OHIO DEPARTMENT OF TRANSPORTATION

OFFICE OF MATERIALS MANAGEMENT

CEMENT & CONCRETE SECTION

Comparison of Length Changes, Flexural Strengths and Compressive Strengths Between Concrete Made with Rounded Gravel and Concrete Made with Crushed Limestone

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Comparison of Length Change, Flexural Strengths and Compressive Strengths Between Concrete Made with Rounded Gravel and Concrete Made with Crushed Limestone

PURPOSE

The purpose of this evaluation was to determine what effects coarse aggregate shape and texture have on concrete regarding shrinkage, flexural strength, and compressive strength. Two (2) similar mixes were made where the coarse aggregate varied in each mix. A smooth textured, cubicle-shaped, rounded gravel, and a rough textured, angular-shaped, crushed limestone were used as the coarse aggregates in the mixes. The specific objectives were as follows:

1) Determine the length changes (shrinkage) of each mix then compare the results;

2) Determine flexural and compressive strengths for each mix then compare the results; and

3) Determine the relationship between flexural strength and compressive strength for each mix.

PROCEDURE

Two (2) mixes were made in the Concrete Lab using #57 sized coarse aggregates. The first mix was made using gravel as the coarse aggregate and the second mix was made using limestone as the coarse aggregate. Prior to mixing, the coarse aggregates were graded and the same coarse aggregate particle size distribution was used in each mix. Prisms, beams, and cylinders were then made from each mix and tested at various ages for length change, flexural strength, and compressive strength.

Materials - Material types and sources were as follows:

Gravel - #57 / Martin Marietta / Apple Grove
Limestone - #57 / Columbus Limestone / Columbus
Natural Sand - Olen Corp. / Columbus
Cement - Type I-II / Cemex
Air Entraining Agent - Sika AEA / Sika Corp**.**

Gradation - The coarse aggregate samples were obtained by OMM's Aggregate Section and segregated by sieve size using a mechanical shaker. Each sample was segregated into particles sizes retained on the 3/4", 1/2", 3/8", and #4 sieves.

Mix Design - The same standard ODOT Class C mix design was used for both mixes. Specific gravities and absorptions were obtained from the Aggregate Section. Moisture contents were determined by the Cement and Concrete Section. Appendix A contains the mix designs.

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Batching - The concrete made with gravel was mixed on 12/15/03 and the concrete made with limestone was mixed on 12/16/03. Natural sand from the same source was used in both mixes. The gradation of the coarse aggregate particle sizes used in each design was the same and is shown below in Table 1. Batch weights were adjusted from design weights based on actual specific gravities, absorptions, and moisture contents. Both mixes were made in accordance with ASTM C 192 at a 0.50 w/c with air entraining agent. Plastic concrete testing for slump, air content, and unit weight were performed in accordance with ASTM C 143, ASTM C 231, and ASTM C 138. Batch weights and plastic concrete test results are included in Appendix A.

TABLE 1 - COARSE AGGREGATE PARTICLE SIZE DISTRIBUTION				
Size	3/4"	1/2"	3/8"	#4 Sieve
Distribution	15%	42%	28%	15%

Making and Curing Specimens - All specimens were made and cured in accordance with ASTM C 192. Three (3) different types of specimens were made from each mix:

a) 3" x 4" x 15" long prisms were made for determining length change;
b) 3" x 4" x 15" long beams were made for determining flexural strength; and
c) 4" diameter x 8" long cylinders were made for determining compressive strength.

Length Change Testing - Length change testing was performed in accordance with ASTM C 157. Three (3) prisms were made from each mix and comparator readings were taken at 24 hours, 3 days, 7 days, 14 days, 28 days, and 56 days. Prisms were cured in a moist room for the first 24 hours, stripped, then placed in a lime bath. After the prisms reached 28 days of age, they were removed from the lime bath and air cured in the Lab. The assumed gauge length of each prism (i.e. distance between embedded studs) is 13 inches.

Flexural Strength Testing - Flexural strength testing was performed in accordance with ASTM C 78 (third point). Twenty-one (21) beams were made from each mix. Four (4) beams from each mix were tested at ages of 3 days, 7 days, and 14 days. The remaining nine (9) beams from each mix were tested at an age of 28 days.

Compressive Strength Testing - Compressive strength testing was performed in accordance with ASTM C 39. Unbonded caps were used in accordance with ASTM C 1231. Twenty-nine (29) cylinders were made from the gravel mix and thirty (30) cylinders were made from the limestone mix. Five (5) cylinders from each mix were tested at ages of 3 days, 7 days, and 14 days. Fourteen (14) cylinders from the gravel mix and fifteen (15) cylinders from the limestone mix were tested at an age of 28 days.

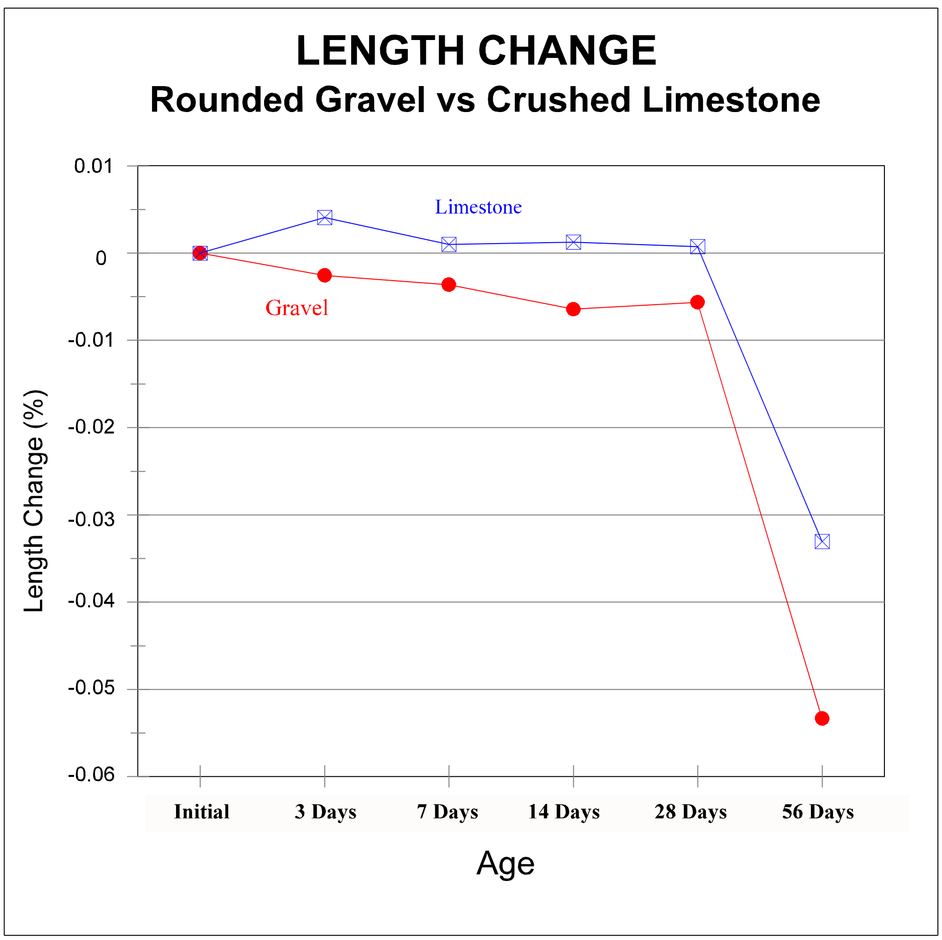
Comparison of Length Change, Flexural Strengths and Compressive Strengths Between Concrete Made with Rounded Gravel and Concrete Made with Crushed Limestone

RESULTS

Length Change Results

During the water cure phase (day 1 through day 28), the concrete made with limestone gained in length but the concrete made with gravel decreased in length. During the air cure phase (day 29 through day 56), both concretes exhibited a loss in length with the concrete made with gravel showing the larger loss. Both concretes exhibited an overall loss in length (day 56) with the concrete made with gravel showing approximately 38% more loss than the concrete made with limestone. The average length change results are included in Table 2 and shown on Graph 1. All length change data and calculations are included in Appendix B.

GRAPH 1



Comparison of Length Change, Flexural Strengths and Compressive Strengths Between Concrete Made with Rounded Gravel and Concrete Made with Crushed Limestone

TABLE 2 - LENGTH CHANGE RESULTS						
	Phase 1 (Water Cure)				**Phase 2 (Air Cure)**	**Overall**
Ages Compared	*3 day vs Initial (%)*	*7 day vs Initial (%)*	*14 day vs Initial (%)*	*28 day vs Initial (%)*	*56 day vs 28 day (%)*	*56 day vs Initial (%)*
Gravel	-0.00256	-0.00359	-0.00641	-0.00564	-0.04769	-0.05333
Limestone	+0.00410	+0.00103	+0.00128	+0.00077	-0.03385	-0.03308

Note - Results shown are averages. A "+" indicates a gain in length and a "-" indicates a decrease in length.

Strength Results

The *Flexural and Compressive Strengths* of both mixes increased with age. The concrete made with limestone exhibited higher flexural and compressive strengths than the concrete made with gravel at all ages tested. The average flexural strength results for both mixes at the ages tested are shown in Table 3 and on Graph 2. The average compressive strength results for both mixes are shown in Table 3 and on Graph 3. All strength results are shown in Appendix C.

The *Relationship Between Flexural and Compressive Strength* was determined using the following PCA recommended equation: $F_s = Z \times (C_s)^{1/2}$

F_s = Flexural Strength (lb/in^2)
C_s = Compressive Strength (lb/in^2)
Z = Flexural-Compressive Coefficient

Since both flexural strength and compressive strength were determined, the equation was re-arranged to solve for Z: $Z = F_s / (C_s)^{1/2}$

The average values for Z were determined to be as follows:

Z (Gravel) = 10.2
Z (Limestone) = 10.9

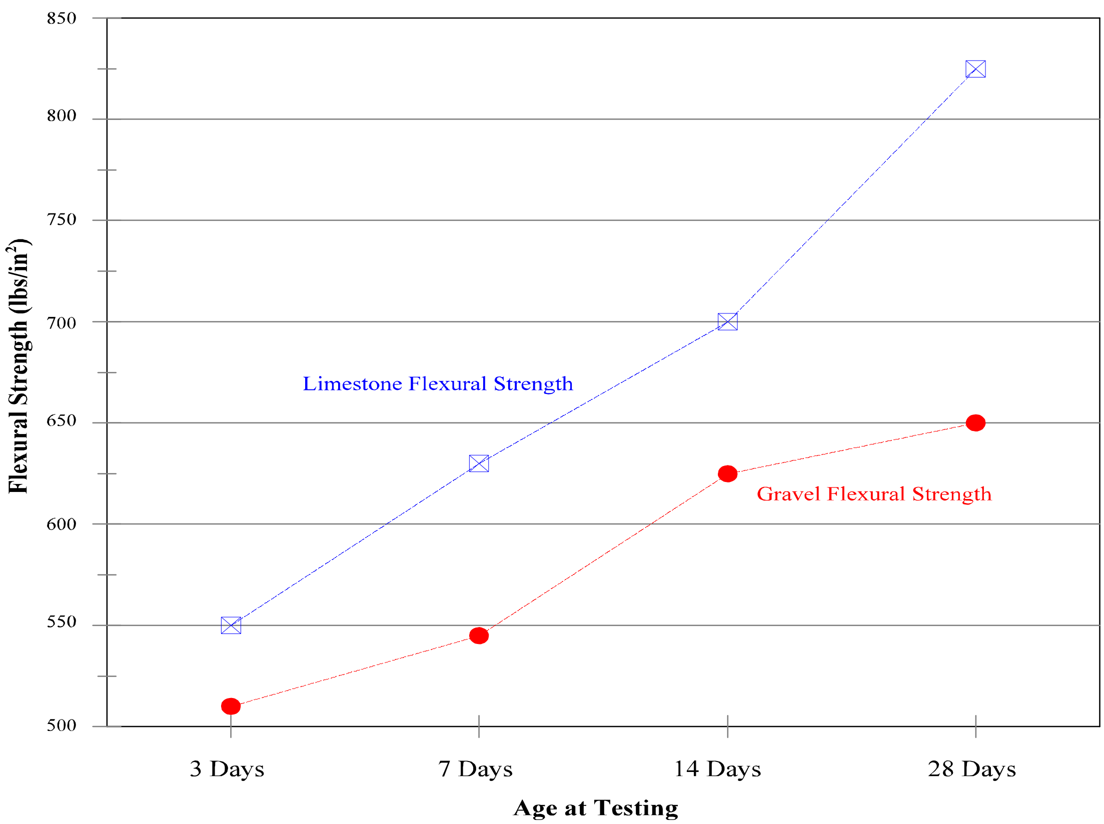
The calculated values for the coefficient Z for both mixes at all ages tested are shown in Table 3. All calculations for the coefficient Z are shown in Appendix C.

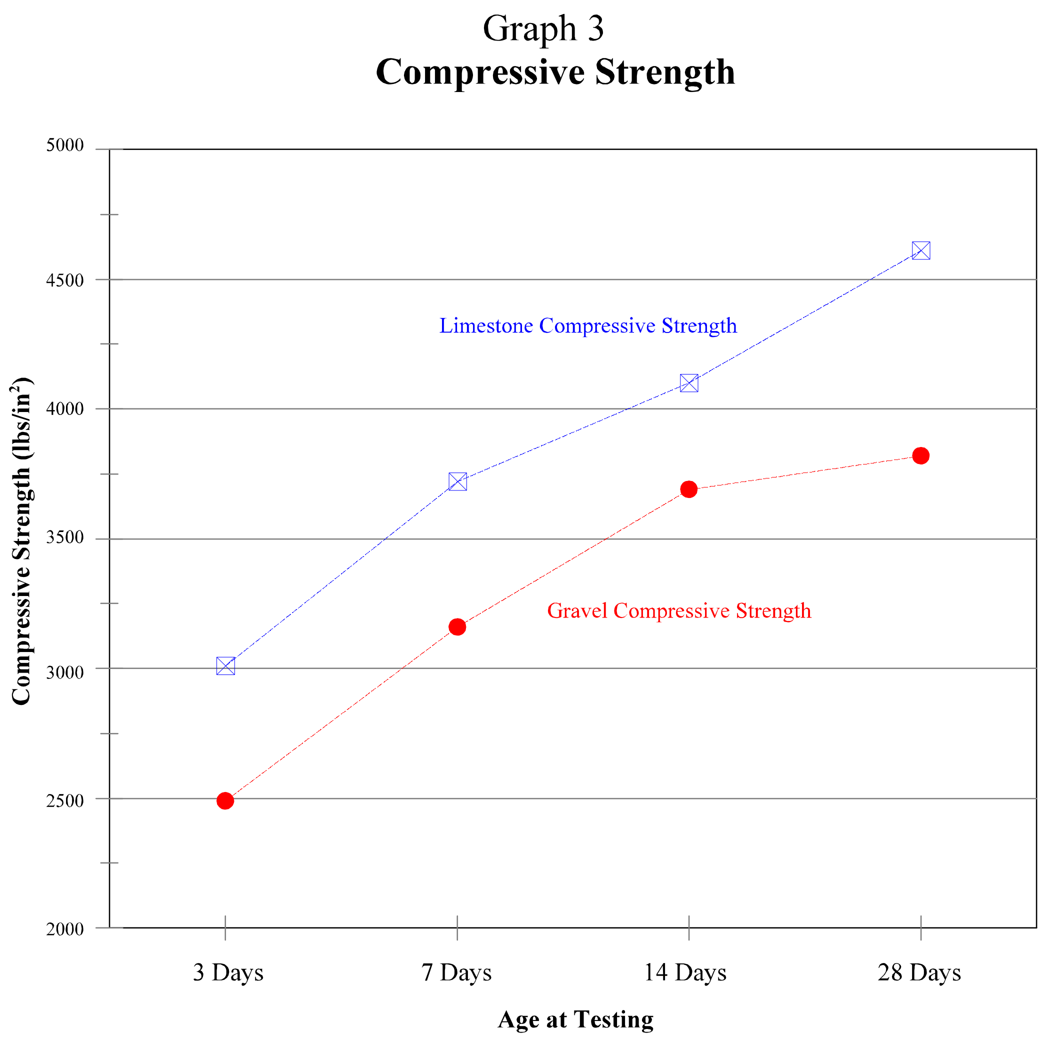
Comparison of Length Change, Flexural Strengths and Compressive Strengths Between Concrete Made with Rounded Gravel and Concrete Made with Crushed Limestone

TABLE 3 - FLEXURAL AND COMPRESSIVE STRENGTHS AND RELATIONSHIP						
	GRAVEL MIX			LIMESTONE MIX		
Age at Testing	*Flexural Strength (lbs/in^2)*	*Compressive Strength (lbs/in^2)*	*Flexural-Compressive Coefficient (Z)*	*Flexural Strength (lbs/in^2)*	*Compressive Strength (lbs/in^2)*	*Flexural-Compressive Coefficient (Z)*
3 Days	510	2,490	10.2	550	3,010	0.183
7 Days	545	3,160	9.7	630	3,720	0.169
14 Days	625	3,690	10.3	700	4,100	0.171
28 Days	650	3,820	10.5	825	4,610	0.179

Note - Strength results shown are averages.

Graph 2
Flexural Strength





CONCLUSIONS

A rounded gravel and a crushed limestone were used as coarse aggregates in similar concrete mixes. Both concretes were evaluated for length change, flexural strength, and compressive strength. The gravel had a cubicle-shape with rounded edges and a smooth surface texture. This is typical of rounded gravels because they are mined from river beds where erosion and time make them smooth and round. The limestone had an angular-shape with sharp edges and a rough surface texture. This is typical of crushed limestones due to the crushing that occurs during the manufacturing process.

The purpose of this evaluation was to determine what impact that the surface texture and shape of a coarse aggregate's particles have on a concrete regarding length change, flexural strength, and compressive strength. Poor aggregate strength could also have an impact, but the aggregates used in this evaluation had performed well in the past and were not considered to have poor strength.

Comparison of Length Change, Flexural Strengths and Compressive Strengths Between Concrete Made with Rounded Gravel and Concrete Made with Crushed Limestone

The **surface texture** of the coarse aggregate used in a concrete should affect the internal friction of the concrete. Internal friction is the friction between the coarse aggregate particles and the hardened cement paste.

> The internal friction should have an impact on length change, flexural strength, and compressive strength. Concretes with more internal friction should have less change in length, higher flexural strengths, and higher compressive strengths than concretes with less internal friction because the internal friction should provide resistance to the stresses created by the contraction or expansion of the concrete and to the stresses created by flexural and compressive loads. Internal friction is dependent upon the surface texture of a coarse aggregate. In this evaluation, the rough surface texture of the limestone aggregate should provide more internal friction than the smooth texture of the gravel aggregate. *The expected outcome is that a higher internal friction in the limestone mix will result in less length change, higher flexural strength, and higher compressive strength than the gravel mix.*

The **shape** of the coarse aggregate used in a concrete should affect the bond strength and the amount of aggregate overlap. Bond strength is the strength of the bond between the cement paste and the coarse aggregate particles. Aggregate overlap is determined by how much the coarse aggregate particles overlap each other (how they are positioned with respect to each other in the concrete).

> Bond strength should have an impact on length change, flexural strength, and compressive strength. Concretes with a strong bond should have less change in length, higher flexural strengths, and higher compressive strengths because a strong bond should provide more resistance than a weak bond to the stresses created by the contraction or expansion of the concrete and the stresses created by flexural and compressive loads. Bond strength depends upon the amount of surface area of a coarse aggregate that is available for bonding with the cement paste. In this evaluation, both coarse aggregates have the same particle size (#57), but the angular-shape of the limestone aggregate should provide more surface area for bonding than the cubicle-shape of the gravel aggregate. *The expected outcome is that a higher bond strength in the limestone mix will result in less length change, higher flexural strength, and higher compressive strength than the gravel mix.*

> Aggregate overlap in a concrete should have an impact on the flexural strength. Concretes with more aggregate overlap should have higher flexural strengths than concretes with less aggregate overlap because aggregate overlap should help resist the stresses created by a flexural load. If the compressive strength of a concrete is not affected at all by aggregate overlap, or affected to a lesser degree than flexural strength, the flexural-compressive coefficient (Z) of a concrete with more aggregate overlap should be higher than that of a concrete with less aggregate overlap. In this evaluation, the angular-shape of the limestone aggregate should provide more aggregate overlap than the cubicle-shape of the gravel aggregate. *The expected outcome is that the higher aggregate overlap in the limestone mix will result in a higher flexural-compressive coefficient (Z) than that of the gravel mix.*

In summary, the limestone mix should exhibit less length change, higher flexural strength, higher compressive strength, and a higher flexural-compressive coefficient (Z) than the gravel mix. The rough surface texture of the limestone aggregate should provide more internal friction than the smooth surface texture of the gravel aggregate. The angular-shape of the limestone aggregate should provide more surface area for bonding resulting in a higher bond strength than the cubicle-shape of the gravel aggregate. Higher internal friction and higher bond strength within the limestone mix should resist the stresses from length change, flexural loads, and compressive loads better than the gravel mix. In addition, the limestone mix should have a higher flexural-compressive coefficient (Z) than the gravel mix due to more aggregate overlap. Table 4 summarizes the test results of this evaluation.

TABLE 4 - SUMMARY OF RESULTS

	GRAVEL MIX				LIMESTONE MIX			
Age at Testing	*Flexural Strength (lbs/in^2)*	*Compressive Strength (lbs/in^2)*	*Flexural-Compressive Coefficient (Z)*	*Length Change (%)*	*Flexural Strength (lbs/in^2)*	*Compressive Strength (lbs/in^2)*	*Flexural-Compressive Coefficient (Z)*	*Length Change (%)*
3 Days	510	2,490	10.2	-0.00256	550	3,010	10.0	+0.00410
7 Days	545	3,160	9.7	-0.00359	630	3,720	10.3	+0.00103
14 Days	625	3,690	10.3	-0.00641	700	4,100	10.9	+0.00128
28 Days	650	3,820	10.5	-0.00564	825	4,610	12.2	+0.00077
56 Days	N/A	N/A	N/A	-0.05333	N/A	N/A	N/A	-0.03308
Average	N/A	N/A	10.2	N/A	N/A	N/A	10.9	N/A

In conclusion, the test results for length change were lower in the limestone mix as expected, the test results for both flexural strength and compressive strength were higher in the limestone mix as expected, and the limestone mix had a higher flexural-compressive coefficient as expected.

The rougher surface texture of the limestone aggregate created more internal friction in the limestone mix than that of the mix containing the smooth textured gravel aggregate. The higher internal friction in the limestone mix when compared to the gravel mix *resulted in the limestone mix having better resistance to length change and higher flexural and compressive strengths.*

The angular shape of the limestone aggregate gave it more surface area for bonding with the cement paste and more aggregate overlap than did the rounded shape of the gravel aggregate. The larger surface area of the limestone aggregate resulted in a stronger bond between the aggregate and paste. The stronger bond in the limestone mix when compared to the gravel mix *resulted in the limestone mix having better resistance to length change and higher flexural and compressive strengths.* The increased aggregate overlap of the limestone aggregate when compared to the gravel aggregate *resulted in the limestone mix having higher flexural strengths and a higher flexural-compressive coefficient (Z).*

APPENDIX A

MIX DESIGN, BATCH WEIGHTS AND PLASTIC CONCRETE TEST RESULTS

TABLE A1 - STANDARD ODOT CLASS C MIX DESIGN*				
Aggregate Type	*Fine Aggregate (SSD Weight in lbs)*	*Coarse Aggregate (SSD Weight in lbs)*	*Cement (lbs)*	*Max w/c Ratio*
Gravel	1,160	1,735	600	0.50
Limestone	1,285	1,630	600	0.50

* From Table 499.03-2 of ODOT's 2002 Construction and Material Specifications

TABLE A2 - GRAVEL MIX DESIGN AND BATCH WEIGHTS			
Mix Ingredient	*Design Weight (SSD) lbs / yd^3*	*Batch Weight lbs / yd^3*	*Batch Weight based on 0.186 yd^3*
3/4" coarse agg.	15 % of 1,735 = 260.25	253.1	47.1
1/2" coarse agg.	42 % of 1,735 = 728.70	708.7	131.8
3/8" coarse agg.	28 % of 1,735 = 485.80	472.4	87.9
#4 coarse agg.	15 % of 1,735 = 260.25	253.1	47.1
sand	1,160	1195.4	222.3
cement	600	600	111.6
water (w/c = 0.50)	300	246.7	45.9
Specific Gravities (SG), Absorptions (ABS), and Moisture Contents			
Item	*Design*	*Actual*	
SG coarse agg.	2.62 lbs / ft^3	2.534 lbs / ft^3	
ABS coarse agg.	N/A	2.00 %	
Moisture coarse agg.	N/A	2.56 %	
SG fine agg.	2.62 lbs / ft^3	2.61 lbs / ft^3	
ABS fine agg.	N/A	1.65 %	
Moisture fine agg.	N/A	5.15 %	

APPENDIX A

MIX DESIGN, BATCH WEIGHTS AND PLASTIC CONCRETE TEST RESULTS

TABLE A3 - LIMESTONE MIX DESIGN AND BATCH WEIGHTS

Mix Ingredient	*Design Weight (SSD) lbs / yd^3*	*Batch Weight lbs / yd^3*	*Batch Weight based on 0.186 yd^3*
3/4" coarse agg.	15 % of 1,630 = 244.50	242.3	45.1
1/2" coarse agg.	42 % of 1,630 = 684.60	678.3	126.2
3/8" coarse agg.	28 % of 1,630 = 456.40	452.2	84.1
#4 coarse agg.	15 % of 1,630 = 244.50	242.3	45.1
sand	1,285	1318.5	245.2
cement	600	600	111.6
water (w/c = 0.50)	300	276.5	51.4

Specific Gravities (SG), Absorptions (ABS), and Moisture Contents

Item	*Design*	*Actual*
SG coarse agg.	2.68 lbs / ft^3	2.687 lbs / ft^3
ABS coarse agg.	N/A	1.26 %
Moisture coarse agg.	N/A	0.07 %
SG fine agg.	2.62 lbs / ft^3	2.61 lbs / ft^3
ABS fine agg.	N/A	1.65 %
Moisture fine agg.	N/A	4.7 %

** - Batch weights adjusted from design weights based on actual specific gravities, absorptions, and moisture contents.

TABLE A4 - PLASTIC CONCRETE TEST RESULTS

Coarse Aggregate Type	*Slump*	*Air Content*	*Unit Weight*
Gravel	7 inches	9.5 %	133.5 lbs/ft^3
Crushed Limestone	6.5"	10.5 %	136.1 lbs/ft^3

APPENDIX B

LENGTH CHANGE TEST RESULTS

TABLE B1 - COMPARATOR READINGS						
Age at Reading	*Initial (24 hour)*	*3 days*	*7 days*	*14 days*	*28 days*	*56 days*
Gravel Prism #1	0.0755	0.0751	0.0749	0.0748	0.0749	0.0685
Gravel Prism #2	0/0379	0.0375	0.0375	0.0371	0.0368	0.0306
Gravel Prism #3	0.0330	0.0328	0.0326	0.0320	0.0325	0.0265
Limestone Prism #1	0.0340	0.0346	0.0340	0.0346	0.0342	0.0299
Limestone Prism #2	0.0573	0.0577	0.0575	0.0572	0.0572	0.0526
Limestone Prism #3	0.0757	0.0763	0.0759	0.0757	0.0759	0.0716

TABLE B2 - LENGTH CHANGE CALCULATIONS	
Ages Compared	*Calculation*
3 day vs Initial	100% x (3 day reading - initial reading) / 13 inches
7 day vs Initial	100% x (7 day reading - initial reading) / 13 inches
14 day vs Initial	100% x (14 day reading - initial reading) / 13 inches
28 day vs Initial	100% x (28 day reading - initial reading) / 13 inches
56 day vs 28 day	100% x (56 day reading - 28 day reading) / 13 inches
56 day vs Initial	100% x (56 day reading - initial reading) / 13 inches

NOTE - The assumed length between the studs in each prism (i.e. gauge length) is 13 inches.

APPENDIX B

LENGTH CHANGE TEST RESULTS

TABLE B3 - LENGTH CHANGE RESULTS

	Phase 1 (Water Cure)				*Phase 2* (Air Cure)	*Overall*
	3 days vs Initial (%)	7 days vs Initial (%)	14 days vs Initial (%)	28 days vs Initial (%)	56 days vs 28 days (%)	56 days vs Initial (%)
Gravel Prism #1	-0.00308	-0.00462	-0.00538	-0.00462	-0.04923	-0.05385
Gravel Prism #2	-0.00308	-0.00308	-0.00615	-0.00846	-0.04769	-0.05615
Gravel Prism #3	-0.00154	-0.00308	-0.00769	-0.00385	-0.04615	-0.05000
Limestone Prism #1	+0.00462	+0.00000	+0.00462	+0.00154	-0.03308	-0.03154
Limestone Prism #2	+0.00308	+0.00154	-0.00077	-0.00077	-0.03538	-0.03615
Limestone Prism #3	+0.00462	+0.00154	+0.00000	+0.00154	-0.03308	-0.03154
Gravel Prism Average	**-0.00256**	**-0.00359**	**-0.00641**	**-0.00564**	**-0.04769**	**-0.05333**
Limestone Prism Average	**+0.00410**	**+0.00103**	**+0.00128**	**+0.00077**	**-0.03385**	**-0.03308**

Note - A “+” indicates a gain in length and a “-“ indicates a decrease in length.

APPENDIX C

FLEXURAL AND COMPRESSIVE STRENGTH RESULTS AND RELATIONSHIP

TABLE C1 - GRAVEL MIX FLEXURAL STRENGTH RESULTS		
AGE	LOAD AT FAILURE	FLEXURAL STRENGTH
3 Days (12/18/03)	2,000 lbs	500 lbs/in^2
	2,180 lbs	545 lbs/in^2
	1,960 lbs	490 lbs/in^2
	2,000 lbs	500 lbs/in^2
3 Day Average	**2,035 lbs**	**510 lbs/in^2**
7 Days (12/22/03)	2,230 lbs	560 lbs/in^2
	1,840 lbs	460 lbs/in^2
	2,400 lbs	600 lbs/in^2
	2,240 lbs	560 lbs/in^2
7 Day Average	**2,180 lbs**	**545 lbs/in^2**
14 Days (12/29/03)	2,350 lbs	590 lbs/in^2
	2,320 lbs	580 lbs/in^2
	2,600 lbs	650 lbs/in^2
	2,700 lbs	675 lbs/in^2
14 Day Average	**2490 lbs**	**625 lbs/in^2**
28 Days (01/12/04)	2,430 lbs	610 lbs/in^2
	2,510 lbs	630 lbs/in^2
	2,680 lbs	670 lbs/in^2
	2,400 lbs	600 lbs/in^2
	2,640 lbs	660 lbs/in^2
	2,450 lbs	615 lbs/in^2
	2,760 lbs	690 lbs/in^2
	2,820 lbs	705 lbs/in^2
	2,580 lbs	645 lbs/in^2
28 Day Average	**2,590 lbs**	**650 lbs/in^2**

APPENDIX C

FLEXURAL AND COMPRESSIVE STRENGTH RESULTS AND RELATIONSHIP

TABLE C2 - GRAVEL MIX COMPRESSIVE STRENGTH RESULTS		
AGE	LOAD AT FAILURE	COMPRESSIVE STRENGTH
3 Days (12/18/03)	32,100 lbs	2,550 lbs/in^2
	30,600 lbs	2,430 lbs/in^2
	31,600 lbs	2,510 lbs/in^2
	32,500 lbs	2,590 lbs/in^2
	29,700 lbs	2,360 lbs/in^2
3 Day Average	**31,300 lbs**	**2,490 lbs/in^2**
7 Days (12/22/03)	39,400 lbs	3,130 lbs/in^2
	39,700 lbs	3,160 lbs/in^2
	39,600 lbs	3,150 lbs/in^2
	39,900 lbs	3,170 lbs/in^2
	40,200 lbs	3,200 lbs/in^2
7 Day Average	**39,760 lbs**	**3,160 lbs/in^2**
14 Days (12/29/03)	46,500 lbs	3,700 lbs/in^2
	46,100 lbs	3,670 lbs/in^2
	46,600 lbs	3,710 lbs/in^2
	46,100 lbs	3,670 lbs/in^2
	46,800 lbs	3,720 lbs/in^2
14 Day Average	**46,420 lbs**	**3,690 lbs/in^2**
28 Days (01/12/04)	47,200 lbs	3,750 lbs/in^2
	50,500 lbs	4,020 lbs/in^2
	47,600 lbs	3,790 lbs/in^2
	48,100 lbs	3,830 lbs/in^2
	48,900 lbs	3,890 lbs/in^2
	48,400 lbs	3,850 lbs/in^2
	45,500 lbs	3,620 lbs/in^2
	46,700 lbs	3,720 lbs/in^2
	49,500 lbs	3,940 lbs/in^2
	46,500 lbs	3,700 lbs/in^2
	49,000 lbs	3,900 lbs/in^2
	47,500 lbs	3,780 lbs/in^2
	49,600 lbs	3,950 lbs/in^2
	47,400 lbs	3,770 lbs/in^2
28 Day Average	**48,030 lbs**	**3,820 lbs/in^2**

APPENDIX C

FLEXURAL AND COMPRESSIVE STRENGTH RESULTS AND RELATIONSHIP

TABLE C3 - LIMESTONE MIX FLEXURAL STRENGTH RESULTS		
AGE	LOAD AT FAILURE	FLEXURAL STRENGTH
3 Days (12/19/03)	2,210 lbs	555 lbs/in^2
	2,200 lbs	550 lbs/in^2
	2,280 lbs	570 lbs/in^2
	2,030 lbs	510 lbs/in^2
3 Day Average	**2,180 lbs**	**550 lbs/in^2**
7 Days (12/23/03)	2,630 lbs	660 lbs/in^2
	2,610 lbs	655 lbs/in^2
	2,600 lbs	650 lbs/in^2
	2,210 lbs	555 lbs/in^2
7 Day Average	**2,510 lbs**	**630 lbs/in^2**
14 Days (12/30/03)	2,990 lbs	750 lbs/in^2
	2,940 lbs	735 lbs/in^2
	2,620 lbs	655 lbs/in^2
	2,630 lbs	660 lbs/in^2
14 Day Average	**2,800 lbs**	**700 lbs/in^2**
28 Days (01/13/04)	3,540 lbs	885 lbs/in^2
	3,350 lbs	840 lbs/in^2
	3,350 lbs	840 lbs/in^2
	3,610 lbs	900 lbs/in^2
	3,340 lbs	835 lbs/in^2
	3,430 lbs	860 lbs/in^2
	2,770 lbs	695 lbs/in^2
	3,060 lbs	765 lbs/in^2
	3,130 lbs	785 lbs/in^2
28 Day Average	**3,290 lbs**	**825 lbs/in^2**

APPENDIX C

FLEXURAL AND COMPRESSIVE STRENGTH RESULTS AND RELATIONSHIP

TABLE C4 - LIMESTONE MIX COMPRESSIVE STRENGTH RESULTS		
AGE	LOAD AT FAILURE	COMPRESSIVE STRENGTH
3 Days (12/18/03)	38,500 lbs	3,060 lbs/in^2
	37,200 lbs	2,960 lbs/in^2
	39,200 lbs	3,120 lbs/in^2
	37,300 lbs	2,970 lbs/in^2
	36,700 lbs	2,920 lbs/in^2
3 Day Average	**37,800 lbs**	**3,010 lbs/in^2**
7 Days (12/22/03)	47,200 lbs	3,750 lbs/in^2
	47,000 lbs	3,740 lbs/in^2
	46,300 lbs	3,680 lbs/in^2
	45,700 lbs	3,640 lbs/in^2
	46,400 lbs	3,780 lbs/in^2
7 Day Average	**46,500 lbs**	**3,720 lbs/in^2**
14 Days (12/29/03)	49,600 lbs	3,950 lbs/in^2
	51,400 lbs	4,090 lbs/in^2
	52,600 lbs	4,180 lbs/in^2
	52,000 lbs	4,140 lbs/in^2
	51,900 lbs	4,130 lbs/in^2
14 Day Average	**51,500 lbs**	**4,100 lbs/in^2**
28 Days (01/12/04)	56,400 lbs	4,490 lbs/in^2
	56,400 lbs	4,490 lbs/in^2
	57,200 lbs	4,550 lbs/in^2
	57,400 lbs	4,570 lbs/in^2
	58,500 lbs	4,650 lbs/in^2
	57,900 lbs	4,610 lbs/in^2
	56,700 lbs	4,510 lbs/in^2
	58,000 lbs	4,610 lbs/in^2
	58,400 lbs	4,650 lbs/in^2
	57,100 lbs	4,540 lbs/in^2
	66,600 lbs	5,300 lbs/in^2
	56,400 lbs	4,490 lbs/in^2
	58,000 lbs	4,610 lbs/in^2
	57,300 lbs	4,560 lbs/in^2
	56,800 lbs	4,520 lbs/in^2
28 Day Average	**57,900 lbs**	**4,610 lbs/in^2**

APPENDIX C

FLEXURAL AND COMPRESSIVE STRENGTH RESULTS AND RELATIONSHIP

$Z = F_s / (C_s)^{1/2}$

F_s = Flexural Strength (lb/in^2)
C_s = Compressive Strength (lb/in^2)
Z = Flexural-Compressive Coefficient

GRAVEL MIX CALCULATIONS FOR Z

$Z_{3\ days} = F_s / (C_s)^{1/2} = 510\ lb/in^2 / (2{,}490\ lb/in^2)^{½} = 10.2$

$Z_{7\ days} = F_s / (C_s)^{1/2} = 545\ lb/in^2 / (3{,}160\ lb/in^2)^{½} = 9.7$

$Z_{14\ days} = F_s / (C_s)^{1/2} = 625\ lb/in^2 / (3{,}690\ lb/in^2)^{½} = 10.3$

$Z_{28\ days} = F_s / (C_s)^{1/2} = 650\ lb/in^2 / (3{,}820\ lb/in^2)^{½} = 10.5$

$Z_{AVG} = (10.2 + 9.7 + 10.3 + 10.5) / 4 = 10.2$

LIMESTONE MIX CALCULATIONS FOR Z

$Z_{3\ days} = F_s / (C_s)^{1/2} = 550\ lb/in^2 / (3{,}010\ lb/in^2)^{½} = 10.0$

$Z_{7\ days} = F_s / (C_s)^{1/2} = 630\ lb/in^2 / (3{,}720\ lb/in^2)^{½} = 10.3$

$Z_{14\ days} = F_s / (C_s)^{1/2} = 700\ lb/in^2 / (4{,}100\ lb/in^2)^{½} = 10.9$

$Z_{28\ days} = F_s / (C_s)^{1/2} = 825\ lb/in^2 / (4{,}610\ lb/in^2)^{½} = 12.2$

$Z_{AVG} = (10.0 + 10.3 + 10.9 + 12.2) / 4 = 10.9$