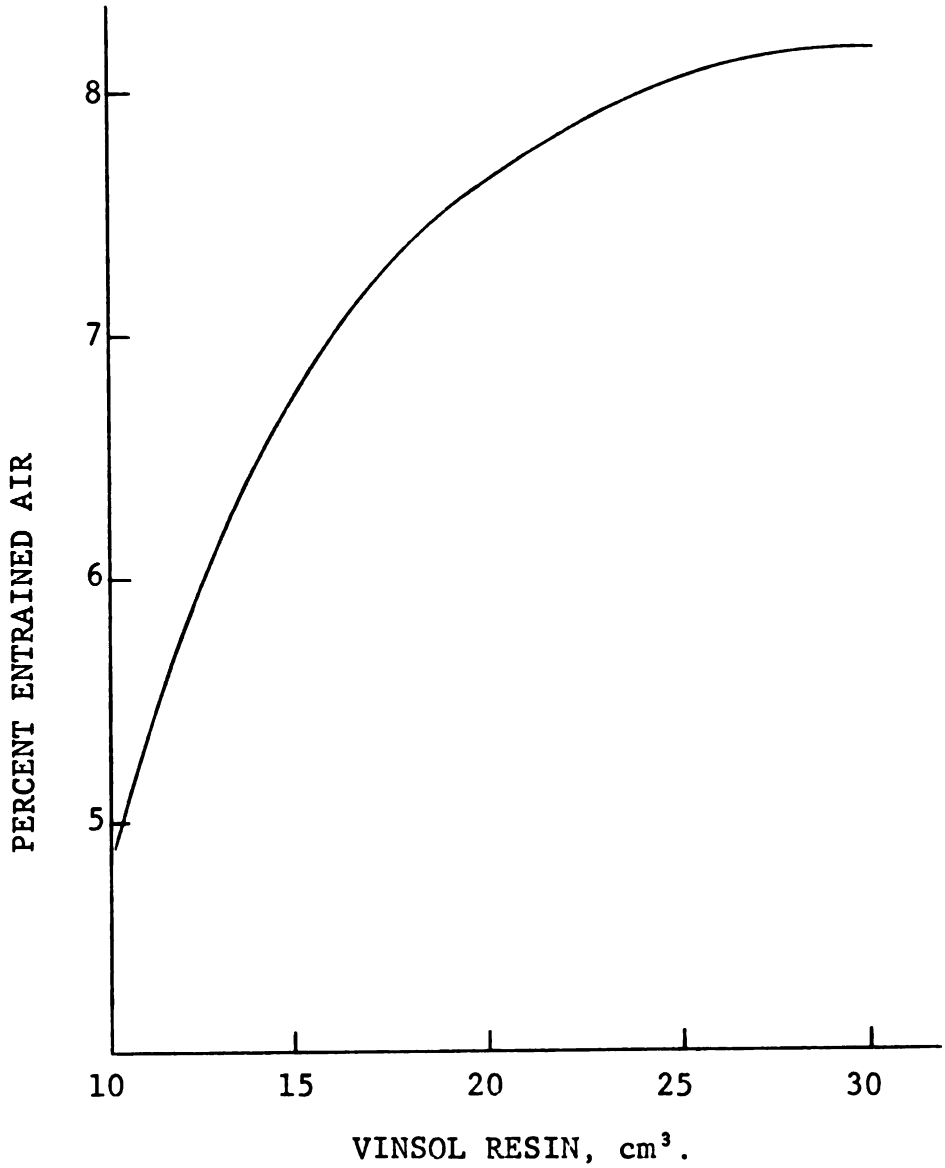

Figure 5-3. Air Contents of Concrete, Containing Proportions of Crushed Bituminous Concrete for Aggregate with the Addition of Various Amounts of Air Entraining Admixture.

5.4.2 Compressive (f'_c) and Flexural (MR) Strengths

Concrete test cylinders and beams were tested at 7 and 28 days. Test results are shown in Tables 5-8 and 5-9 where:

$$f'_c = P/A \qquad (5\text{-}1)$$

where:

P = Total load at failure, lb.;

A = Cross sectional area of the cylinder, in^2.

and:

$$MR = 3Pl/2bd^2 \qquad (5\text{-}2)$$

where:

l = Span length, in.;

b = Average width of beam specimen, in.;

d = Average depth of beam specimen, in.

Standard deviations for 28 day strengths were within an acceptable range for concrete tests.

The relationship of the various ratios of recycled PCC and natural fine aggregates used in the standard mix to concrete strengths are illustrated in Figures 5-4 and 5-5. Both cases indicated that maximum strengths were achieved when recycled PCC was incorporated as part of the total fine aggregate in a concrete mixture.

The Michigan Department of Transportation specifies minimum 28-day compressive and flexural strengths of 3500 psi and 650 psi, respectively, for pavement concrete design.

Table 5-8. Compressive and Flexural Strengths of Concrete Made with Recycled PCC and Control Aggregate.

Batch	Compressive Strength, psi			Flexural Strength, psi		
Ident.	7 day	28 day	Std. Dev.	7 day	28 day	Std. Dev.
Field Crushed Slabs						
1A-B-C-D	4080	4760	260	640	730	40
1E*	3750	4550	---	670	770	--
2A-B-C	4330	5540	280	700	755	35
3A-B-C	5000	5590	310	785	840	25
4A-B-C	4600	5770	280	760	865	45
5A-B-C	4100	4910	140	715	805	35
Laboratory Crushed Cores						
6A**	3110	4080	---	625	675	--
7A	4470	5130	---	760	870	--
8A	4580	5820	---	780	875	--
Laboratory Freeze-Thaw Beams (Re-Recycled Concrete)						
9A	4390	5570	---	710	865	--
Control Mix - Gravel						
10A-B	4520	5260	260	695	850	70

* W/C = 0.46 and b/b_o = 0.70 for a check on workability.
** Batching error - W/C = 0.49 - Included for information.

Table 5-9. Compressive and Flexural Strengths of Concrete Made with a Combination of Recycled PCC and Bituminous Concrete

Batch Ident.	Compressive Strength, psi 7 day	Compressive Strength, psi 28 day	Compressive Strength, psi Std. Dev.	Flexural Strength, psi 7 day	Flexural Strength, psi 28 day	Flexural Strength, psi Std. Dev.
Field Crushed Slabs, Natural Sand, and Crushed Bituminous Concrete - To Determine the Effect of Overlay Material on Air Content						
11A-B-C	3070	3680	550	605	710	65
12A	2550	3280	---	540	640	--
Field Crushed Slabs and Bituminous Concrete						
13A	4100	4790	---	635	725	--
14A	3180	4130	---	655	770	--
15A	3330	4130	---	630	760	--
16A	2640	3110	---	620	615	--
Laboratory Crushed Cores with Bituminous Overlay						
17A	3590	4390	---	640	740	--
Crushed Bituminous Concrete - Tested for Information						
18A	940	1100	---	315	375	--

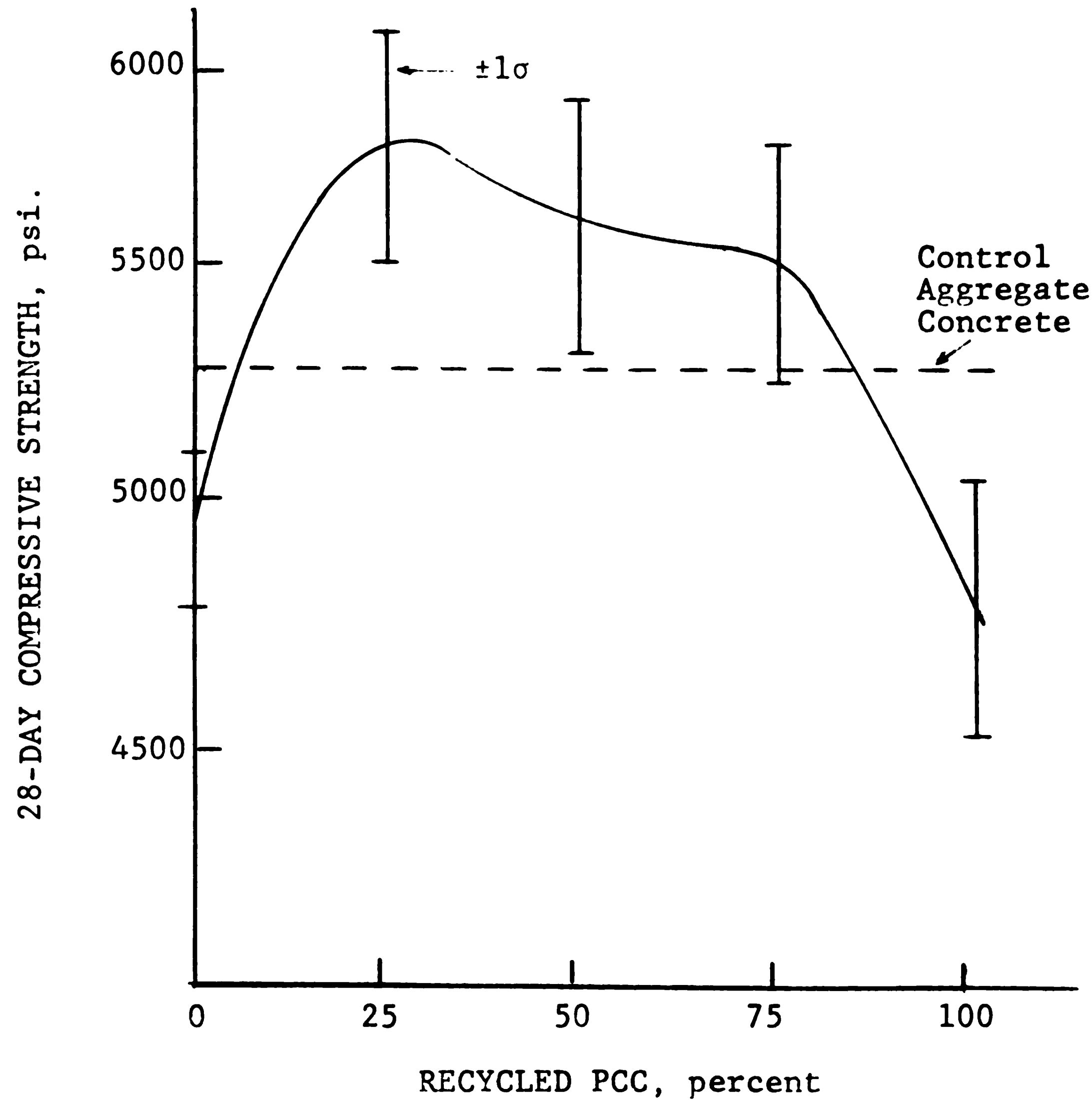

Figure 5-4. The Effects of the Percent of Recycled PCC Fine Aggregate, in Total Fine Aggregate, on Compressive Strength.

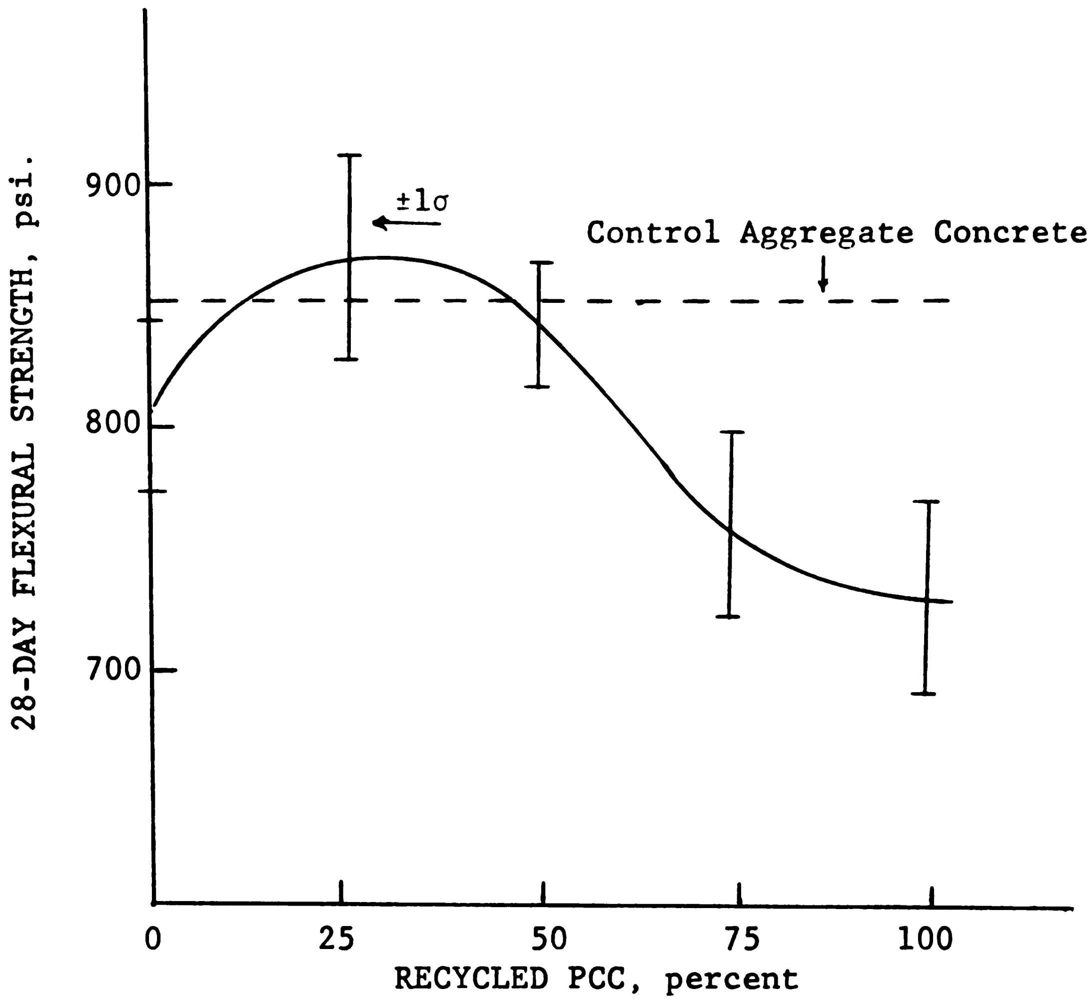

Figure 5-5. The Effects of the Percent of Recycled PCC Fine Aggregate, in Total Fine Aggregate, on Flexural Strength.

5.4.3 Sonic Testing.

A Soiltest CT - 366C Sonometer (Figure 5-6) was used to determine the fundamental transverse and torsional frequencies of test beam specimens from each experimental concrete batch. In this test, a specimen's mechanical resonant frequency is determined by driving it with sound vibrations from a known frequency source and varying the frequency until a resonant condition is achieved.

Durability Factor (DF)

Test beams were exposed to 300 freeze-thaw cycles in accordance with Procedure B stated in ASTM C 666-77. This procedure specifies that the test specimens must be completely surrounded by air during the freezing phase of the cycle and by water during the thawing phase while in the freezing-and-thawing apparatus (Figure 5-7). The durability factor is calculated from:

$$P_c = (n_1{}^2/n^2) \text{ X } 100 \qquad (5\text{-}3)$$

where:

P_c = Relative dynamic modulus of elasticity after c cycles of freezing and thawing, percent;

n = Fundamental transverse frequency at 0 cycles of freezing and thawing;

n_1 = Fundamental transverse frequency after c cycles of freezing and thawing.

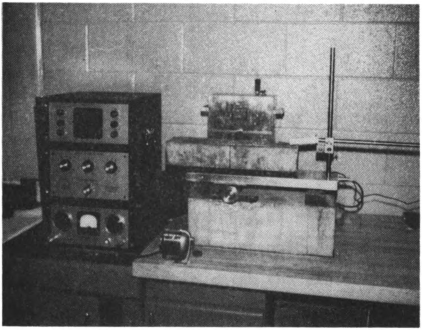

Figure 5-6. Soiltest CT 366C Sonometer.

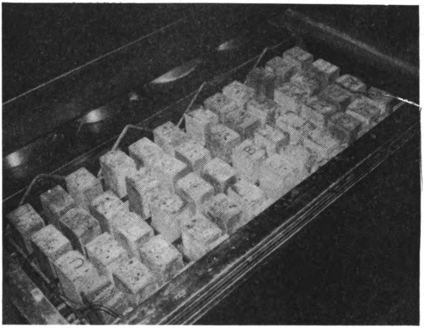

Figure 5-7. Freeze-Thaw Chamber.

and:

$$DF = PN/M \tag{5-4}$$

where:

DF = Durability factor of the test specimen;

P = Relative dynamic modulus of elasticity at N cycles, percent;

N = Number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less;

M - Specified number of cycles at which exposure is to be terminated.

The Michigan Department of Transportation specifies a minimum durability factor of 20 for concrete made with various aggregates. A minimum P value of 70 and M value of 300 is also specified. The durability factors for concrete made with the recycled aggregates in this research were exceptionally high (Table 5-10).

<u>Dynamic Young's Modulus of Elasticity (E) and Poisson's Ratio (μ)</u>

These dynamic values were calculated from the fundamental transverse and torsional resonant frequencies of beam specimens using the following formulae:

$$\text{Dynamic } E = CWn^2 \tag{5-5}$$

Table 5-10. Durability Factors (DF)* for Research Mixes.

Batch Series	Durability Factor	Batch Series	Durability Factor
1	99	10**	81
2	99	11	101
3	100	12	100
4	98	13	101
5	99	14	98
6	105	15	99
7	95	16	93
8	97	17	99
9	95	18***	37

* Tests started at 14 days of age.
** Control Mix
***Concrete using all crushed bituminous concrete for aggregates - Tested for information.

where:

W = Weight of specimen, lb.;

n = Fundamental transverse frequency, Hz.;

$C = 0.00245\ L^3T/bt^3$;

L = Length of specimen, in.;

t,b = Dimensions of the cross section of the beam, in., t being in the direction in which it is driven;

T = A correction factor (ASTM C 215-60)

and:

$$\text{Dynamic } \mu = (E/2G) - 1 \qquad (5\text{-}6)$$

where:

$G = BW\,(n'')^2$;

$B = 4LR/gA$;

R = A shape factor (ASTM C 215-60);

g = Gravitational acceleration (386.4 in/sec^2);

A = Cross sectional area of specimen, in^2;

n''= Fundemental torsional frequency.

Test results for selected specimens (Table 5-11) were in the normal range for saturated concrete.

Table 5-11. Dynamic Young's Modulus of Elasticity (E) and Poisson's Ratio (μ) for Selected Research Test Specimens.

Batch Ident.	E,psi $10X^6$	μ	Batch Ident.	E,psi $10X^6$	μ
1D	4.48	0.18	10B*	5.81	0.20
2B	4.69	----	11A	4.44	0.23
3A	4.97	----	12A	4.00	0.19
4A	5.30	0.20	13A	5.18	0.25
5B	4.87	----	14A	4.92	0.24
7A	5.28	0.18	15A	5.11	0.27
8A	5.55	0.22	16A	4.15	0.26
9A	4.92	0.26	17A	4.97	0.18

*Control Mix

CHAPTER VI

APPLICATION OF EXPERIMENTAL RESULTS

Inasmuch as there was good correlation between various research test results, the experimental data is considered a valid basis for predicting the procedures required to utilize recycled PCC in practical field application. In addition, the data also provides a means for evaluating the economic and design aspects of crushing existing PCC pavement and using the resulting aggregate in new concrete.

6.1 Economic Evaluation

Discussions and projections offered in this section are related to comparing the use of a recycled PCC pavement for concrete aggregate to furnishing new natural gravel and sand The following assumptions are made:

1. Conditions dictate that the existing pavement surface has to be removed and replaced.

2. The resulting broken PCC material is either hauled to a dump site or recycled.

3. The crushing operation is at the project site, at a central location, and on the same site as the concrete batch plant.

4. A ten mile dual pavement removal and replacement paving project.

5. Pavement in each direction is 9 inches thick and 24 feet wide and has temperature reinforcement.

6.1.1 Crushing PCC for Aggregate

Figure 6-1 shows a schematic of a completely portable crushing operation which should be capable of handling approximately 250 tons of material an hour when operating under full capacity. Problems with steel removal may reduce production to 150 tons per hour.

The estimated cost of running the crushing operation is offered in Table 6-1. Calculations were based on average monthly rental rates and hourly operating costs (29) in addition to costs for labor. It was assumed the plant would operate 200 hours each month.

On the basis of this estimate and assuming a practical production rate of 150 tons per hour, a price of $2.52 was assigned to the cost of producing one ton of recycled PCC aggregate using a temporary field crushing setup.

6.1.2 Cost Comparisons

Costs for purchasing and hauling conventional aggregates were based on an investigation of 1979 prices paid by Michigan paving contractors. Inasmuch as there are certain operations peculiar to the type of project being discussed, regardless of recycling the old pavement surface or bringing in new aggregate for concrete, they were not included in the comparison. These operations are:

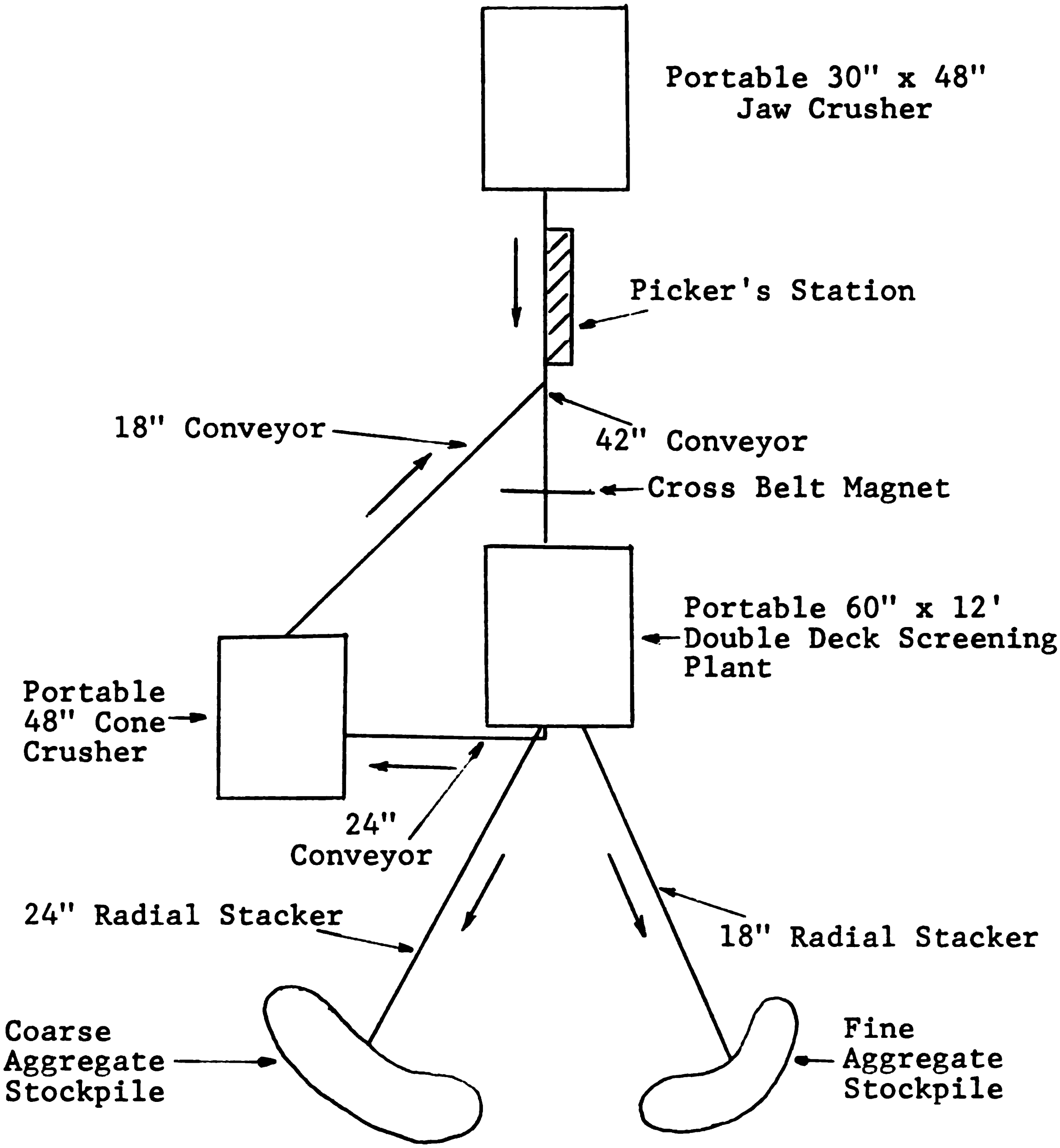

Figure 6-1. Schematic of a Portable Recycled PCC Crushing Operation.

Table 6-1. Estimated Hourly Costs for Recycled PCC Crushing Operation

Portable Equipment	Rental Cost, Hr.	Operating Cost, Hr.	Total Cost, Hr.	Required Horsepower
Primary 30" x 48" Jaw Crusher with Feeder and Discharge Belt	$63.27	$15.40	$ 78.67	200
60" x 12' Double Deck Screening Plant with 42" x 40' Conveyor	15.38	5.80	21.18	60
Secondary 48" Cone Crusher	26.30	5.45	31.75	150
Belt Conveyors:				
1 - 24" x 90' Radial Stacker	6.80	2.70	9.50	15
1 - 18" x 90' Radial Stacker	6.18	2.35	8.53	7.5
1 - 24" x 40' Scalping	3.18	1.50	4.68	10
1 - 18" x 50' Cone Return	3.53	1.50	5.03	5
Diesel Powered Generator - 450 KW	12.10	21.30	33.40	-----
1.5 - 5 yd^3. Wheel Loaders*	50.96	31.95	82.91	409.5
Subtotal			$276.65	857.0
Add:				
4% Michigan Factor			11.07	
Labor (4.5 Operators)			90.00	
TOTAL			$377.72 per hour	

*Available half-time for charging the concrete batch plant.

1. Breaking and removing the existing pavement.
2. Adding new or reworking the old base material.
3. Corrections of highway geometrics.
4. Mixing and hauling the concrete to the project.
5. The paving operation.

Using information gained from studying the gradation characteristics of crushed concrete and allowing for a 10 percent loss, the final crushed aggregate product should provide approximately 190 percent of the coarse aggregate and 61 percent of the fine aggregate required for concrete to replace an equal section. If all of the coarse aggregate is utilized in concrete, approximately 33 percent of the fines would be available from the crushed PCC. Calculations are based on research mix design.

Aggregate proportions for one cubic yard of concrete using recycled PCC or natural aggregates are provided in Table 6-2. Proportions were based on utilizing all of the available crushed PCC fine aggregate.

Cost differentials based on required aggregate proportions and current Michigan prices are shown in Table 6-3. It was assumed the salvage value of steel reinforcement would be offset by pickup or transportation charges.

6.2 Environmental Considerations

Assigning a quantitative value to the environmental impact of utilizing recycled PCC was difficult to accomplish.

Table 6-2. Aggregate Proportions Using Recycled PCC or Natural Aggregate for One Cubic Yard of Pavement Concrete - Based on Replacing an Equal Section.

Description	Gravel		Sand		Recycled PCC Coarse Aggregate		Recycled PCC Fine Aggregate	
	Volume ft^3	Weight lb	Volume ft^3	Weight lb	Volume ft^3	Weight lb	Volume ft^3	Weight lb
Conventional Concrete	12.135	2022	6.605	1072	----	----	----	----
Recycled PCC Concrete	----	----	3.311	537	9.907	1477	5.179	698

Table 6-3. Cost Comparisons for Aggregate Alternatives for a Ten Mile Dual PCC Pavement Removal and Replacement Project- Based on 1979 Michigan Prices

Description	Conventional Concrete	Recycled PCC Concrete
Hauling waste concrete from the job site	$175,016	$ 68,904
Disposal Charges	68,904	------
Aggregate Costs:		
Gravel	249,110	------
Sand	56,602	28,354
Recycled PCC (Production Cost)	------	192,931
Hauling new aggregate to the job site	193,858	50,470
Subtotal	$743,490	$340,659
Value of excess recycled PCC course aggregate over production costs	-------	46,376
TOTAL	$743,490	$294,283

This was due to the absence of overall measurement standards. One standard which could be considered was the total energy required for various aggregate alternatives.

6.2.1 Energy Requirements

Estimated fuel usage and other energy consuming factors were converted to British thermal units (BTU) to compare the energy requirements for using recycled PCC or conventional aggregates in the volume of concrete necessary to replace the pavement on the design project. Conversions were based on accepted standards (21) or calculated from values furnished by Michigan paving contractors. Concrete mix designs are identical to those discussed in Section 6.1.2. Energy comparisons for gravel and recycled PCC concrete are shown in Table 6-4.

6.2.2 Natural Resources

Needless to say, substituting recycled PCC aggregates for conventional natural aggregates does conserve a depletable natural resource. Many natural aggregate sources are already depleted and, when a new source is found, it is virtually impossible to start a new production facility due to a variety of governmental restrictions. In addition, using recycled aggregate eliminates the possible necessity of locating a suitable waste disposal site which is, also, a highly restrictive undertaking. The design project, alone, would have required the disposal of 70,400 cubic yards of broken concrete if not recycled.

Table 6-4. Energy Requirements for Aggregate Alternatives for a Ten Mile Dual PCC Pavement Removal and Replacement Project

Description	Energy, BTU X 10^6 Conventional Concrete	Recycled PCC Concrete
Hauling waste concrete from the job site.	5097	850
Disposal Operation	340	---
Aggregate Production:		
Gravel	1068	---
Sand	566	284
Recycled PCC*	---	1302
Hauling new aggregate to the job site.	6714	1165
TOTAL	13,785	3601

*Energy required for excess recycled aggregate not included.

6.3 Pavement Design

Pavement thickness design using test results from the standard research mix series for recycled PCC concrete, was based on Michigan Department of Transportation design practices. Determinations were compared to AASHO (1) requirements.

6.3.1 Concrete Properties Related to Pavement Design

Although the center-point loading used in this research for the determination of concrete flexural strengths may produce slightly higher values than the third-point loading (40) used for the AASHO Road Test, the differences were considered insignificant.

An average Young's modulus of elasticity of 4.2×10^6 psi, based on static compressive tests, was used to design the AASHO nomograph for thickness design. Inasmuch as the dynamic tests used to determine values for this research may result in a 20 percent error (44), a direct use of the nomographs was considered valid.

6.3.2 Thickness Design Criteria

The Michigan Department of Transportation uses an average working value of 200 pci for the modulus of subgrade reaction (k). This value is based on a specified minimum of 10 to 12 inches of granular subbase required over clay soils (8). Minimum pavement slab thickness is 8 inches and the maximum is 10 inches. Pavement thickness is assumed and checked against the thickness determined by using the nomographs in the AASHO Interim Guide (1).

Table 6-5 shows pavement thickness design requirements for research mixes according to the following:

1. Design period = 20 years.
2. k = 200 pci.
3. 20 year 18-kip ESAL = 10 million.
4. P_t = 2.5
5. f_t = 0.75 X MR
6. MR = 650 psi minimum.

6.3.3 Alternate Working Stress (f_t) Determination

The AASHO Interim Guide (1) suggests that an alternate method of determining the working stress of concrete may be accomplished by applying a statistical adjustment to flexural strength data. This method provides a safety factor for pavement design. Working stress is calculated by:

$$f_t = \overline{MR} - C\sigma_m \qquad (6\text{-}1)$$

where:

$\overline{MR}$ = Mean flexural strength, psi.;

σ_m = Standard deviation of flexural strength tests, psi;

C = 2.326 for a 99 percent confidence level.

This formula was used to check the working stress values used for research pavement thickness design. The results shown in Table 6-6 indicate a more than adequate factor of safety for the recycled PCC concrete.

Table 6-5. Pavement Thickness Design Based on Standard Research Mix Designs.

Batch Series	Flexural Strength, psi	Working Stress, psi	AASHO Design, in.	Michigan Design, in.
1	730	550	9.25	10.00
2	755	565	9.25	10.00
3	840	630	8.50	10.00
4	865	650	8.50	10.00
5	805	605	8.75	10.00
9*	865	650	8.50	10.00
10**	850	640	8.50	10.00

* Re-Recycled PCC Mix.
**Control Mix

Table 6-6. Alternate Determinations of Working Stress for Research Mixes.

Batch Series	Flexural Strength, psi	Standard Deviation, psi	Working Stress, psi Average ASSHO Method	Working Stress, psi Statistical Method
1	730	40	550	635
2	755	35	565	675
3	840	25	630	780
4	865	46	650	760
5	805	35	605	725
9	865	--	650	---
10	850	70	640	690

CHAPTER VII

SUMMARY AND CONCLUSIONS

Previous investigators predicted lower strengths when using recycled Portland cement concrete aggregates in a concrete mixture compared to concrete made with conventional control aggregates. However, one must be aware there will invariably be strength differentials when comparing concrete made with various conventional aggregates. In Michigan for example, concrete is normally made with natural sand for the fine aggregate, and either natural gravel, limestone, or blast furnace slag for the coarse aggregate. Although these aggregates are used on an equal design basis, the resulting concrete properties cover a range of values. The primary criterion for acceptability is that concrete, made with an aggregate from a particular source, must meet minimum standards. Experimental results for this research indicated that aggregates produced by crushing Michigan PCC pavements were equal in quality to conventional aggregates.

7.1 Discussion of Experimental Results

All research concrete mixtures, proportioned with recycled PCC coarse aggregate and various ratios of natural sand and recycled PCC fines, exceeded minimum design standards. Within a certain range, combinations of recycled fines and natural sand produced concrete with higher strengths than for concrete made with control aggregates. As with the results reported by others, recycled PCC concrete made, exclusively, with either conventional or recycled fine aggregate produced lower strengths than control aggregate concrete. Nevertheless, strengths were appreciably higher than minimum Michigan requirements (35).

Initial experimental data resulting from incorporating various proportions of crushed bituminous concrete in the recycled concrete mixtures indicated no serious detrimental effects when this material was used as a percentage of the coarse aggregate. Significantly lower strengths were experienced with the addition of crushed bituminous fines. These fines are almost totally coated with bitumen and may, therefore, have to be considered as voids in a concrete mixture when designing for strength.

Inasmuch as the properties of bituminous materials are susceptible to various temperature ranges (14), and since the experiments in this research were conducted under prescribed laboratory temperature conditions, a valid analysis of the total effects of incorporating this material in a Portland cement concrete mixture is not within the scope of this investigation.

In all experiments, regardless of the proportions of aggregates used, concrete made with the recycled PCC research aggregates exhibited durability properties superior to those of concrete made with normal conventional aggregates.

7.2 Conclusions

The Michigan Department of Transportation has used qualitative methods of designing and proportioning Portland cement concrete since 1928 (31). Therefore, one can assume there are high quality materials in a major portion of the State's existing PCC highway pavements. Usual reasons for pavement removal are due to mechanical failures resulting from subgrade, drainage, or joint problems. However, the methods formulated in this research, for experiments with pavement cores, provide a systematic means of predetermining the properties and mix design requirements of aggregates resulting from recycling any existing PCC material source. There is a high degree of assurance that the result of using these methods will equate to actual field crushing and design requirements.

One of the most interesting aspects of this research was the experiments involving the recycling of recycled PCC concrete. Test results for both aggregate and concrete properties furnished information this re-recycled aggregate was high in quality and durability. Therefore, one may project that existing PCC pavements, in addition to providing an aggregate source for the future, will continue to generate an adequate supply of aggregates for pavement replacement after once being recycled.

Another point of interest is that recycling an existing pavement produces about 150 percent of the total aggregate volume needed for the concrete required to replace the section removed. Therefore, additional high quality aggregates will be available for such construction purposes as concrete shoulders, concrete barriers, necessary concrete pavement widening, subbase aggregate, and a variety of other uses.

Although the concrete mix designs used for experiments in this research are related to utilizing recycled PCC aggregates for pavements, there is strong evidence this material would provide an excellent aggregate for concrete used in bridges, buildings, and other structures. Before utilizing recycled PCC aggregates for structural purposes other than pavements, additional research would be necessary to evaluate aggregate and concrete properties related to the intended use.

The resulting determination of this research is that utilizing recycled PCC aggregates for Portland cement concrete offers a viable alternative to conventional aggregates on an equal design basis. This is especially true for recycling an existing PCC pavement where significant cost savings and energy conservation can be realized.

Additional experimental investigations, covering the range of variables associated with incorporating re-recycled PCC or proportions of bituminous concrete in concrete mixtures, would be necessary to determine the validity of initial research results using these materials.

LIST OF REFERENCES

LIST OF REFERENCES

1. AASHO Interim Guide for Design of Pavement Structures, American Association of State Highway Officials, Washington, D.C., 1972.

2. Bauer, E.E., Plain Concrete, McGraw-Hill, New York 1949.

3. Bergren, J.V. and Britson, R.A., Portland Cement Concrete Utilizing Recycled Pavement, FHWA - DP-47-1, U.S. Department of Transportation, Arlington, Virginia, September, 1978.

4. Buck, A.D., "Recycled Concrete", Highway Research Record No. 430, Highway Research Board, 1973, pp. 1-8.

5. "Concrete and Mineral Aggregates", 1978 Annual Book of ASTM Standards, Part 14.

6. "Crushing Converts Rubble Into Subbase Aggregate", Roads and Streets, May, 1971, pp. 44 and 45.

7. Design and Control of Concrete Mixtures, Portland Cement Association, Skokie, Illinois, 1979.

8. Field Manual Of Soil Engineering, Fifth Edition, Michigan Department of State Highways, Lansing, Michigan, 1970.

9. Fordyce, P. and Teske, W.E., "Some Relationships of the AASHO Road Test to Concrete Pavement Design", Highway Research Record No. 44, Highway Research Board, 1963, pp. 35-70.

10. Fordyce, P. and Yrjanson, W.A., "Modern Design of Concrete Pavements", Transportation Engineering Journal of ASCE Vol. 95, No. TE3, August, 1969, pp. 407-438.

11. Frondistou-Yannas, S. and Itoh, T., "Economic Feasibility of Concrete Recycling", Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, Vol. 103, No. ST4, April, 1977, pp. 885-899.

12. Frondistou-Yannas, S., "Waste Concrete as Aggregate for New Concrete", ACI Journal, August, 1977. pp. 373-376.

13. Gluzhge, P.J., "The Work of Scientific Research Institutes", (From Gidrotekhnicheskoe Stroitelstvo, No. 4, April, 1946, pp. 27 and 28), The Engineer's Digest, Vol. 7, No. 10, 1946, p. 330.

14. Hong, H., "State of the Art" Theory and Application of Sonic Testing to Bituminous Mixtures", HRB Special Report No. 94, Highway Research Board, 1968.

15. Hudson, R.G., The Engineers' Manual, Second Edition, Wiley & Sons, New York, 1961.

16. Hudson, W.R., "Comparison of Concrete Pavement Load-Stresses at AASHO Road Test with Previous Work", Highway Research Record No. 42, Highway Research Board, 1963, pp. 57-98.

17. "Landfill Avoids Concrete Waste by Aiding Recycling Operation", Rural and Urban Roads, March, 1978, pp. 40 and 41.

18. Lokken, E.C., "Recycling Portland Cement Concrete", Paper for Presentation to the UWEX-ENR Technical Institute on Recycling Pavements, New York, October 25, 1978.

19. "Old Pavement Recycled Into New Subbase", Concrete Construction, October, 1975, pp. 441 and 442.

20. Procedures for Determining Salt Content (NaCl) in Portland Cement Concrete, Michigan Department of Transportation, circa 1976.

21. Ray, G.K. and Halm, H.J., "Energy Savings Through Concrete Recycling", Paper for Presentation to the Transportation Research Board, Washington, D. C., January 17, 1978.

22. Ray, G.K. and Geesaman, J.D., "AASHO Road Test And Its Affect On Future Design Standards", Paper for Presentation to the ARBA 10th Annual National Highway Conference, Springfield, Illinois, October 1, 1962.

23. Ray, G.K., "Recycle Old Concrete? It Can Save You Money", Highway and Heavy Construction, January, 1978, pp. 30 and 31.

24. "Recommended Practice for Selecting Proportions for Normal and Heavyweight Concrete", ACI Standard 211.1-77, American Concrete Institute, Detroit, Michigan, 1977.

25. "Recycled Slab is New Runway Base", Highway and Heavy Construction, July 1977, pp. 30-33.

26. "Recycling 640 Tons of Crushed Concrete a Day" Michigan Contractor and Builder, February 4, 1978, pp. 10 and 11.

27. "Recycling Roads and Buildings with Portable Plants", Pit and Quarry, February, 1973, pp. 31, 92 and 106.

28. "Recycled Rubble Saves Contractors Money", Roads and Streets, April, 1973, pp. 80 and 83.

29. Rental Rate Blue Book for Construction Equipment, Equipment Guide-Book Company, Palo Alto, California, updated 1979.

30. Sadler, T.B., "A Crushing Success: Aggregate from Concrete", Public Works, April, 1973, pp. 72 and 73.

31. Shehan, E.L., The Mortar Voids Method of Proportioning Concrete as Used by the Michigan Department of State Highways, Michigan Department of State Highways, September, 1970.

32. Standard Specifications for Road and Bridge Construction, Michigan State Highway Department, Lansing, Michigan, 1942.

33. Standard Specifications for Road and Bridge Construction, Michigan State Highway Department, Lansing, Michigan, 1950.

34. Standard Specifications for Road and Bridge Construction, Michigan State Highway Department, Lansing, Michigan, 1957.

35. Standard Specifications for Construction, Michigan Department of Transportation, Lansing, Michigan, 1979.

36. Talbot, A.N. and Richart, F.E., "The Strength of Concrete Its Relation to the Cement and Water", University of Illinois Engineering Experiment Station, Bulletin No. 136, October, 1923.

37. Thickness Design for Concrete Pavements, Portland Cement Association, Skokie, Illinois, 1966.

38. Urquhart, L.C., et al., Civil Engineering Handbook, Fourth Edition, McGraw-Hill, New York, 1959.

39. Vantil, C.J., et al., "Evaluation of AASHO Interim Guides for Design of Pavement Structures", National Cooperative Highway Research Program Report No. 128, Highway Research Board, 1972.

40. Various, Significance of Tests and Properties of Concrete and Concrete-Making Materials, STP 169B, ASTM, Philadelphia, Pennsylvania, 1978.

41. Vesic, A.S. and Saxena, S.K., "Analysis of Road Test Rigid Pavements", Highway Research Record No. 291, Highway Research Board, 1969.

42. Waddell, J.J., et al., Concrete Construction Handbook, McGraw-Hill, New York, 1968.

43. Westergaard, H.M., "Stresses in Concrete Pavements Computed by Theoretical Analysis", Public Roads, Vol. 7, No. 21, April, 1926, pp. 25-35.

44. Whitehurst, E.A., Evaluation of Concrete Properties from Sonic Tests, American Concrete Institute, Detroit, Michigan, 1967.

45. Woods, K.B., et al., Highway Engineering Handbook, McGraw-Hill, New York, 1960

46. Yoder, E.J. and Witczak, M.W., Principles of Pavement Design, Second Edition, Wiley and Sons, New York, 1975.

APPENDICES

APPENDIX A

VALUES USED FOR ECONOMIC AND ENERGY COMPARISONS

<u>Values Used for Cost Comparisons in Table 6-3</u>:

Volume of concrete to be removed and replaced:

$24 \times 0.75 \times 5280 \times 20/27 = 70{,}400\ yd^3$.

Estimated tonnage of existing concrete at 145 lb/ft^3:

$27 \times 145 \times 70{,}400/2000 = 137{,}808$ tons

<u>Conventional Concrete</u>

Hauling broken concrete from project to dump site:

15 mi @ $1.27/ton.

Hauling gravel and sand to project:

25 mi @ $1.78/ton

Disposal charges:

$0.50/ton

Aggregate costs:

Gravel	$3.50/ton
Sand	$1.50/ton

Aggregate required:

Gravel	2022 X 70,400/2000 = 71,174 tons
Sand	1072 X 70,400/2000 = 37,734 tons

<u>Recycled PCC Concrete</u>

Hauling broken concrete from project to job-site crusher:

2.5 mi @ $0.50/ton

Hauling sand to project:

25 mi @ $1.78/ton

continued next page

Values Used for Cost Comparisons in Table 6-3 continued:

Aggregate costs:

Recycled PCC	\$2.52/ton (production cost)
Sand	\$1.50/ton

Aggregate required:

Recycled F.A.	698 X 70,400/2000	= 24,570 tons
Recycled C.A.	1477 X 70,400/2000	= 51,990 tons
Sand	537 X 70,400/2000	= 18,902 tons

Total recycled coarse aggregate from crusher:

137,808 X .9 X .8 = 99,222 tons

Excess recycled PCC coarse aggregate:

99,222 - 51,990 = 47,232 tons

Note: Hauling and new aggregate costs are based on 1979 prices for Michigan.

<u>Values Used for Energy Comparisons in Table 6-4</u>:

Diesel Fuel: = 184,920 BTU/gal.

Hauling aggregates and broken concrete at 5 mi/gal and 30 tons/load:

184,920/5 X 30 = 1,233 BTU/mi/ton

Disposal operations at 2 gal/hr and 150 ton/hr:

184,920 X 2/150 = 2,467 BTU/ton

Natural Aggregate Production: = 15,000 BTU/ton (FHWA)

Recycled PCC Production:

Generator at 8.8 gal/hr and 150 ton/hr:

184,920 X 8.8/150 = 10,849 BTU/ton

Wheel Loaders at 5.0 gal/hr and 150 ton/hr:

184,920 X 5.0/150 = 6,164 BTU/ton

APPENDIX B

SAMPLE CALCULATIONS

Sample Calculations for Concrete Mix Design - Batch Series 2:

Volume: 1 yd^3; b/b_o: 0.72; γ_b: 76 lb/ft^3;

W/C: 0.43; Cement Factor: 6 sacks Air Content: 5.5%;

Cement: Peerless I-A, G_c - 3.14; PCC C.A.: A, G_b - 2.31, A_b - 5.00%;

F.A.: 75% Recycled Aggregate A, G_a - 2.16, A_a - 8.31%, 25% 2NS, G_a - 2.60, A_a - 1.38%.

Material	Weight, lb.		Volume, ft^3.	
C.A.	0.72 X 27 X 76	= 1477.44	1477.44/2.31 X 62.4	= 10.250
Cement	6 X 94	= 564.00	564/3.12 X 62.4	= 2.897
Water	0.43 X 564	= 242.52	242.52/62.4	= 3.887
Air		-------	0.055 X 27	= 1.485
				18.519
F.A. Required:			27 - 18.519	8.481
Agg. A	.75 X 8.481 X 2.16 X 62.4 =	857.33		
Agg. 2NS	.25 X 8.481 X 2.60 X 62.4 =	343.99		

continued next page

Sample Calculations for Concrete Mix Design - Batch Series 2 Continued:

Additional water required for absorption:

C.A.	147.44 X 0.05	=	73.87 lb.
F.A.:			
Agg. A	857.33 X 0.0831	=	71.24 lb.
			lb.
Agg. 2NS	343.99 X 0.0138	=	4.75 lb.
			149.86 lb.
Total Water	149.86 + 242.52	=	392.38 lb.

Calculations of Constants for Dynamic E and μ - 3" X 4" X 15-1/2" Beams:

$E = CWn^2$

$C = 0.00245\ L^3T/bt^3$

Radius of Gyration (K) = t/3.464 = 3/3.464

From Table I - ASTM C 215 for K/L = .866/15.5, T = 1.28.

$C = .00245 \times (15.5)^3 \times 1.28/4 \times (3)^3 = 0.108$

$E = 0.108\ Wn^2$

$G = BWn''^2$

$B = 4LR/gA$

$R = .75 + 1.3\overline{3}/(4 \times .75) - 2.52\ (.75)^2 + .21\ (.75)^6 = 1.286$

$B = 4 \times 15.5 \times 1.286/386.4 \times 12 = 0.017195$

$G = 0.017195\ W(n'')^2$

$\mu = E/2G - 1$

Example: Beam 4-A

n = 1670

n" = 2730

W = 15.323 lb.

$E = 0.108(15.323)(1790)^2 = 5.30 \times 10^6$ psi

$G = 0.017195(15.323)(2890)^2 = 2.20 \times 10^6$ psi.

$\mu = 5.30 \times 10^6/2(2.20)(10)^6 - 1 = 0.20$

Calculations to Determine the Amount of Course and Fine Aggregates Produced in a PCC Recycling Operation:

Assumptions: 10% Crushing Loss, 20% Passing #4,

F.A. - G_a = 2.18, C.A. - G_b = 2.35,

Concrete Wgt. = 145 lb/ft^3.

Wgt/ft^3 of Agg. Produced = 145 - .1(145) = 130.5 lb.

Wgt/ft^3 of C.A. Produced = 0.8 X 130.5 = 104.5 lb.

Wgt/ft^3 of C.A. Required (New Concrete) ≅ 55 lb.

% C.A. Required = 104.5 X 100/55 = 190%.

Wgt/ft^3 of F.A. Produced = .2 X 130.5 = 26.1 lb.

Vol/ft^3 of F.A. Produced = 26.1/2.18 X 62.4 ≅ 0.192 ft^3.

Vol. F.A. Required = 8.5/27 = 0.315 ft^3.*

% of F.A. Required = 0.192 X 100/0.315 = 61%.*

*To replace an equal section.

Sample Worksheet for PCC Coarse Aggregate Gradation and Other Properties

MICHIGAN DEPARTMENT OF STATE HIGHWAYS AND TRANSPORTATION

1901 (1/78)

MECHANICAL ANALYSIS REPORT

Material PCC Agg A Sampled From I-96

Spec. [illegible] Producer

Job No. Sample #1

Control Section Identity J.F.

Sieve	Retained Fractional Weight	Retained Fractional Percent	Percents Cumulative Retained	Percents Cumulative Passing
2½"				
2"				
1½"	0	0	0	[illegible]
1¼"				
1"	34	[illegible]	[illegible]	[illegible]
¾"	[illegible]	[illegible]	[illegible]	[illegible]
5/8"				
½"	[illegible]	[illegible]	59.02	41
3/8" [illegible]	[illegible]	16.70	75.72	24
No 4 2904	705	24.28		
No. 8		100.00		
No. 10				
~~No 16~~ Pass #4	654	⇒ 18.[illegible]	Fines	
No 30				
No 40				
No. 50				
No. 100				
Pan				
LBW				
Total				

Test No. | Date [illegible]-31-79 | Time | AM PM

Initial Weight of Sample .... Gm.

Weight after Washing .... Gm.

Loss by Washing (Clay and Silt)......... Gm. [illegible] %

Fineness Modulus ....

Crushed Material .... Gm. .... %

Organic Plate No. ....

Thin or Elongated Pieces .... Gm. .... %

Incrusted, more than 1/3 Area .... Gm. .... %

Incrusted, Total .... Gm. .... %

(1) Soft Particles .... 17 .... Gm. [illegible] %

(2) Chert .... 9 .... Gm. [illegible] %

Sum of (1) + (2) .... Gm. [illegible] %

Material Meets or Fails ....

Remarks: ....

Unbraced [illegible] gr. ⇒ 11.7%

(Signed) ....

Plant Inspector

Sample Worksheet for PCC Fine Aggregate Gradation and Other Properties

MICHIGAN DEPARTMENT OF STATE HIGHWAYS AND TRANSPORTATION

1901 (1/78)

MECHANICAL ANALYSIS REPORT

Material PCC Agg A Sampled From 276

Spec. F.A. Producer

Job No. Sample #3

Control Section Identity

Sieve	Retained Fractional		Percents Cumulative	
	Weight	Percent	Retained	Passing
2½"				
2"				
1½"				
1¼"				
1"				
¾"				
5/8"				
½"				
3/8"	0	0	0	100
No. 4	5	0.99	0.99	99
No. 8	181	37.43	38.42	62
No. 10				
No. 16	111	21.98	60.40	40
No. 30	60	11.88	72.28	28
No. 40				
No. 50	47	9.31	81.59	18
No. 100	35	6.93	88.52	12
Pan	24	4.75		
LBW	34	6.73		
Total	505	100.00	342.2	

Test No.	Date	Time AM PM
	[illegible]	

Initial Weight of Sample 505 Gm.

Weight after Washing 471 Gm.

Loss by Washing (Clay and Silt) 34 Gm. 6.7 %

Fineness Modulus 3.42

Crushed Material .... Gm. .... %

Organic Plate No. -1

Thin or Elongated Pieces .... Gm. .... %

Incrusted, more than 1/3 Area .... Gm. .... %

Incrusted, Total .... Gm. .... %

(1) Soft Particles .... Gm. .... %

(2) Chert .... Gm. .... %

Sum of (1) + (2) .... Gm. .... %

Material Meets or Fails ....

Remarks: ....

(Signed) ....

Plant Inspector

Sample Worksheet for Unit Weight of PCC Coarse Aggregate

MICHIGAN DEPARTMENT OF STATE HIGHWAYS AND TRANSPORTATION

1914 (6/74)

COMPUTATION SHEET FOR CONCRETE PROPORTIONING

~~Control Section~~	Job No.
Recycled PCC - Agg. A	
F. A. No.	
Test No. 1	Date 2-26-79

UNIT WEIGHT DETERMINATION—COARSE AGGREGATE
(REFERENCE: CONSTRUCTION MANUAL)

(a) Volume factor of measure 0.503 cu. ft.

(b) Gross wt. of sample and measure 56.25 lb.

(c) Wt. of ½ cu. ft. measure 16.75 lb.

(d) Net wt. of sample (b) − (c) 39.50 lb.

(e) Wt. of 6A or 6AA moisture sample 3027 g.

(f) Wt. of bone dried sample 2936 g.

(g) Wt. of moisture (e) − (f) 91 g.

(h) Moisture content $\frac{(g)}{(f)}$ 0.031

(i) Wt. per cu. ft. of loose, bone dry, C. A. $\frac{(d) - (h \times d)}{(a)}$ 76 lb.

Sample Worksheet for Soundness of PCC Coarse Aggregate

1802A (3/78)

AGGREGATE SOUNDNESS TEST
WORK SHEET

MATERIAL: PCC Cores - Agg. C	SPECIFICATION: C.A.	LAB. NO.: JF #7
PRODUCER: BL - I-94	PIT NO.	CSI/JOB NO.
DATE REC'D.	DATE REPORTED: 5-21-79	

SIEVE SIZE			GRADATION OF ORIGINAL SAMPLE, FRACTION RETAINED		WEIGHT OF TEST FRACTIONS, GRAMS		Percentage Passing Designated Sieve After Test	Weighted Percentage Loss
Passing	Retained Before	Retained After	Grams	Per Cent	Before Test	After Test		
2 1/2 in.	1 1/2 in.	1 1/4 in.						
1 1/2 in.	3/4 in.	5/8 in.		24	1506	1473	2.19	0.53
3/4 in.	3/8 in.	5/16 in.		51	1000	990	1.00	0.51
3/8 in.	No. 4	No. 5		25	300	289	3.67	0.92
No. 4	No. 8							
No. 8	No. 16							
No. 16	No. 30							
No. 30	No. 50							
No. 50	No. 100							
No. 100								
Totals								1.96

PARTICLE SIZE	NUMBER OF PARTICLES				
	Before Test	Disintegrated	Split	Cracked	Flaked
2 1/2-1 1/2 in.					
1 1/2-3/4 in.	96	1	1		

FIVE ALTERNATIONS OF MAGNESIUM SULFATE

Tested by ______ Computed by ______ Checked by ______

REMARKS:

Sample Worksheet for Soundness of PCC Fine Aggregate

1802A (3/79)

AGGREGATE SOUNDNESS TEST
WORK SHEET

MATERIAL: Pcc Cores - Agg. D
SPECIFICATION: F.A.
LAB. NO.: J.F #9
PRODUCER
PIT NO.
CSI/JOB NO.
DATE REC'D.
DATE REPORTED: 5-27-79

SIEVE SIZE			GRADATION OF ORIGINAL SAMPLE, FRACTION RETAINED		WEIGHT OF TEST FRACTIONS, GRAMS		Percentage Passing Designated Sieve After Test	Weighted Percentage Loss
Passing	Retained Before	Retained After	Grams	Per Cent	Before Test	After Test		
2 1/2 in.	1 1/2 in.	1 1/4 in.						
1 1/2 in.	3/4 in.	5/8 in.						
3/4 in.	3/8 in.	5/16 in.						
3/8 in.	No. 4	No. 5						
No. 4	No. 8			38	100	90.9	9.10	3.46
No. 8	No. 16			22	100	90.5	9.50	2.09
No. 16	No. 30			12	100	96.1	3.90	0.47
No. 30	No. 50			9	100	89.6	10.40	0.94
No. 50	No. 100			7				
No. 100				12				
Totals				100	400			6.96

PARTICLE SIZE	NUMBER OF PARTICLES				
	Before Test	Disintegrated	Split	Cracked	Flaked
2 1/2-1 1/2 in.					
1 1/2-3/4 in.					

FIVE ALTERNATIONS OF MAGNESIUM SULFATE

Tested by ______ Computed by ______ Checked by ______

REMARKS:

Sample Worksheet for Specific Gravity and Absorption of PCC Aggregates

STATE OF MICHIGAN
DEPARTMENT OF STATE HIGHWAYS
TESTING AND RESEARCH DIVISION
TESTING LABORATORY SECTION

(Work Sheet)

COARSE AND FINE AGGREGATES
(SPECIFIC GRAVITY)

Form 1804 B (Rev. 3/

TYPE PCC Beams SPEC. Agg D

PRODUCER 350 F-T cycles

Lab. No. JF14

DATE RECEIVED

DATE REPORTED 6-21-79

C.S. ID. – Job No.

COARSE AGGREGATE

	Test 1	Test 2
SSD Wt. in Air	2447.5	2420.0
SSD Wt. in H_2O	1373.0	1366.5
Oven Dry Wt.	2256.0	2236.0
Sp. Gr.	2256.0 / 1074.5 = 2.0996	2236.0 / 1053.5 = 2.1224
Abs., %	191.5 / 2256.0 × 100 = 8.488	184.0 / 2236.0 × 100 = 8.229

Bulk Specific Gravity (dry basis) 2.11

Absorption, % 8.36

FINE AGGREGATE

	Test 1	Test 2
Sample Wt., gm.	50.0	50.0
Final Reading	23.1	23.2
Initial Reading	0.7	0.8
Volume, ml.	22.4	22.4
Sp. Gr.	2.232	2.232
SSD Wt.	500.0	500.0
Oven Dry Wt.	447.2	447.3
Abs., gm.	52.8	52.7
Abs., %	52.8 / 447.2 × 100 = 11.807	52.7 / 447.3 × 100 = 11.782

Bulk Specific Gravity (dry basis) 2.00

Absorption, % 11.79

TESTED BY: COMPUTED BY: CHECKED BY:

REMARKS: Pit No.

Sample Worksheet for Concrete Mix

CONCRETE MIX WORK SHEET — J. S. Fergus

Batch No.: 4-A — Date Made 4-11-73

Materials		Moisture Content	Sp. Gr.	Abs. %
Cement	Peerless - IA		3.12	
Fine Agg. #1	PCC-A	0.112	3.16	9.31
Fine Agg. #2	Morgan - 2NS	0.004	2.60	1.38
Course Agg. #1	PCC-A	0.022	2.31	5.00
Course Agg. #2				

Mix Quantities, lb.

Material	Dry Weight	Moisture	Corrected Weight	Saturated Weight	Excess Water over Dry Weight
Cement	29.24				
F.A. #1	14.83	1.66	16.49	71.50 (F.A. #1 + #2)	
F.A. #2	53.57	0.21	53.78		3.10
C.A. #1	76.61	1.69	78.30	82.06	5.45
C.A. #2					
Water	18.35				
	192.60				

Vinsol Resin 20 cc.

Slump 1 1/2 in.

Air Content 4.8 %

Conc. Temp. 72 °F.

Unit Weight

Tare + Conc. 115.81

Tare 46.70

Wgt. of Conc. 69.11

Vol. 0.50 ft.³

Unit Wgt. 138.22 lb/ft³

Yield -0.5 %

Corrected Yield +0.2 %

Mix Water

Dry Weight 18.35

Minus Excess 8.55

Net 9.80

Tare 1.22

Total 11.02

Remarks:

Very workable mix.

Sample Worksheet for Flexural Strength Tests

FLEXURAL STRENGTH OF
3" X 4" X 16" Concrete Beams

J. S. Fergus

A.S.T.M. #C 293-68 (1974)

Date of Mix 3-28-79 Date of 7 Day Test 4-4-79 Date of 28 Day Test 4-25-79

Batch Number	Age (days)	Width (in.)	Depth (in.)	Span (in.)	Factor	Load (lb)	Strength (psi)	Average (psi)
3-A	7	3.05	4.05	14.5	.4347	1800	783	805
		3.00	4.05	14.5	.4420	1880	831	
	28	3.00	4.00	14.5	.4531	1940	879	865
		3.00	4.05	14.5	.4420	1920	849	
3-B	7	3.00	4.00	14.5	.4531	1770	802	775
		3.00	4.05	14.5	.4420	1690	747	
	28	3.00	4.05	14.5	.4420	1840	813	820
		3.00	4.05	14.5	.4420	1860	822	
3-C	7	3.00	3.95	14.5	.4647	1770	823	770
		2.95	4.00	14.5	.4608	1560	719	
	28	3.00	4.05	14.5	.4420	1840	813	840
		3.05	4.05	14.5	.4348	1990	865	

Sample Worksheet for Compressive Strength Tests

COMPRESSIVE STRENGTH

Of 4" X 8" Concrete Cylinders

A.S.T.M. *C 39-72

J. S. Fergus

Date of Mix 4-11-79 Date of 7 Day Test 4-18-79 Date of 28 Day Test 5-9-79

Batch Number	Age (days)	Diameter (in.)	Area (sq.in.)	Load (lb.)	Strength (psi)	Average (psi)
4-A	7	3.99	12.50	63,500	5080	4900
		3.99	12.50	65,100	5208	
		4.00	12.57	55,500	4415	
	28	3.98	12.44	70,500	5667	5910
		3.99	12.50	73,900	5912	
		3.98	12.44	76,700	6166	
4-B	7	4.00	12.57	64,800	5155	4570
		3.99	12.50	52,400	4192	
		3.99	12.50	54,700	4376	
	28	3.98	12.44	73,600	5916	5830
		3.98	12.44	66,900	5378	
		3.99	12.50	77,300	6184	
4-C	7	3.97	12.38	50,400	4071	4330
		3.98	12.44	56,700	4558	
		3.99	12.50	54,600	4368	
	28	3.98	12.44	67,100	5394	5580
		3.98	12.44	69,600	5595	
		3.98	12.44	71,600	5755	

REMARKS:

Sample Worksheet for Dynamic Moduli

3" x 4" x 16" BEAMS - FREEZE-THAW DURABILITY

IDENTIFICATION Recycled Concrete

LAB NO. JF 3-A

SPACE NO. IN FREEZE-THAW CHAMBER: 4

BATCH MADE: 3-28-79 AT 14 DAYS: START OF FREEZE-THAW 4-11-79

CYCLE COUNTER READING	DATE	DAYS OF FREEZE-THAW	CYCLES OF FREEZE-THAW	WEIGHT GRAMS	3" N	3" RELATIVE E %	4" N	4" RELATIVE E %	RELATIVE E AVG. %	SPACE No.	REMARKS	
644	4-11	0	0	6985	1730	100.0	2230	100.0	100	5		1
649	12	1	5		1720	98.8	2150	93.0	96	45		2
682	16	5	38		1730	100.0	2200	97.3	99	39		3
715	20	9	71		1720	98.8	2220	99.1	99	57		4
776	30	16	132		1740	101.2	2210	98.2	100	38		5
849	5-9	25	205		1730	100.0	2230	100.0	100	25		6
905	16	32	261		1740	101.2	2210	98.2	100	52		7
959	23	39	315	6945	1740	101.2	2190	96.4	99	56		8
												9
												10
												11
												12
												13
												14
												15

Interpolated on curve at 99 %: 300 cycles

Relative E = $100 \times \frac{N^2}{N_o^2}$ 2992900 & 4972900

Durability factor $\frac{PN}{M} = \frac{99 \times 300}{300} = 99$

Key: M = Morning
N = Noon
A = Afternoon

Computed by: ____________

Checked by: ____________