

Performance of Concrete Pavement Mixtures with Marginal Aggregates: Laboratory Investigation

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Abstract

Pavement engineers strive to design and construct portland cement concrete (PCC) airfields that are high quality and economical to maintain during their intended lifecycle. When designing concrete mixtures, locally available materials are desired to minimize transportation or processing expenses. Aggregate costs are of significant concern, because aggregate comprises 70% of the mixture volume. To reduce cost, local aggregates of marginal quality may be used in production; however, the use of these materials may reduce concrete quality and pavement performance.

A laboratory investigation of 16 different aggregate materials was conducted, where each aggregate's physical properties were in some way outside of the U.S. military's specifications. Recycled materials were also included in the analysis because these materials are generally perceived as inferior. Forty-three mixture designs were created, where one mixture component or material property varied from a specified control mixture. Different proportions of each material were considered to test the effect of deviating from current specifications. Compression and flexural strength test specimens were cast for testing at 28 and 90 days, utilizing 850 total specimens. Statistical analyses were used to evaluate the effect of marginal quality aggregates on concrete strength.

Introduction

PCC is an essential construction material for airfield construction. Its usage is required, rather than asphalt concrete, for U.S. military airfield pavement features where aircraft park regularly for long periods of time, at intersections where aircraft induce higher shear loads [braking, turning, or tire pressures over 2.1 MPa (300 psi)], on specific specialized aprons, in areas prone to jet blast greater than 150°C (300°F), and in areas with a high potential for spillage of fuel, oils, or other solvents.

When designing a concrete mixture, use of locally available materials is desirable to minimize transportation or processing related expenses associated with aggregates, since they make up about 70 % of the total mixture volume. However, using locally available materials in contingency environments, or areas with poor access to construction aggregates, typically means using materials regarded as inferior for PCC, and results in reductions in overall concrete quality and performance. Currently, the Unified Facilities Criteria guidance for concrete paving construction, road and airfield design are supported by the Department of Defense (DOD) for material and construction protocol for PCC road and airfield pavements. Concrete aggregate properties, both fine and coarse, are bound by a modified version of the requirements set forth by ASTM C33. Compliance with these specifications may produce concrete mixture designs that are either costly due to the high transportation cost involved in obtaining the specified aggregate or be overly conservative for the desired performance level (UFC 2004b, UFC 2004a, UFC 2001).

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Since aggregates contribute significant volume to the concrete as a whole, they affect the resulting concrete's properties. Maximizing the aggregate content of the mixture is preferred when designing a PCC mixture, because the aggregates are economic volume fillers, are more dimensionally stable under environmental loads, and perform better in wearing applications when compared to portland cement. The effect of the aggregates used for PCC production are typically overlooked for normal weight concrete mixture since the strength of aggregates used is typically stronger than the cement paste and the bond between the cement paste and aggregate (Mehta 2006, Mindess 2003, Taylor 2007).

Objective and Research Significance

The objective of this paper is to explore the use of aggregates that do not have optimum engineering properties and determine which properties are most significant to performance. Since strength is used as the major design factor for DOD projects, understanding the effect of aggregate properties on strength is critical. Materials recycled from previous construction were also considered for this study, because they are perceived not to have optimum engineering properties compared to virgin materials. The overall objective of this project is to update UFC concrete pavement construction guidance to include the use of a wider range of marginal materials in PCC pavements, particularly in contingency environments where local aggregate supplies may not be suitable for use based on current guidance and specifications.

This study's research purpose is twofold. First, the paper explores the potential use of marginal materials that may be encountered when these construction materials are more readily available or require less processing compared to conventional materials. Hauling large pieces of equipment or quantities of acceptable materials into remote locations may be uneconomical or logistically impossible within the scope of the required paving project, leaving local materials as the only option. Without the proper engineering knowledge of how marginal quality construction materials perform, any design utilizing these materials will either be prone to failure from under-design, will fail to efficiently use the materials to their true capacity, or will lead to unrealistic performance expectations. Second, this project investigates the incorporation of recycled construction materials into PCC pavement. Executive Order 13423 states the federal government's commitment to energy efficiency and sustainable development, including reducing the environmental impact of waste construction materials or demolition debris (White House 2007). During a project's planning stage, local recycling and salvage operations that contain site related waste are to be identified, and the design should include at least 50% recycled or salvaged construction, demolition and/or land clearing waste where markets or onsite recycling opportunities exist, with the exception of soil. UFC pavement recycling guidance states that recycled materials have proven to be an option to rehabilitate failed pavements, even though it is not always the most efficient option (UFC 2004c). The disposal of materials with potentially beneficial engineering properties, compared to limited new materials, should be explored at a minimum to conform to the given sustainability mandate and to research any performance trends that would lead to continued use or would support discontinued use.

Testing and Analysis Procedure

To test the effect of aggregate physical properties on PCC strength performance, the compressive and flexural strengths of the mixtures batched were statistically tested to investigate the responses of the different mixtures. Statistical approaches were used to

evaluate the effect of aggregate design features on material strength over time. Visual analyses of the data were completed by plotting box plots and normal quantile plots. Controlled hypothesis testing of the dataset means of individual groupings (bivariate analysis) and analysis of variance (ANOVA) testing of regression equations covering all characteristics were conducted to determine the significance of particular aggregate properties on measured concrete strength parameters.

Laboratory Testing Setup. This project evaluated PCC mixture strength performance as it relates to different aggregate properties, current UFC guidance, and Unified Facilities Guide Specifications (UFGS) used by the DOD. Various aggregate materials, with differing physical properties, were located or prepared for laboratory testing. Batches of PCC made with varying proportions of marginal aggregates were produced and cast into standard laboratory strength testing specimens. The hardened strengths at 28 and 90 days were measured, and changes in strength between the mixtures were analyzed for each mixture produced.

Aggregate Production. The main stock aggregates used for the concrete produced were a crushed limestone and a locally available natural sand. The #357 gradation for the stock limestone was achieved by blending as-delivered stock #57 and #4 material with a custom screened material of similar rock that ranged in size from 50 to 25 mm (2 to 1 in.). The natural sand was not processed before use; however, it was known to be outside of ASTM C33 specifications.

The additional aggregates were either used as-delivered or they were processed by a combination of crushing, sieving and/or hand sorting. All processed custom aggregate blends were sieved using a series of rectangular screens with sieve sized openings typically used in PCC aggregate quality control operations. The screened fraction of material retained on each sieve was stored in individual steel drums. All crushing was accomplished with a single steel drum vibratory soil compactor, simulating a single roller crusher, and all material was screened as previously described. Unused larger crushed material was recrushed and screened until enough of each size was made. Only the flat and elongated particle material, ranging from material retained on the 50 to 19 mm (2 to 0.75 in.) sieve, was hand-sorted from stock or crushed material. Material passing the 19 mm (0.75 in.) sieve could not be efficiently sorted by hand to achieve the quantities required to make a completely flat and/or elongated aggregate material. This material was blended together with the stock #57 limestone to provide the change in aggregate shape for the flat and elongated #357 gradation.

Once the custom aggregates were processed and sorted by size, the individual aggregate sizes for each mixture were weighed out to specific quantities backcalculated from sieve analysis calculations and the desired percent passing values for a #357 gradation. The desired gradation was placed in the center of the allowable percent passing range given for a #357 gradation. Aggregate optimization by the Shilstone method could not be implemented due to the difficulties in obtaining and controlling the production of all materials used. This method requires having multiple stockpiles of different size-graded materials, but some materials could only be obtained in one size. After all of the required sizes were measured out, the segregated material was blended together in a 0.37 m³ (13 ft³) capacity flow-through drum mixer and stored in steel drums.

Final blended aggregate physical properties for each material used were determined and are detailed in Table 1. Only properties that would be easily measured

for rapid expeditionary construction use or were basic requirements for the PCC mixture design process were used in this analysis.

Material Proportioning and Selection. Various concrete mixtures were made where one mixture component or property varied from the specified control mixture. For each concrete mixture design component investigated, three different variations were made to test the effect on concrete performance that resulted from deviating from current specification or common practice. The mixture differences ranged from borderline acceptable to “minor” and “major” failing when compared to specifications. The control mixture was considered as a “line in the sand”, where any deviation crossing this line was grounds for rejecting the mixture during design checks or quality assurance inspections. When analyzing the strength data, this one mixture was referenced as the control mixture for each of the variables investigated.

The failure descriptors (“minor” and “major”) had no real relevance to any values selected other than to describe the amount of deviation from the control mixture. Some materials selected pass specifications, like those used for coarse aggregate degradation and maximum nominal aggregate size, but were utilized due to the difficulty in obtaining failing materials, and to maintain the experimental control needed to generate data for the statistical portion of the analysis. All other untested variables for each mixture remained as close to the control mixture as possible to minimize lurking variables that would influence the experimental procedure and statistical analysis results.

In addition to the “line in the sand” mentality, the DOD minimum amount of portland cement [284 kg/m^3 (470 lb/yd^3)] at the highest water/cement (w/c) ratio allowed [0.45] was used for material proportioning. These values would represent a worst case design scenario in an expeditionary situation where portland cement supplies would be extended due to their limited availability. Trial mixes completed on the control mixture required additional paste to achieve workability requirements and 296 kg/m^3 (500 lb/yd^3) of cement was used instead.

Each of the aggregate combinations considered had its own custom mixture design made following American Concrete Institute (ACI) 211.2 (volumetric method). Table 3 details the aggregates proportioning used for all the mixtures batched. The column labeled “Amount of Failure” qualitatively describes the deviation of the aggregate blend from the control mixture. Quantative information on the deviation is shown in the “Aggregate Usage Proportioning” column also within Table 2. Additional target mixture design properties were chosen to also be at the borderline of DOD allowable values, and included:

Table 1. Measured Aggregate Origins and Properties

Type	Aggregate Description			Material Origins		Properties											
	Type		ASTM C33 Gradation	Quarry/ Yard	Processing	Max Size, mm (in)	Max Nom. Size, mm (in)	Fineness Modulus	-75 μm (#200), %	Gradation Coefficient	Unit Weight (lb/ft³)	Dry Bulk Specific Gravity	SSD Bulk Specific Gravity	Absorption (%)	Mass Loss (%)	Weighted Avg. % Flat¹	Weighted Avg. % Elong¹
1	Coarse	≤ 3:1 Stone	357	MMA	ERDC	63 (2.5)	50 (2)	7.73	0.9	0.98	107	2.66	2.68	0.79	23	1.94	0.03
2	Fine	Natural Sand	-	MMC	-	12.5 (0.5)	4.75 (#4)	2.72	1.3	0.93	106	2.61	2.62	0.41	-	-	-
4	Coarse	Flat/ Elongated Stone	357	MMA	ERDC	63 (2.5)	50 (2)	7.81	2.2	0.99	101	2.65	2.67	0.9	31	7.97	0.19
5	Coarse	≤ 3:1 Crushed Stone	357	MMA	ERDC	50 (2)	38 (1.5)	8.15	0.2	1.06	99	2.65	2.67	1.1	24	1.6	0.84
6	Fine	Crushed Natural Sand	-	MMC	ERDC	9.5 (0.38)	4.75 (0.19)	2.39	8.9	3.27	118	2.55	2.58	1.2	-	-	-
7	Coarse	Taconite	357	Virginia, MN	Laurentian Aggregates	63 (2.5)	50 (2)	7.71	0.4	1.09	116	3.11	3.13	0.7	14	7.78	0.41
8	Coarse	≤ 3:1 Stone	357	Shepardsville, KY	Quality Stone	63 (2.5)	50 (2)	7.70	1.2	0.96	98	2.73	2.77	1.42	32	1	0.17
9	Coarse	≤ 3:1 Stone	2	MMA	ERDC	88 (3.5)	75 (3)	8.83	0.7	0.97	99	2.64	2.67	1.07	29	1.39	0
10	Coarse	≤ 3:1 Stone	1	MMA	ERDC	100 (4)	88 (3.5)	9.15	0.6	1.06	104	2.65	2.68	0.96	26	0.68	0.04
11	Coarse	Recycled Concrete (RCA)	357	MMC/ ERDC	ERDC	75 (3)	63 (2.5)	7.66	1.1	1.14	88	2.17	2.33	7.03	55	5.24	0
12	Fine	RCA	-	MMC/ERDC	ERDC	9.5 (0.38)	4.75 (#4)	2.72	13.8	2.18	101	2.28	2.41	5.91	-	-	-
13	Coarse	Recycled Asphalt (RAP)-1	graded	APAC	APAC	19.5 (0.75)	12.5 (0.5)	4.54	2.2	1.11	98	2.33	2.4	2.87	16	2.97	0

Type	Aggregate Description			Material Origins		Properties											
	Type		ASTM C33 Gradation	Quarry/ Yard	Processing	Max Size, mm (in)	Max Nom. Size, mm (in)	Fineness Modulus	-75 μ m (#200), %	Gradation Coefficient	Unit Weight (lb/ft ³)	Dry Bulk Specific Gravity	SSD Bulk Specific Gravity	Absorption (%)	Mass Loss (%)	Weighted Avg. % Flat ¹	Weighted Avg. % Elong ¹
14	Coarse	RAP-2	ungraded	APAC	APAC	63 (2.5)	50 (2)	6.20	1.1	3.43	90	2.3	2.33	1.54	37	2.22	0
15	Coarse	Clay Masonry	357	Tri-State Brick	ERDC	75 (3)	50 (2)	8.10	0.1	1.12		2.09	2.21	5.50	35	5.12	3.37
16	Fine	Clay Masonry (RMA)	-	Tri-State Brick	ERDC	9.5 (0.38)	4.75 (#4)	2.88	12.5	2.94	96	2.35	2.36	0.73	-	-	-
18	Coarse	$\leq$ 3:1 Stone	467	MMA	MMA	50 (2)	38 (1.5)	6.77	2	0.98	106	2.64	2.67	1.1	25	5.04	0
29	Coarse	Concrete Masonry (CMU)	357	Block USA	ERDC	75 (3)	38 (1.5)	6.13	3.3	1.04	63	1.66	1.85	11.2	51	0	0
1) At a dimension to thickness ratio of 3 to 1.																	

- Slump: 50 mm (2 in.)
- Total air content: 6 %
- Maximum aggregate size: 63 mm (2.5 in.)

The slump and total air content requirements were only used for trial designs of the control mixture and were not enforced on the other mixtures to draw conclusions about the plastic properties of the mixtures made with different aggregate properties. No mixture redesigns were made after the control batch was made and its properties and material proportioning were set. Aggregate moisture corrections were made on every production day to control the amount of water used.

Testing and Sample Preparation. Typical strength specimens and laboratory tests were conducted to characterize each batched mixture. 0.30 m³ (10.5 ft³) batches of PCC were made using a 0.35 m³ (13 ft³) capacity flow-through drum mixer. Rosin based air entrainer and modified lignosulfate (with catalyst) admixtures were used to achieve the design air content and slump. Twelve 150- by 300-mm (6 by 12 in.) cylinders and twelve 150 mm by 150 mm by 533 mm (6 in. by 6 in. by 21 in. long) beams were cast following ASTM C192 procedures. Specimens were consolidated by internal vibration using a 38-mm (1.5-inch) square spud vibrator.

Specimens were demolded the day after casting and moist cured for either 28 or 90 days in a controlled high humidity room. Six of each specimen type were tested at each of the two cure times following ASTM C39 or C78 on a 440 kip capacity hydraulic load frame. Sulfur caps were cast onto the cylinder specimens before testing following ASTM C617 to provide a plane, smooth surface for testing.

Statistical Analysis. The final stage of the project involved using the strength data and measured aggregate properties to infer conclusions about their influence on PCC response. To test for the strength loss from different aggregate characteristics, the calculated mean and standard deviation values were statistically tested to investigate the response in the data. The statistical approach used in this study was similar to that used by Bly et al (2008) when investigating the effects of pavement design features on frost heaving at the MnROAD Pavement Testing Facility.

Aggregate physical properties effects on PCC strength over time were investigated in this study for both compressive and flexural strength. For each aggregate design feature considered, a visual and bivariate analysis was completed where the mixtures were grouped such that they differed by a single design feature as best as possible. Further investigation into the interaction of design features within a composite design was statistically investigated by multivariable regression analysis and ANOVA testing on the selected data.

[Type text]

Table 2. Aggregates Usage for Mixture Designs

Mix Design	Item Investigated	Amount of Failure	Aggregate Usage							
			Type (From Table 1)				Proportion (% Mass)			
			Coarse		Fine		Coarse		Fine	
			A	B	C	D	A	B	C	D
1	Control	-	1	-	2	-	100	-	100	-
2	CA Shape	Minor	1	4	2	-	75	25	100	-
3	CA Shape	Major	1	4	2	-	50	50	100	-
4	Angularity	Minor	1	5	2	6	75	25	100	0
5	Angularity	Major	1	5	2	6	50	50	100	0
6	Angularity	-	1	5	2	6	100	0	75	25
7	Angularity	-	1	5	2	6	100	0	50	50
8	Angularity	-	1	5	2	6	75	25	75	25
9	Angularity	-	1	5	2	6	75	25	50	50
10	Angularity	-	1	5	2	6	50	50	75	25
11	Angularity	-	1	5	2	6	50	50	50	50
12	CA Degradation	Weaker	-	8	2	-	0	100	100	-
13	CA Degradation	Stronger	-	7	2	-	0	100	100	-
14	Max Aggregate Size	Smaller	-	18	2	-	0	100	100	-
15	Max Aggregate Size	Minor	-	9	2	-	0	100	100	-
16 ¹	Max Aggregate Size	Major	-	10	2	-	0	100	100	-
17	RCA	Minor	1	11	2	12	75	25	100	0
18	RCA	Major	1	11	2	12	50	50	100	0
19	RCA	Minor	1	11	2	12	100	0	75	25
20 ¹	RCA	Major	1	11	2	12	100	0	50	50
21	RCA	Minor	1	11	2	12	75	25	75	25
22	RCA	Major	1	11	2	12	75	25	50	50
23	RCA	Major	1	11	2	12	50	50	75	25
24	RCA	Major	1	11	2	12	50	50	50	50
25	RMA	Minor	1	15	2	16	75	25	100	0
26	RMA	Major	1	15	2	16	50	50	100	0
27	RMA	Minor	1	15	2	16	100	0	75	25
28 ¹	RMA	Major	1	15	2	16	100	0	50	50
29	RMA	Minor	1	15	2	16	75	25	75	25

Mix Design	Item Investigated	Amount of Failure	Aggregate Usage							
			Type (From Table 1)				Proportion (% Mass)			
			Coarse		Fine		Coarse		Fine	
			A	B	C	D	A	B	C	D
30 ¹	RMA	Major	1	15	2	16	75	25	50	50
31 ¹	RMA	Major	1	15	2	16	50	50	75	25
32 ¹	RMA	Major	1	15	2	16	50	50	50	50
33	Graded Rap	Minor	1	13	2	-	75	25	100	-
34	Graded Rap	Major	1	13	2	-	50	50	100	-
35	Ungraded Rap	Minor	1	14	2	-	75	25	100	-
36	Ungraded Rap	Major	1	14	2	-	50	50	100	-
37 ²	Gap Graded 1	Minor	1	-	2	-	100	-	100	-
38 ³	Gap Graded 2	Minor	1	-	2	-	100	-	100	-
39 ⁴	Gap Graded 3	Major	1	-	2	-	100	-	100	-
40 ⁵	Gap Graded 4	Major	1	-	2	-	100	-	100	-
41	Control	Retest of 1	1	-	2	-	100	-	100	-
42	Control	Retest of 1	1	-	2	-	100	-	100	-
43	Angularity	Retest of 5	1	5	2	6	50	50	100	0
44 ¹	RCA	Retest of 20	1	11	2	12	100	0	50	50
45	RCA	Retest of 17	1	11	2	12	75	25	100	0
46	RMA	Retest of 25	1	15	2	16	75	25	100	0
47 ¹	RMA	Retest of 31	1	15	2	16	50	50	75	25
48	CMU	Minor	1	28	2	-	75	25	100	-
49	CMU	Major	1	28	2	-	50	50	100	-
1) Mixture not usable with current mix design 2) 50% removed from 0.75" sieve and reflected in fineness modulus calculations 3) 100% removed from 0.75" sieve and reflected in fineness modulus calculations 4) 50% removed from 0.75" & 0.5" sieve and not reflected in fineness modulus calculations 5) 100% removed from 0.75" & 0.5" sieve and not reflected in fineness modulus calculations										

Outlier Reduction. Before analysis on the datasets was completed, the data were examined for outliers. Outliers were data points that did not correspond to the majority of the data points collected. Box and whisker and normal probability plots were used to detect and remove outliers to construct a normally distributed data set. The following strength data points were removed from the total dataset:

- 28 day compressive: 7 of 221
- 90 day compressive: 2 of 221
- 28 day flexural: 9 of 221
- 90 day flexural: 11 of 219

Visual and Bivariate Analysis. Comparing distributions of PCC strength for mixtures differing by a single design feature yielded a preliminary idea about the contribution of that design feature to the mixture strength. Statistical hypothesis testing was used to compare the distributions of the batched mixture varying by the different design characteristics. The means for two different groups, separated by a single design characteristic, were tested to determine if there was a difference between the groups. In this study, a two-sample t-test was used to determine a statistic for hypothesis testing, assuming an unequal variance and sample size between the groups. Resulting probabilities from calculated t-test statistics less than the selected level of significance resulted in rejecting the null hypothesis (no change in data set means) for the alternative (statistically significant change observed).

The statistical testing method used requires data with an approximately normal distribution and independent variables. The data used were checked for normality using the normal probability plots. Independence was maintained in each design feature grouping. By breaking the analysis up into separate design features and carefully controlling the mixtures made, the analysis forced results for a single design feature to reduce the interaction between features as much as possible.

Multivariable Regression Analysis. As mentioned before, the bivariate statistical analysis only considered one design feature at a time. However, a PCC design is based on multiple design factors that must be balanced for optimal performance based on funding options and the desired life cycle. The bivariate analysis does not take into account the interactions of the different variables and their effects on performance. The t-tests described earlier cannot be used to isolate differences in pavement performance caused by the variables. Determining interrelationships between variables can only be statistically accomplished through a multivariate analysis.

Multiple linear regression was used in this study in an exploratory manner to identify the most significant variables. The linear coefficients were computer estimated by the method of least squares. Hypothesis testing was used to test the significance of explanatory variables to a regression model and followed a similar procedure used in the bivariate analysis. The regression model was optimized to include only relevant terms using a backwards stepwise variable selection process. The Akaike Information Criteria (AIC) for each model considered was determined and used to choose the best model that minimized the model's lack of fit (residual error) with its complexity (number of predictors).

Results and Analysis

Forty-three mixtures were batched for this study; however, only 37 were used in the analysis due to workability issues. The strength testing data collected were examined for outlying data and normality. In general, the data were fairly normal and a minimal amount of data points were removed for the statistical analysis. The final box and whisker plots are shown in Figure 1. A typical level of significance value of 0.05 was used for all hypothesis testing analyses conducted (Moore 2006, Weisberg 2005).

Bivariate Analysis. The bivariate analysis results for the compressive and flexural concrete strength results considered are summarized in Table 4. The details of the results are described and discussed below, where insignificant properties were removed from the analysis before entering the multivariable testing phase.

Shape. The means for both failure amounts considered were not equal. The null hypothesis from the statistical hypothesis testing was rejected for the alternative. Coarse aggregate shape has an effect on the long term compressive and flexural strength of PCC. Even though aggregate of any shape can be used to make high quality (strong and durable) concrete, mixture design modifications are required for increased flat and elongated particles because the aggregate will not pack together well or cannot support the global stress based on their geometry. Decreased volume packing of aggregates requires more paste to fill the unfilled void space (Graves 2006, Taylor 2007). The experimental setup utilized verifies this concept because the amount of paste designed for mixes 1, 2 and 3 was held constant and the strength was found to decrease with increasing proportions of flat and elongated particles. Not filling the additional voids produces concrete that cannot transmit load as efficiently internally and causes additional stress concentrations that amplify the resulting stress in the material around the void. Particle orientation of flat and elongated aggregates within PCC can also affect strength values. Also, thin particles tend to lay flat during construction and break along this weaker axis under applied loading, thereby reducing strength (D'Angleo 1996 ,Graves 2006).

Crushed Particles. The majority of the results showed that aggregate angularity affected strength. Compression and 28-day flexural strength results showed decreases in strength; however, a majority of the 90-day flexural strength results compared favorably with the control mixture. The compressive strength loss observed is most likely due to the additional paste demanded by the crushed aggregate to coat the additional surface, preventing paste from filling the voids in between the aggregates. The flexural strength testing did not show as large a change as the compression testing, and this is to be expected based on previous tensile strength studies summarized by Graves (2006). Many other sources conclude that flexural strength should increase from the additional surface area crushed aggregates provide, providing more area for paste to bond to and lock aggregates into place (Kosmatka 2011, Taylor 2007, Graves 2006, Mehta 2006, Mindess 2003); however, this was not seen.

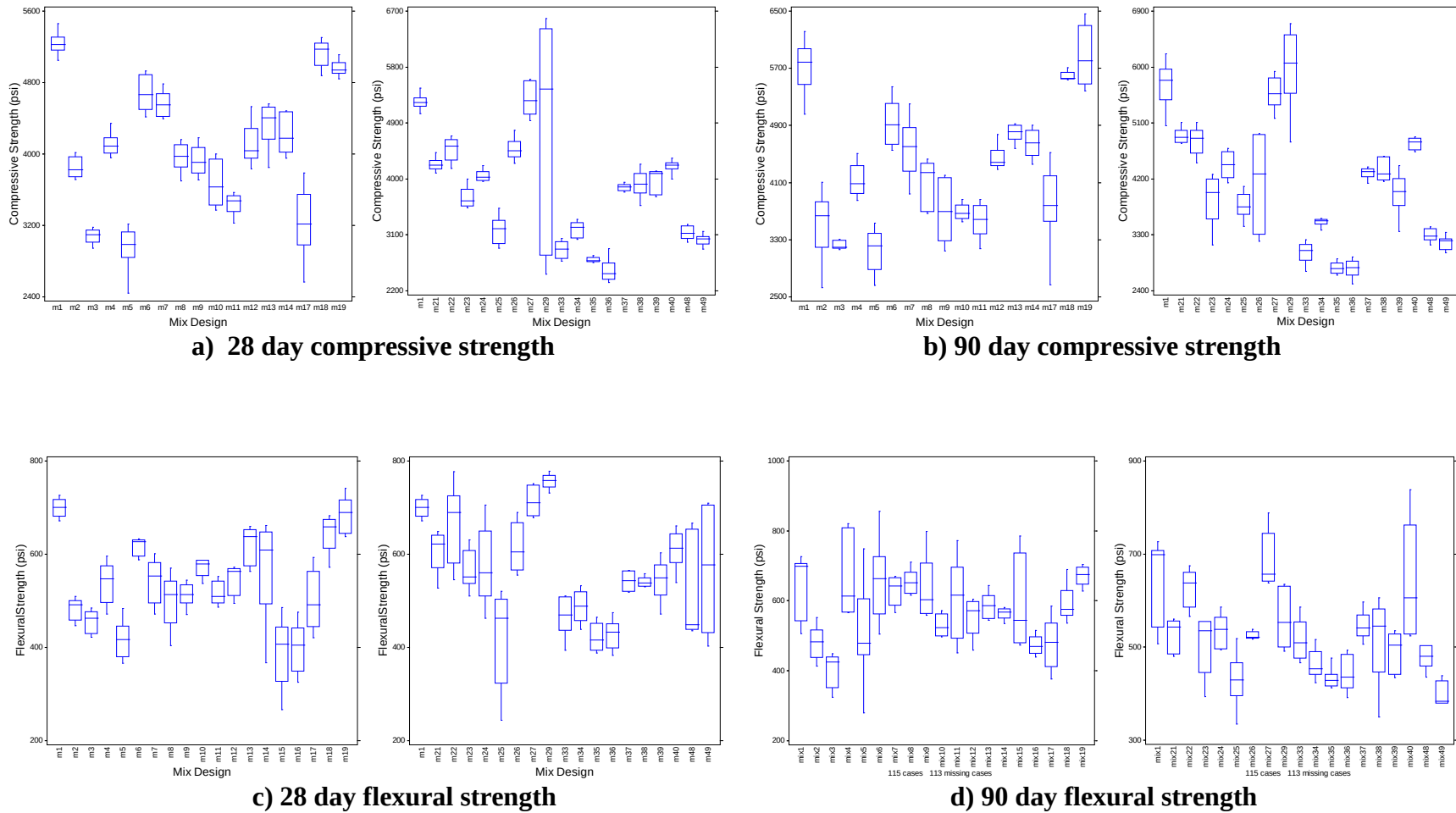


Figure 1. Box and Whisker Plots

Table 4. Bivariate Analysis Results
a) 28 day compressive strength

Design Feature				Mix Designs Considered				Mean Value, psi		Std. Deviation, psi		Difference, psi		Statistic Testing			
				Group 1	Sample Size	Group 2	Sample Size	Group 1	Group 2	Group 1	Group 2	Mean	Std. Error	t – value	df	P - value	
Conventional Aggregates	CA Shape	Minor		1	6	2	6	5239	3848	133	120	1391	73	18.99	9.9	0.00E+00	
		Major				3	5		3084		87	2155	67	32.15	8.6	0.00E+00	
	Angularity	Minor				4	6		4106		133	1132	77	14.73	10	0.00E+00	
		Major				5	12		2942		227	2297	85	26.93	15.4	0.00E+00	
	Mass Loss	More				12	6		4105		241	1133	112	10.08	7.8	0.00E+00	
		Less				13	6		4334		262	905	120	7.54	7.4	1.00E-04	
	Aggregate Size	2 sizes larger				16	-		-		-	-	-	-	-	-	-
		1 size larger				15	-		-		-	-	-	-	-	-	-
		1 size smaller				14	6		4217		221	1022	105	9.71	8.2	0.00E+00	
	Gap Graded	Minor Deviation	Reflects FM calculation			37	6		3866		60	1372	60	23	6.9	0.00E+00	
			Not reflects FM calculation			38	6		3920		227	1318	108	12.26	8.1	0.00E+00	
		Major Deviation	Reflects FM calculation			39	5		3961		208	1277	108	11.86	6.6	0.00E+00	
			Not reflects FM calculation			40	6		4204		112	1034	71	14.56	9.7	0.00E+00	
Recycled Aggregates	Concrete	Slab	Minor	1	6	17	11	5239	3252	133	366	1987	123	16.16	13.8	0.00E+00	
			Major			18	6		5132		154	107	83	1.28	9.8	2.29E-01	
		Masonry	Minor			48	5		3142		115	2097	75	27.99	9	0.00E+00	
			Major			49	6		3019		93	2220	66	33.42	8.9	0.00E+00	
	Clay Masonry		Minor			25	12		3182		225	2056	85	24.26	15.3	0.00E+00	
			Major			26	6		4478		180	760	91	8.32	9.2	0.00E+00	
	Asphalt	Graded	Minor			33	5		2859		150	2380	86	27.59	8.2	0.00E+00	
			Major			34	6		3194		129	2045	76	27.03	10	0.00E+00	
		Ungraded	Minor			35	5		2699		47	2539	58	43.56	6.4	0.00E+00	
			Major			36	6		2523		197	2715	97	27.97	8.8	0.00E+00	

b) 90 day compressive strength

Design Feature				Mix Designs Considered				Mean Value, psi		Std. Deviation, psi		Difference, psi		Statistic Testing			
				Group 1	Sample Size	Group 2	Sample Size	Group 1	Group 2	Group 1	Group 2	Mean	Std. Error	t – value	df	P - value	
Conventional Aggregates	CA Shape	Minor		1	6	2	6	5726	3522	387	498	2204	258	8.56	9.4	0.00E+00	
		Major				3	5		3229		64	2497	161	15.54	5.3	0.00E+00	
	Angularity	Minor				4	6		4131		237	1595	185	8.61	8.3	0.00E+00	
		Major				5	12		3158		286	2568	178	14.4	7.8	0.00E+00	
	Mass Loss	More				12	6		4442		174	1284	173	7.41	6.9	2.00E-04	
		Less				13	6		4797		125	929	166	5.59	6	1.40E-03	
	Aggregate Size	2 sizes larger				16	-		-		-	-	-	-	-	-	-
		1 size larger				15	-		-		-	-	-	-	-	-	-
		1 size smaller				14	5		4658		205	1068	183	5.85	7.8	4.00E-04	
	Gap Graded	Minor Deviation	Reflects FM calculation			37	6		4297		96	1429	163	8.77	5.6	2.00E-04	
			Not reflects FM calculation			38	6		4340		184	1386	175	7.92	7.1	1.00E-04	
		Major Deviation	Reflects FM calculation			39	6		3970		350	1756	213	8.24	9.9	0.00E+00	
			Not reflects FM calculation			40	6		4771		105	955	164	5.83	5.7	1.30E-03	
Recycled Aggregates	Concrete	Slab	Minor	1	6	17	11	5726	3738	387	539	1987	222	8.95	13.6	0.00E+00	
			Major			18	6		5516		189	210	176	1.19	7.3	2.70E-01	
		Masonry	Minor			48	5		3296		109	2430	164	14.79	5.8	0.00E+00	
			Major			49	6		3174		116	2552	165	15.46	5.9	0.00E+00	
	Clay Masonry		Minor			25	12		3777		192	1949	168	11.58	6.4	0.00E+00	
			Major			26	6		4158		814	1568	368	4.26	7.2	3.60E-03	
	Asphalt	Graded	Minor			33	5		3020		176	2706	174	15.58	7	0.00E+00	
			Major			34	6		3508		69	2217	161	13.81	5.3	0.00E+00	
		Ungraded	Minor			35	5		2768		107	2957	164	18.03	5.8	0.00E+00	
			Major			36	6		2760		157	2965	171	17.39	6.6	0.00E+00	

c) 28 day flexural strength

Design Feature				Mix Designs Considered				Mean Value, psi		Std. Deviation, psi		Difference, psi		Statistic Testing					
				Group 1	Sample Size	Group 2	Sample Size	Group 1	Group 2	Group 1	Group 2	Mean	Std. Error	t – value	d _f	P - value			
Conventional Aggregates	CA Shape	Minor		1	6	2	5	700	482	20	24	218	14	16	7.8	0.00E+00			
		Major				3	6		456		26	243	13	18.16	9.4	0.00E+00			
	Angularity	Minor				4	6		539		46	161	20	7.88	6.9	1.00E-04			
		Major				5	12		415		39	285	14	20.45	15.9	0.00E+00			
	Mass Loss	More				12	6		547		33	153	16	9.79	8.3	0.00E+00			
		Less				13	6		621		41	78	18	4.24	7.3	3.50E-03			
	Aggregate Size	2 sizes larger				16	6		400		54	300	23	12.8	6.4	0.00E+00			
		1 size larger				15	6		391		76	309	32	9.69	5.7	1.00E-04			
		1 size smaller				14	6		571		111	129	46	2.81	5.3	3.50E-02			
	Gap Graded	Minor Deviation	Reflects FM calculation			37	6		543		25	157	15	10.38	5.4	1.00E-04			
			Not reflects FM calculation			38	6		541		11	159	9	17.12	7.7	0.00E+00			
		Major Deviation	Reflects FM calculation			39	6		545		46	155	20	7.57	6.8	1.00E-04			
			Not reflects FM calculation			40	6		610		43	90	19	4.65	7.1	2.30E-03			
Recycled Aggregates	Concrete	Slab	Minor	1	6	17	9	700	502	20	62	198	22	8.91	10.3	0.00E+00			
			Major			18	5		647		43	53	21	2.52	5.4	4.94E-02			
		Masonry	Minor			48	5		527		117	173	53	3.25	4.2	2.92E-02			
			Major			49	6		569		150	131	62	2.12	5.2	8.55E-02			
	Clay Masonry		Minor			25	12		420		98	280	29	9.5	12.7	0.00E+00			
			Major			26	6		614		53	86	23	3.72	6.4	8.70E-03			
	Asphalt	Graded	Minor			33	6		467		45	233	20	11.67	6.9	0.00E+00			
			Major			34	6		488		35	212	17	12.75	7.9	0.00E+00			
		Ungraded	Minor			35	6		421		32	279	15	18.18	8.4	0.00E+00			
			Major			36	6		428		32	271	15	17.56	8.4	0.00E+00			

d) 90 day flexural strength

Design Feature				Mix Designs Considered				Mean Value, psi		Std. Deviation, psi		Difference, psi		Statistic Testing						
				Group 1	Sample Size	Group 2	Sample Size	Group 1	Group 2	Group 1	Group 2	Mean	Std. Error	t – value	d _f	P - value				
Conventional Aggregates	CA Shape	Minor		1	6	2	5	648	479	93	50	169	44	3.85	7.9	5.00E-03				
		Major				3	5		402		51	246	44	5.58	8	5.00E-04				
	Angularity	Minor				4	5		673		126	-25	68	-0.37	7.2	7.22E-01				
		Major				5	12		508		140	140	55	2.53	14.4	2.37E-02				
	Mass Loss	More				12	6		555		55	93	44	2.12	8.2	6.67E-02				
		Less				13	5		583		39	65	42	1.56	7	1.63E-01				
	Aggregate Size	2 sizes larger				16	6		473		29	175	40	4.4	6	4.60E-03				
		1 size larger				15	4		587		142	61	81	0.75	4.7	4.87E-01				
		1 size smaller				14	6		564		17	84	39	2.18	5.3	7.81E-02				
	Gap Graded	Minor Deviation	Reflects FM calculation			37	6		546		32	102	40	2.55	6.2	4.27E-02				
			Not reflects FM calculation			38	6		517		92	132	53	2.46	10	3.37E-02				
		Major Deviation	Reflects FM calculation			39	6		491		43	157	42	3.76	7	7.00E-03				
			Not reflects FM calculation			40	6		640		126	8	64	0.13	9.2	9.01E-01				
Recycled Aggregates	Concrete	Slab	Minor	1	6	17	12	648	480	93	72	168	43	3.88	8.1	4.50E-03				
			Major			18	6		592		54	56	44	1.27	8	2.38E-01				
		Masonry	Minor			48	6		479		26	170	39	4.31	5.8	5.50E-03				
			Major			49	6		398		27	250	39	6.33	5.8	8.00E-04				
	Clay Masonry		Minor			25	12		430		50	219	41	5.29	6.5	1.30E-03				
			Major			26	4		524		9	124	38	3.24	5.2	2.20E-02				
	Asphalt	Graded	Minor			33	6		516		44	132	42	3.15	7.1	1.57E-02				
			Major			34	6		463		32	185	40	4.62	6.2	3.30E-03				
		Ungraded	Minor			35	6		433		23	215	39	5.52	5.6	1.90E-03				
			Major			36	6		443		39	205	41	4.99	6.7	1.80E-03				

e) Comparison of recycled concrete aggregates made with different mixture designs

Design Feature		Mix Designs Considered				Mean Value, psi		Std. Deviation, psi		Difference, psi		Statistic Testing		
		Group 1	Sample Size	Group 2	Sample Size	Group 1	Group 2	Group 1	Group 2	Mean	Stand. Error	t – value	df	P - value
PCC Mix Design	28 day compressive													
	Minor	17	12	46	5	3123	3142	567	115	-19	260	-0.1	12.9	0.9131
	Major	18	6	49	6	5132	3019	154	93	2113	74	28.7	8.2	0.0000
	90 day compressive													
	Minor	17	12	46	6	3738	3295	539	109	443	226	2.7	12.7	0.1740
	Major	18	5	49	6	5588	3173	69	116	2415	59	42.6	8.3	0.0000
	28 day flexural													
	Minor	17	9	46	5	502	527	62	117	-25	47	-0.4	5.3	0.6762
	Major	18	5	49	6	647	569	43	150	78	70	1.2	6.0	0.2707
	90 day flexural													
	Minor	17	12	46	6	480	479	72	26	2	31	0.1	15.1	0.9437
	Major	18	6	49	6	592	398	54	27	194	25	7.9	7.3	0.0001

Mass Loss. The means for both failure amounts considered for compressive strength were not equal. The null hypothesis from the statistical hypothesis testing was rejected for the alternative for both curing times considered. Different results were found with the flexural strength testing. The means for the 28-day samples were not equal, and the null hypothesis from the statistical hypothesis testing was rejected for the alternative; however, the opposite occurred with the 90-day samples. The null hypothesis was not rejected because there was not enough statistical evidence against this. This suggests there is no long term difference in the flexural strength of PCC made with aggregates of differing abrasion resistance.

Maximum Aggregate Size. The compressive strength means for the #467 and #357 stone were not equal, and the null hypothesis from the statistical hypothesis testing was rejected for the alternative for both testing times considered. This suggests that compressive strength is affected by the size of the aggregates used. Different results were found with the flexural strength testing. The means for the 28-day samples were not equal, and the null hypothesis from the statistical hypothesis testing was rejected for the alternative; however, the opposite occurred with the 90-day samples. The null hypothesis was not rejected. This suggests there is a difference in flexural strength at 28 days, but there are no long term differences in the flexural strength of PCC made with aggregates different sizes.

The strength loss seen with the smaller aggregates is likely the result of the mixture being deficient in paste to coat and bond the aggregates together. Smaller aggregates have a larger surface area per unit volume than larger aggregates, requiring more paste to surround their surface (Cordon 1963, Graves 2006, Mehta 2005, Mindess 2003). For this experiment, the cementitious material content and water-to-cementitious ratio were held constant to control the experimental design. If the paste content was increased above what was used to effectively cover the aggregate particles, the expected results would most likely not show a change in means.

The strength loss observed with the larger sized aggregates follows the same surface area principle as described with the smaller aggregates. In this case, there is more than enough paste to coat the larger aggregates; however, there is only a limited amount of particle surface to which the paste can bond the mixture together. This entails an optimal amount of cementitious material is necessary to coat aggregates and provide maximum strength. Graves (2006) summarized the effect of maximum aggregate size on strength in relation to optimal cementitious usage from various sources. Using the airfield pavement design guidance given (UFC 2001), Graves's information would limit the maximum aggregate size used for paving mixtures to 38 mm (1.5 in.) to achieve the specified 4.5 MPa (650 psi) with a minimized amount of cementitious material (Cordon 1963, Graves 2006). Cordon's research also showed that the 38-mm (1.5-in.) maximum sized mixture was the optimal size to achieve strength per amount of cementitious material batched (Cordon 1963). It should be noted that the main research conclusions given by Graves are based on PCC mixtures made with 100% portland cement. Today, the DOD allows up to 25% replacement with supplementary cementitious materials within proposed PCC mixture designs without approval from the appropriate engineering command personnel. The strength

values and plots given in the original reports may produce different strength and efficiency values at 28 days.

The durability of concrete pavements constructed using larger sized marginal aggregates with high absorption values in heavy freeze-thaw environments may not be appropriate. Considerations for reducing moisture related damage (durability “D” cracking) should be taken if a full investigation of the aggregates is not completed. D-cracking is more significant with large aggregates where internal water must travel further within the aggregate to escape when freezing (O’Doherty 1987, Schwartz 1987, Janssen 1994, Folliard 2003, Kosmatka 2011). Failure of water to expand into volume outside the aggregates’ available internal pore volume leads to aggregate and eventually concrete damage. Typically sedimentary-based aggregates with very fine pore distributions and high absorptions may be susceptible to freeze-thaw damage; however, many types of high absorption aggregates are still durable (Schwartz 1987, Folliard 2003). The DOD does not have any specific construction specifications limiting the use of these materials and only lists ASTM C1646 in its list of specified testing standards. The DOD only has mixture design guidance which recommends recycled concrete aggregates that have exhibited D-cracking should be crushed to a maximum size of 19mm (0.75 in.) for pavement use (UFC 2004b). Using smaller sized aggregate, 25 mm (1 in.) maximum (Aberdeen Group 1988), should be used when high absorption aggregates are encountered to ensure some amount of durability in wet climates with frequent freeze-thaw cycles until aggregate performance can be verified under standard freeze-thaw tests.

Gap Gradation. All cases considered show performance loss from removing particular aggregate sizes from the gradation. As the material loses certain size particles in its distribution, more void volume is introduced that must be filled. Additional cement paste was required to completely fill the void volume around the aggregates for the gap graded mixtures than for the dense graded mixture. Since the same amount of cement was used for both mixtures, the gap graded mixture was significantly deficient in cement paste to fill resulting increase in void volume.

Recycled Concrete Aggregate (RCA and CMU). The change in means between the control mixture and all of the RCA mixtures batched showed varying results and are inconclusive. No firm conclusion on the use of recycled conventional aggregate can be drawn from the data. This trend is expected, however, because previous results indicated that mixtures using fine aggregate material only gave unpredictable results (Vancura 2009). Mixtures 17 and 18 used only coarse RCA for replaced aggregates at 25 and 50 percent replacement, respectively. From the statistical results, the data showed the 50 percent replaced mixture to have similar values as the control mixture, but the 25 percent replaced mixture did show significant differences. This goes against the expected results. It would be expected that mixture 18 would show at least similar performance, if not further strength reductions, compared to mixture 17 because a decrease in performance was measured with a mixture with less marginal aggregate.

The means for both CMU mixtures showed a different trend than the RCA mixtures. Unlike the RCA mixes, the majority of the strength values are not equal and

the null hypothesis from the statistical hypothesis testing was rejected for the alternative. CMU has an effect on the long term compressive and flexural strength of PCC. This is unexpected since the mass loss testing for conventional aggregates showed different results; However, this material was the weakest of all aggregate considered, and so weak that ASTM C33 would not allow its use for paving projects. Further information into the effects of mass loss on concrete performance was drawn from the multivariable regression and used to further develop this trend.

Table 4e documents the bivariate analysis conducted between the two different concrete based aggregates used in this study to determine the effect of the aggregate's mixture design on strength performance. The results show very little difference in both compressive and flexural strength between the minor design failure (25 percent replacement) mixtures batched. The major design failure (50 percent replacement) mixtures show different results, and most strength values are significantly different from one another. Looking deeper in the values, the major difference between the numbers seen is that the mix 18 strength values are higher than the mix 17 values, indicating the mixture is getting stronger as more marginal material is added. The addition of more weaker aggregates should produce weaker strength values. Further review of the fresh property data collected showed that mixture 18 contained significantly less air than the other three mixtures considered, making the mixture mechanically stronger with less defects and able to take more loading before failure. A mixture with similar air content most likely would have yielded similar strength values as the other three mixtures considered.

Recycled Clay Masonry (RMA). Many of the mixtures batched with the clay masonry fine aggregate showed varied results, or the workability was so poor that the mixture could not be used. When comparing only the use of clay masonry for coarse aggregate replacement, the means of both samples measured and replacement rates are not equal, and the null hypothesis from the statistical hypothesis testing is rejected for the alternative. This suggests that the use of clay masonry coarse aggregates yields a significant strength reduction in concrete. This is different from the results presented by Hanson (1992); however, a range of cement contents was not provided to where little to no effect of material replacement on strength was observed. Since the aggregates were highly angular and flat-shaped from crushing, additional paste was required to completely fill the additional voids made by the coarse aggregate in these mixtures.

Recycled Asphalt Pavement (RAP). All cases considered showed drastic performance loss from the inclusion of aggregates covered to some degree with asphalt binder, and this trend follows the results of previous research. Previous studies have indicated that the relatively softer asphalt layer creates stress concentrations that enhance stresses from applied loads. Other studies have shown the asphalt binder coated aggregate debonding from the concrete matrix as the cause for the strength decrease (Huang 2005).

Multivariate Regression Analysis. The final part of the statistical analysis consisted of multivariable regression modeling on each of the strength values determined from

the laboratory samples tested. This analysis was designed to show how each of the design factors considered affects the resulting strength of the mixtures produced. The physical properties of the blended aggregate (stock plus replaced material) were calculated and used as the regression analysis predictor variables. Only results for the replaced coarse aggregate mixtures were used, since these mixtures had the most complete data sets. All categorical (descriptor) variables were measured as being included in the mixture or not using a binomial reporting system.

To make the discussion of the variable removal and stepwise model updating results easier to follow, a predictor variable labeling scheme was developed and is detailed in Table 5. The full regression models used for all strength cases considered are shown as Equation 1. Two models were considered after reviewing the differences in results from the concrete based aggregates. The first model considers the concrete based aggregates separately, whereas the second model groups the concrete based materials into a single variable. In most cases, the calculated AIC values were less for the second model compared to the first; however, this is expected since this model is initially less complex and starts with one less predictor variable. Only variables that were insignificant enough for removal from both models were considered insignificant to PCC strength. Table 6 documents the results of the multivariate regression analysis for all sample types and testing ages considered.

Model 1: y

$$= \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_8 x_8 + \beta_9 x_9 + \beta_{10} x_{10}$$

Model 2: y

$$= \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_8 x_8 + \beta_9 x_9 + \beta_{10} x_{10} + \beta_{11} x_{11}$$

Where: y_i = Response value from resulting model

β_i = Linear predictor coefficients

x_i = Predictor value for each predictor variable used

Equation 1. Models considered for regression analysis

Table 5. Regression equation variable labeling

Variable Subscript	Test Item
0	Constant
1	Coefficient of gradation
2	Fineness modulus
3	Mass loss
4	Maximum nominal size
5	Includes RAP (factor)
6	Includes CMU (factor)
7	Includes RCA (factor)
8	Crushed material (factor)
9	Percent elongated
10	Percent flat
11	Includes concrete based aggregates (factor)

Table 6. Multivariable regression analysis results

Sample type	Removed predictor variable (by subscript number)	Model RSS	Model Terms, n	AIC
28 day compressive strength	Concrete based aggregates are individual factors			
	Full Model	$3.10 \cdot 10^7$	11	1797.1
	6	$3.10 \cdot 10^7$	10	1794.8
	6 and 4	$3.19 \cdot 10^7$	9	1794.3
	6,4, and7	$3.22 \cdot 10^7$	8	1795.6
	Concrete based aggregates are single factor			
	Full Model	$3.12 \cdot 10^7$	10	1795.4
	4	$3.13 \cdot 10^7$	9	1793.7
	4 and 10	$3.20 \cdot 10^7$	8	1794.7
28 day flexural strength	Concrete based aggregates are individual factors			
	Full Model	$8.00 \cdot 10^5$	11	1338.5
	7	$8.00 \cdot 10^5$	10	1336.2
	7 and 10	$8.08 \cdot 10^5$	9	1335.4
	7, 10 and 6	$8.23 \cdot 10^5$	8	1335.9
	Concrete based aggregates are single factor			
	Full Model	$7.74 \cdot 10^5$	10	1263.2
	10	$7.74 \cdot 10^5$	9	1260.9
	10 and 4	$7.80 \cdot 10^5$	8	1259.6
	10, 4 and 3	$7.88 \cdot 10^5$	7	1258.7
	10, 4, 3 and 11	$9.26 \cdot 10^5$	6	1349.4
90 day compressive strength	Concrete based aggregates are individual factors			
	Full Model	$3.98 \cdot 10^7$	11	1844.6
	7	$3.99 \cdot 10^7$	10	1842.8
	6	$4.09 \cdot 10^7$	9	1843.9
	Concrete based aggregates are single factor			
	Full Model	$3.97 \cdot 10^7$	10	1818.9
	4	$4.04 \cdot 10^7$	9	1819.0
90 day flexural strength	Concrete based aggregates are individual factors			
	Full Model	$1.02 \cdot 10^6$	11	1382.9
	4	$1.02 \cdot 10^6$	10	1380.8
	4 and 8	$1.03 \cdot 10^6$	9	1380.7
	4, 8 and 3	$1.04 \cdot 10^6$	8	1379.3

Sample type	Removed predictor variable (by subscript number)	Model RSS	Model Terms, n	AIC
	4, 8, 3 and 10	$1.04 \cdot 10^6$	7	1377.4
	Concrete based aggregates are single factor			
	Full Model	$1.02 \cdot 10^6$	10	1381.1
	4	$1.02 \cdot 10^6$	9	1379.0
	4 and 8	$1.04 \cdot 10^6$	8	1379.9

From the analysis conducted, no predictor variable considered was removed consistently in all four strength cases. However, the condition that predictor variables must be insignificant in all strength models considered may be too stringent. Looking back over the regression results and using the model (1 or 2) that provided the minimum AIC value, maximum nominal size is the only insignificant predictor variable for all strength values. Also, mass loss is also insignificant for the 90 day flexural strength and follows the results determined in the bivariate analysis.

Conclusions and Recommendations

A laboratory investigation of 17 different aggregates and 37 different mixture designs was completed that compared the strengths of mixtures made following with different amounts of marginal quality aggregates. The mixtures proportioned were designed to have the lowest strength possible, without considering the effects of the aggregates, while still being within the DOD's airfield pavement specifications. Test specimens for compression and bending were cast and tested for their respective strengths, and a statistical analysis was completed to determine the laboratory performance of the mixtures. Conclusions and recommendations from this investigation include:

Conclusions

- The majority of the PCC mixtures tested did not achieve the minimum DOD required 90 day flexural strength of 4.5 MPa (650 psi) for airfield pavement construction. Modifying the mixtures by increasing the cement content above the minimum of 284 kg/m^3 (470 lb/yd^3), using supplementary cementitious materials, and/or optimizing the total aggregate gradation would likely increase flexural strengths to meet DOD airfield design.
- Many mixtures were deficient in cementitious paste to coat the surface of aggregate blends made with smaller, angular, flat, or elongated aggregates. Use of such aggregates created additional voids within the concrete as the aggregate skeleton changed with replacement of conventional aggregates. Optimizing the total aggregate gradation will partially assist with minimizing void space; however, additional cementitious paste will be needed to counteract this increase in void volume. Mixture costs will increase with the addition of portland cement alone to provide additional paste. Additional supplementary cementitious materials could be added to provide additional paste and enhance the mechanical and physical properties without the majority of the projected cost increases.

- The statistical analysis showed that the maximum nominal aggregate size of the material used was the only aspect of the aggregate physical properties that did not affect strength. Mass loss of the aggregate used did not affect the 90 day flexural strength of the concrete specimens.

Recommendations

- A formal laboratory mixture design procedure, the same used for conventional aggregates, should be used to optimize and verify fresh mixture properties, hardened results and admixture dosage rates for any potential mixture made with non-conventional aggregates before use in construction.
- The Shilstone method for optimizing concrete aggregate gradations with the coarseness/workability factor chart, maximum density gradation (0.45 power) chart and percent aggregate retained charts should be used to optimize the aggregate skeleton for any PCC paving mixture using non-conventional aggregates. This method ensures a dense graded aggregate blend that minimizes voids within the concrete, and an appropriate amount of cementitious material is used for the type of placement planned. Use of this methodology requires individual stockpiles of different sized aggregates to allow for variable blending rates of each aggregate in order to achieve a dense composite aggregate skeleton.
- Further study into the long-term performance of any PCC made with non-conventional materials is recommended to ensure that it is compatible with current DOD layered pavement design procedures (fatigue strength) and that it can provide a quality paving material that resists deterioration over its intended lifecycle.

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