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EFFECTS OF CHANGES IN TOTAL AGGREGATE GRADATION ON PORTLAND CEMENT CONCRETE PROPERTIES - PHASE II DURABILITY

FINAL REPORT

WISCONSIN TECHNOLOGY ADVANCEMENT DEPARTMENT OF TRANSPORTATION

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16. Abstract

Transportation-related agencies are experimenting with increased control of aggregate gradation in their concrete pavement specifications. There is anecdotal evidence that shows that total aggregate gradation can be optimized to yield improved concrete performance during construction and service life. Strong scientific data are less numerous in supporting this idea because of the variability in aggregates that can occur and the practical considerations in avoiding waste particle sizes. This laboratory study examined the influence of total aggregate gradation on the freeze-thaw durability of concrete test specimens that employed a variety of sedimentary and igneous aggregates common in Wisconsin. Optimized gradations consisted of increased amounts of aggregate particles in the No. 4 to No. 16 sieve size range and decreased amounts of fines in the No. 50 to No. 200 sieve size range. A near-gap gradation was fabricated by removing some particles in the No. 4 to No. 16 sieve size range and increasing the amount of fine material in the No. 30 to No. 100 sieve size range. Several methodologies and practical considerations were considered in establishing the aggregate gradations. A control gradation utilized a 60-40 blend of coarse/fine aggregate with gradations determined by the naturally occurring particle sizes. The concrete specimens prepared in this study were subject to strength, shrinkage, permeability and accelerated-freeze-thaw testing. All concretes showed excellent freeze-thaw durability. The optimized gradation mixes did not show consistently improved performance compared to the control mixes. The near-gap mixes showed reduced strength, reduced freeze-thaw durability and increased shrinkage.

17. Key Words	18. Distribution Statement
Portland Cement Concrete, Aggregates, Gradations, Freeze/Thaw Durability,	Unlimited

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Effect of Changes in Total Aggregate Gradation on Portland Cement Concrete Properties - Phase II Durability

FINAL REPORT # WI/SPR-02-99
WisDOT Study # 94-15

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1. Problem Statement

Current mix design practice allows a wide variation in total aggregate gradation without consideration of the effect on concrete properties. Results of Phase I of this study suggested that more precise controls on the aggregate gradation could lead to improvements in some Portland cement concrete (PCC) properties.

2. Objectives and Scope of the Study

The overall objective that encompassing this study and other related efforts is to develop a more rational approach to aggregate proportioning in PCC. Specific objectives of this study include:
1) To evaluate the effects of changes in total aggregate gradation on concrete freeze-thaw durability using a range of aggregate types commonly used for WisDOT projects;
2) To evaluate the correlation of freeze-thaw durability with other measured PCC properties.

3. Background

There are a growing number of transportation-related agencies that are experimenting with increased control of aggregate gradation in their specifications. Minnesota (1996) provides an optional incentive of $0.50 per cubic yard of concrete if the mix aggregate gradation meets the following requirements: "The combined aggregates shall be well graded from the coarsest to the finest with no more than 18 percent nor less than 8 percent of the combines aggregate retained on any individual sieve with the exceptions that the No. 50 sieve may have less than 8% retained, and the coarsest sieve may have less than 8 percent retained." This requirement applies to all sieve sizes listed in the MinnDOT Job Mix Formula except the 1-1/4" and 5/8" sieves.

The US Air Force Concrete Pavement Specifications from the Airfield Task Group (USAF 1997) have adopted a method from Shilstone (1990). As described below, a coarseness factor and a workability factor are primary control parameters in this method. The USAF specification limits the coarseness factor to greater than 30 and less than or equal to 80. Mixes placed mechanically should plot just above but not on the coarseness factor chart trend line. Mixtures that are placed by hand should plot 4 to 6 points above the trendline.

Shilstone (1990) has presented a practitioner's rationale and case histories that optimizing total aggregate gradation improves mix workability, mix durability and provides a more reliable basis for mix design. This methodology for optimizing concrete mixtures is based upon 1) aggregate particle size distribution, 2) a coarseness factor, 3) a workability factor, and 4) a mortar factor. A definite formula for optimizing particle distribution has not been presented by Shilstone, but it appears that the examples of optimized particle distribution offered by Shilstone are similar to the 0.45 power curve dating back to work by Fuller and Thompson (1907), yet significant differences exist. Precisely how Shilstone has computed the optimal particle distribution is not described in his publications (Shilstone 1990) and the actual algorithm is likely proprietary information existing within his computer software. Shilstone's methodology does not rely on particle size distribution alone. The percent of material larger than the No. 8 sieve retained on or above the 9.5-mm (3/8-in.) sieve is described as the *coarseness factor*. The *workability factor* is the percent of material passing the No. 8 sieve. The *mortar factor* is the percent mortar as defined by the fine aggregate passing the No. 8 sieve and the paste. The coarseness and workability factor are assessed together in a coarseness factor chart presented by Shilstone. This chart reflects the need to balance the fine aggregate with the larger inert aggregate particles. Too much aggregate passing the No. 8 sieve will lead to a sticky mix with a high water demand. Too little sand will create a harsh mix with other finishing problems.

Phase I of this study explored the potential benefits of using a Shilstone-type methodology in Wisconsin (Cramer et al. 1996). The effects of changes in total aggregate gradation were studied by monitoring: ease of placement, unit weight, change in w/c at constant slump, change in slump at constant w/c, compressive strength, shrinkage, and possible segregation under vibration. Durability was not studied. The study examined laboratory and two field trials - a bridge deck and a pavement. The greatest benefits were achieved with the field pavement mix. Compared to a near gap-graded mix, an optimized mix in some circumstances resulted in:

- increased compressive strength (10 to 20 percent)
- reduced water demand at comparable slumps (up to 15 percent)
- reduced amounts of air entraining agent to achieve comparable air content
- significantly reduced segregation and higher density surfaces following extended vibration (1 to 3 minutes)

Unpublished work by Basri (1996) found that the trend bar identifying preferred gradations in the coarseness factor chart by Shilstone did not always result in workable mixes. Some gradations would yield a harsh and less workable mix. Combined and intermediate values of fineness modulus as originally proposed by Abrams and Walker were reproposed as an effective way to define optimal gradations. Basri's work emphasized the complex interaction between reduced water content in optimal mixes and workability. The precision of the slump test was again found to be inadequate for distinguishing workability in these mixes. A modified, but simple flow table test was proposed as a more effective alternative.

4. Methodology and Testing Regime

Aggregates and corresponding mixes selected for study are shown in Table 1. Aggregates were obtained from both Northern and Southern Wisconsin to provide research results that represent a large portion of the State. Two fine aggregates were obtained, one from the Madison area in Southern Wisconsin and one from the Eau Claire area in Northern Wisconsin. Four coarse aggregate sources were used conforming to WisDOT No. 1 and No. 2 stone. Gravel and crushed stone sources in the Madison area provided limestone aggregates from Southern Wisconsin. A source in the Eau Claire area provided igneous gravel aggregate and a source in the Wisconsin Rapids area provided igneous crushed stone.

Table 1. Aggregates Used in This Study

Aggregate Source	**Crushed Stone**		**Gravel**	
Mineralogical Type	Sedimentary	Igneous	Sedimentary	Igneous
Concrete Mixes	1. Control	4. Control	7. Control	10. Control
by Gradation	2. Near-Gap	5. Near-Gap	8. Near-Gap	11. Near-Gap
	3. Optimized	6. Optimized	9. Optimized	12. Optimized

Each aggregate source was sieved and separated into its respective particle size categories. Recombining the size constituents, a total aggregate gradation was then generated. A major concern in the research was that artificial combinations of particle sizes that differ significantly from the natural particle size distribution could generate large amounts of waste material, rendering some gradations impractical in even a research environment. Considerable effort was expended in attempting to define an optimized gradation within the context of practical restraints. The work of Shilstone was examined closely as well as the work of others. The concepts of optimal particle packing and lower permeability have been discussed in the literature but experimental evidence of the influence of these factors on strength and durability are scarce. The optimized gradation developed from combined criteria including Shilstone's coarseness factor chart, practical concerns to minimize waste, and Fuller-Thompson optimized particle packing. The practical result of the optimizing process was to increase the amount of particles in the No. 4 to No. 16 sieve size range and to decrease the amount of fines in the No. 50 to No. 200 sieve size range. The near-gap gradation involved removing particles in the No. 4 to No. 16 sieve size range and increasing the amount of fine material in the No. 30 to No. 100 sieve size range. The near-gap gradation was selected as an extreme gradation with regards to a lack of particles in the intermediate size range, but still met the requirements of the WisDOT Standard Specifications (State of Wisconsin DOT 1996).

After consultation with the Technical Oversight Committee the blends of aggregate shown in Figs. 1-4 were adopted for the research. These gradations presented a compromise in minimizing the generation of waste particle sizes and offering meaningful differences in gradation. The near-gap gradation was the same for all aggregate sources. The optimized gradation was identical for the Southern Wisconsin aggregates and differed only slightly for the Northern Wisconsin aggregates. The optimized gradations were essentially a Fuller power curve gradation using an exponent 0.45, but with reductions in the amounts of p100 material (Fuller and Thompson 1907). In terms of Shilstone's Coarseness factor chart, the selected mixes were positioned relative to the trend bar as shown in Figure 5. A value in or slightly above the trend bar is considered optimal with larger distances from the trend bar considered less optimal.

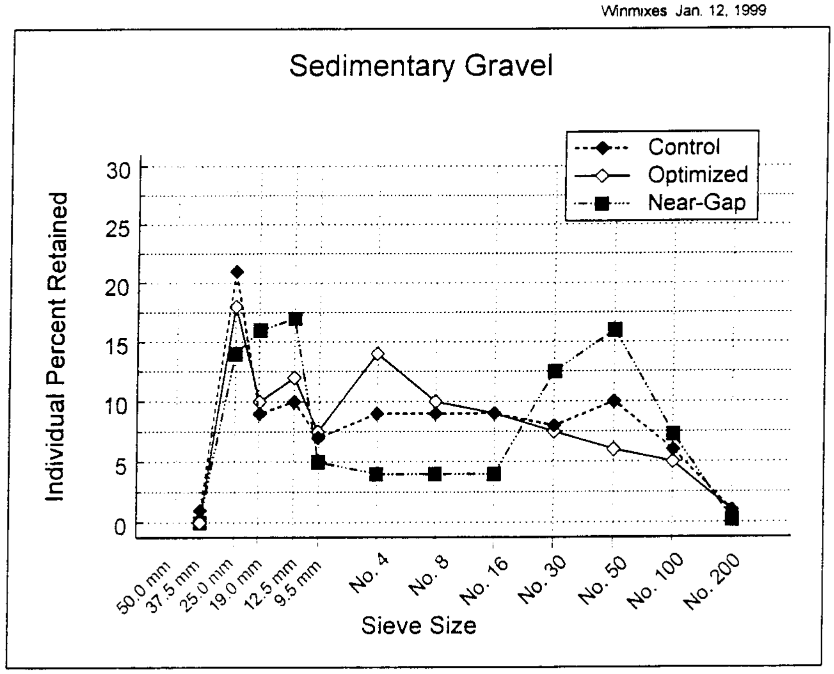

Figure 1. Gradations Selected for the Concrete Mixes with Sedimentary Gravel Aggregates

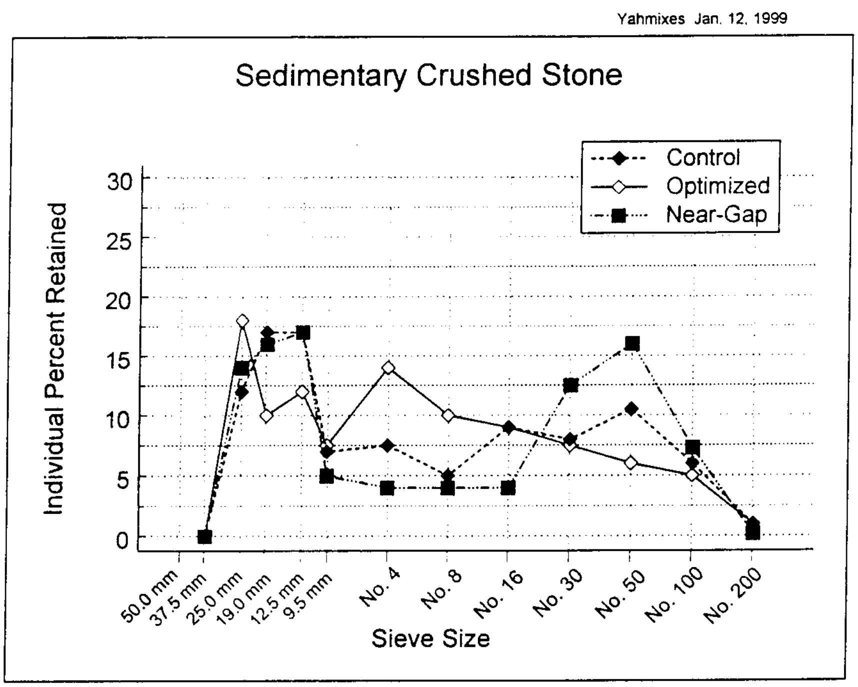

Figure 2. Gradations Selected for the Concrete Mixes with Sedimentary Crushed Stone Aggregates

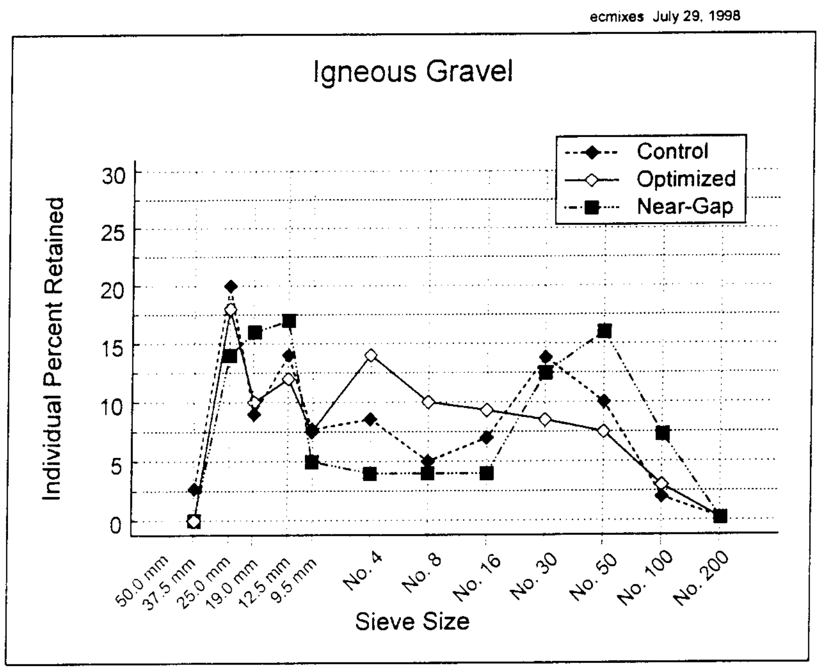

Figure 3. Gradations Selected for the Concrete Mixes with Igneous Gravel Aggregates

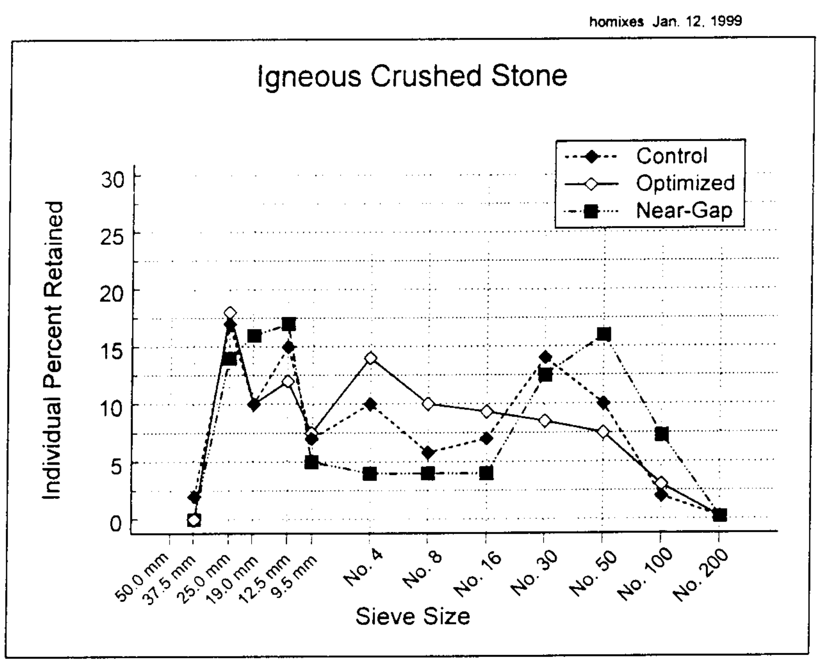

Figure 4. Gradations Selected for the Concrete Mixes with Igneous Crushed Stone Aggregates

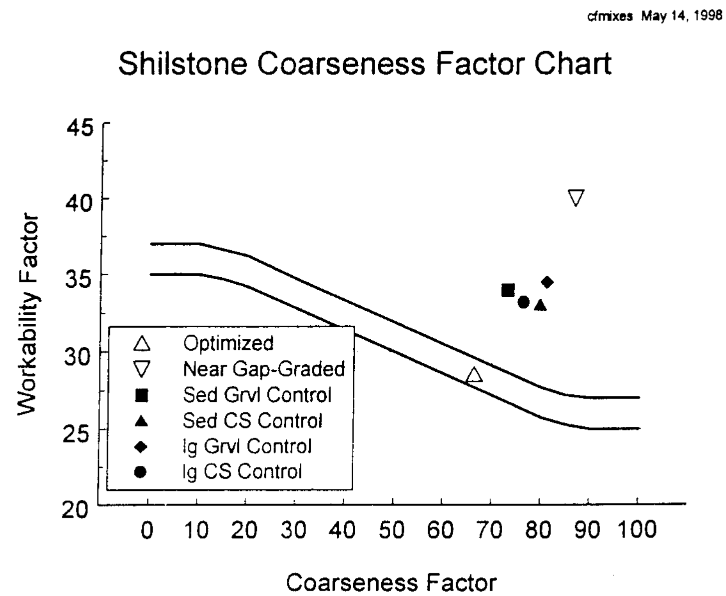

Figure 5. The Relationship of the Chosen Gradations to the Shilstone Coarseness Factor Chart

Using the gradations described above, concrete was prepared in the laboratory in 0.05 cubic meter batches in general compliance with ASTM C192 and using Wisconsin's A-FA mix (285 kg of Type I cement and 65 kg of Class C fly ash per cubic meter of concrete) (State of Wisconsin DOT 1996). Table 1 presents the tests conducted on the concrete and the curing conditions followed prior to the tests.

Water permeability testing of hardened concrete wet cured for 56 days was explored following procedures developed at the Univ. of Florida and Florida DOT, and described by Soongswang et al. (1988). This approach was eventually abandoned, as we believed the permeabilities were too low to provide reliable data on differences in permeabilities between the mixes. The extensive time needed to obtain even single measures of water permeability eliminated the possibility of conducting repeated measures. Water permeability testing by Florida DOT was conducted on concretes with considerably higher water cement ratios compared to those in this test program. ASTM C1202 Rapid Chloride Ion Permeability testing was conducted as a replacement for the water permeability testing. Florida DOT indicated that they had observed a strong correlation between their water permeability test and rapid chloride ion permeability test results.

Freeze-thaw testing was conducted in general compliance with ASTM C666 with transverse frequency and weight loss monitored according to ASTM C215 to reveal durability degradation. Specimens were subject to as many as 1000 freeze-thaw cycles in water, and if they survived, were subject to an additional 1000 cycles in a 3% sodium chloride solution. Following the 1000 cycles of testing in water, the freeze-thaw testing was temporarily suspended. Samples were air dried and then soaked for 48 hours in a 3 percent sodium chloride solution before freeze-thaw testing was resumed in the 3 percent sodium chloride solution.

Table 2. Summary of Tests Conducted

Test	Frequency	Applicable ASTM Standard	Curing Conditions	Age of Concrete at Test, days
Slump	1 per batch	C143	None	0, fresh
fresh air content	1 per batch	C231	None	0, fresh
unit weight	1 per batch	C138	None	0, fresh
accelerated freeze/thaw	3 per mix	C666	56 day wet	begin cycles @ 56 days
28-day compressive strength	3 per mix & at least 2 per batch	C39	28 day wet	28
Water permeability	1 per mix	None	56 day wet	Varied
Rapid chloride ion permeability	1(or 2?) per mix	C1202	56 day wet	Varied
Air dry shrinkage	3 per mix	C490, C157 modified	14 day wet	Varied
Air void analysis	1 per mix	C457	56 day wet	NA

5. Test Results

5.1 Tests of Fresh Concrete

The mixing water was controlled on the basis of slump (50 mm ± 25 mm) because phase I research had shown that optimized mixes require less water to achieve the same consistency. Should this hypothesis been proven true, we intended to quantify the reduced water demand of the optimized mixes and show impacts on durability resulting from the reduced water demand. The resulting water-cement ratios based on the specified slump were low resulting in durable concrete in all cases.. The resulting average slump values and water-cement ratios recorded for each mix are shown in Fig. 6. All slumps were between 25 and 75 mm and more than 80 percent of the batches had a slump between 50 and 75 mm. Within this range of slump, the optimized mixes did not yield reduced water contents as found in the previous phase of research. Average air contents measured in the plastic mixtures ranged from 5.1 to 6.8 percent as shown in Table 3. Spacing factors were highest in the near-gap mixes in two of the four gradation types (Table 3). Appendix A provides a complete listing of specimen air content measurements.

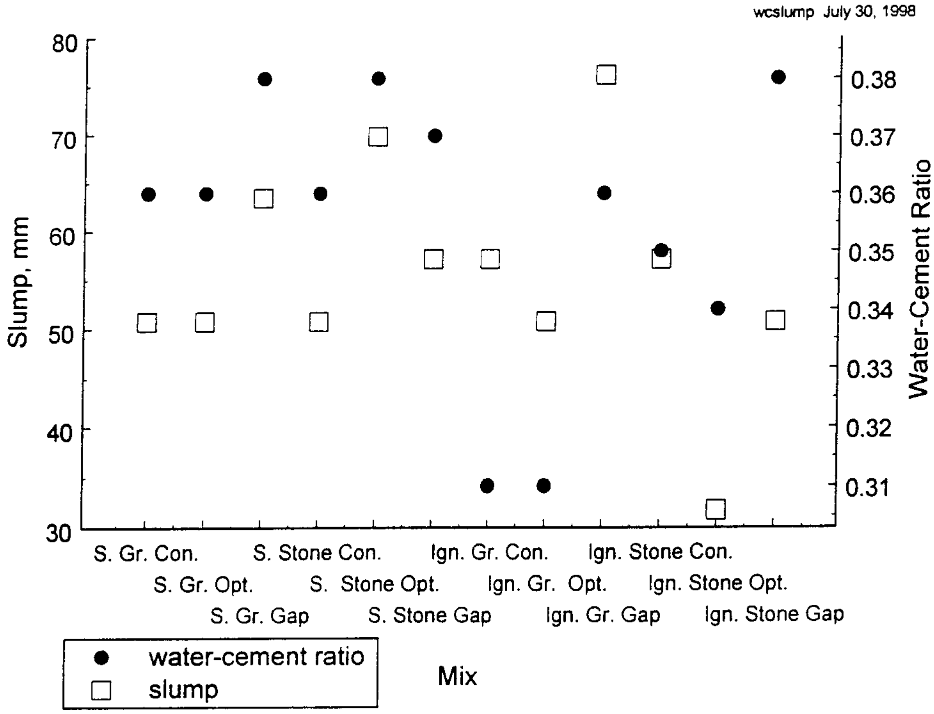

Figure 6. Slump and Water-Cement Ratios for Each Mix

Table 3. Air Content Parameters Measured

Aggregate Type	Gradation Type	Percent Air Plastic	Percent Air Hardened	Spacing factor, mm	Specific Surface, mm^{-1}
Sedimentary Gravel	Control	5.8	5.9	0.118	34.0
	Near-gap	6.7	5.8	0.149	27.0
	Optimized	5.9	5.1	0.119	33.8
Sedimentary Crushed Stone	Control	5.0	4.9	0.119	33.8
	Near-gap	6.0	6.0	0.118	34.0
	Optimized	5.8	4.9	0.118	33.9
Igneous Gravel	Control	6.5	5.6	0.114	35.4
	Near-gap	6.8	6.1	0.130	31.6
	Optimized	5.4	3.9	0.108	37.1
Igneous Crushed Stone	Control	6.5	5.1	0.114	35.2
	Near-gap	6.4	5.4	0.121	32.9
	Optimized	5.1	4.3	0.130	30.9

5.2 Compressive Strength

Compressive strengths measured at 28 days displayed some subtle trends. Figure 7 shows the average strength with 95% confidence bars on the results. An analysis of variance was conducted using the F statistic to test the null hypothesis of equal population means and Table 4 shows the findings (Laplin 1990). As with most concrete research, sample sizes were small (4 samples) and the analysis of variance provides only an indication of data trends. Significantly different means could be established in most situations at 85% confidence or higher. In all cases the near-gap mix presented the lowest or near lowest strengths and in the gravel aggregates, the optimized gradation yielded the highest strengths. Although the percent differences in mean strengths were small, they were significant. For two aggregate types, the control mix and the optimized mixes had identical water-cement ratios. In both of these instances, the optimized mix had the higher strength.

5.3 Shrinkage

The results obtained from the air-dry shrinkage tests were consistent with those obtained for strength. Trends were present but the differences tended to be small. Without exception, the near-gap mixes exhibited shrinkages that were 4 to 14 percent greater than the comparable control mixes as indicated in Table 5. Although the maximum confidence levels tended to below at which the difference in means were shown to be statistically significant, in all cases, the mean near-gap shrinkages were greater than the control mix shrinkages. The control mixes tended to produce the lowest shrinkages and the optimized mixes exhibited no clear reduced-shrinkage advantage. Figures 8 through 11 show dimensional changes for each aggregate type through 140 days of dry air exposure. The control mixes tended to produce the lowest shrinkages and the optimized mixes exhibited no clear reduced-shrinkage advantage.

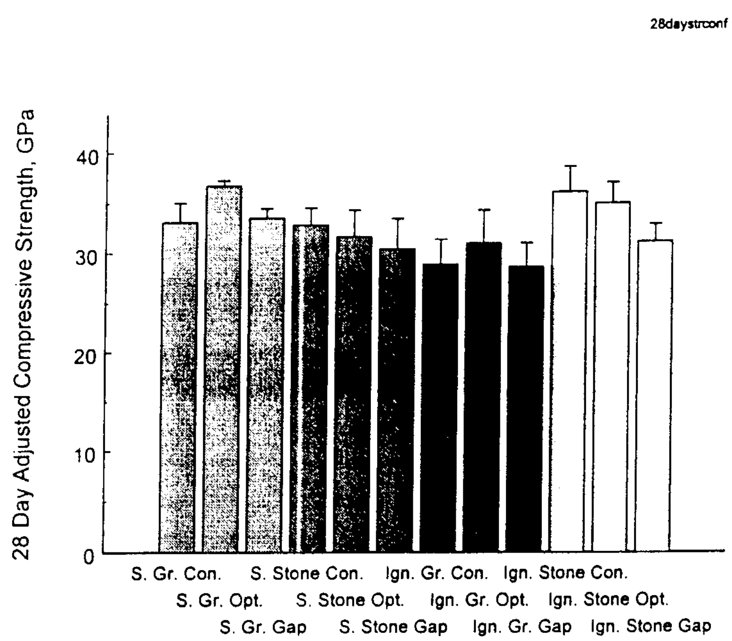

Figure 7. 28-day Compressive Strengths with 95% Confidence Bars

Table 4. 28-day Strength Summary

Aggregate Type	Mean Strengths Compared		Percent Difference in Mean Strength	Maximum Confidence Level at Which Means Differ
Sedimentary Gravel	**Control** (33.2 MPa)	Near-gap (33.6 MPa)	-1%	<50%
	Control (33.2 MPa)	Optimized (36.7 MPa)	-11%	95%
	Optimized (36.7MPa)	Near-gap (33. 6 MPa)	9%	95%
Sedimentary Crushed Stone	**Control** (32.8 MPa)	Near-gap (31.2 MPa)	5%	80%
	Control (32.8 MPa)	Optimized (31.7 MPa)	3%	70%
	Optimized (31.7 MPa)	Near-gap (31.2 MPa)	2%	<50%
Igneous Gravel	**Control** (28.9 MPa)	Near-gap (28.7 MPa)	1%	<50%
	Control (28.9 MPa)	Optimized (31.0 MPa)	-7%	85%
	Optimized (31.0 MPa)	Near-gap (28.7 MPa)	8%	85%
Igneous Crushed Stone	**Control** (36.2 MPa)	Near-gap (31.2 MPa)	14%	95%
	Control (36.2 MPa)	Optimized (35.0 MPa)	3%	65%
	Optimized (35.0 MPa)	Near-gap (31.2 MPa)	11%	95%

Table 5. Shrinkage Summary

Aggregate Type	Mean Shrinkages Compared Age	Mix compared to Mix		Percent Difference in Mean Shrinkage	Maximum Confidence Level	Means are significantly different
Sedimentary Gravel	14 days	**Control** (-.0256%)	Near-gap (-.0271%)	6%	55%	Yes
	42 days	**Control** (-.0392%)	Near-gap (-.0407%)	4%	50%	Yes
Sedimentary Crushed Stone	14 days	**Control** (-.0200%)	Near-gap (-.0218%)	9%	55%	Yes
	42 days	**Control** (-.0324%)	Near-gap (-.0338)	4%	50%	Yes
Igneous Gravel	14 days	**Control** (-.0204%)	Near-gap (-.0217%)	6%	50%	Yes
	42 days	**Control** (-.0310%)	Near-gap (-.0348%)	12%	70%	Yes
Igneous Crushed Stone	14 days	**Control** (-.0208%)	Near-gap (-.0229%)	10%	80%	Yes
	42 days	**Control** (-.0289%)	Near-gap (-.0329%)	14%	95%	Yes

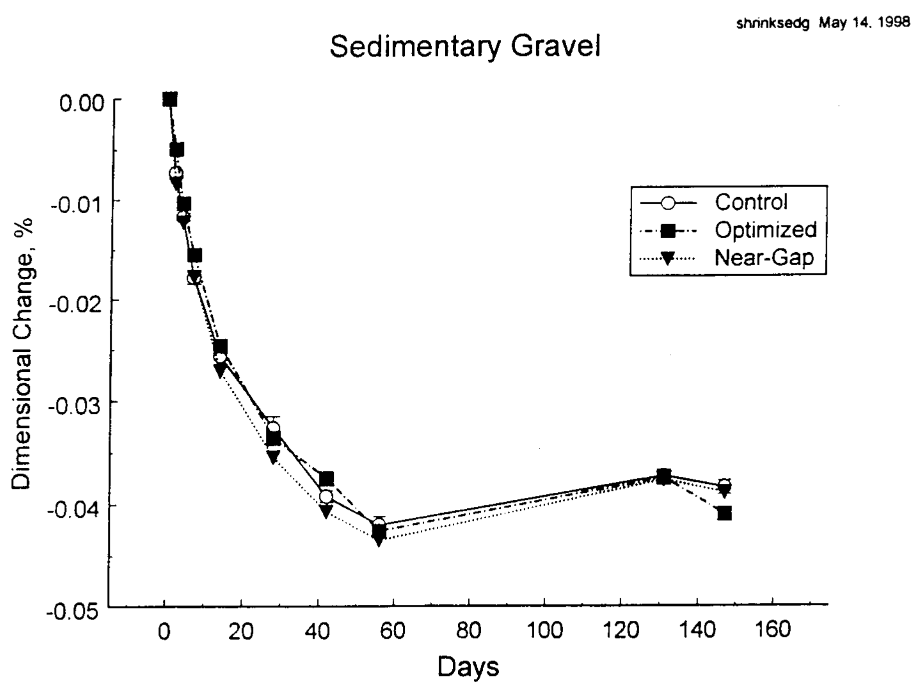

Figure 8. Air-dry Shrinkage Results for Sedimentary Gravel

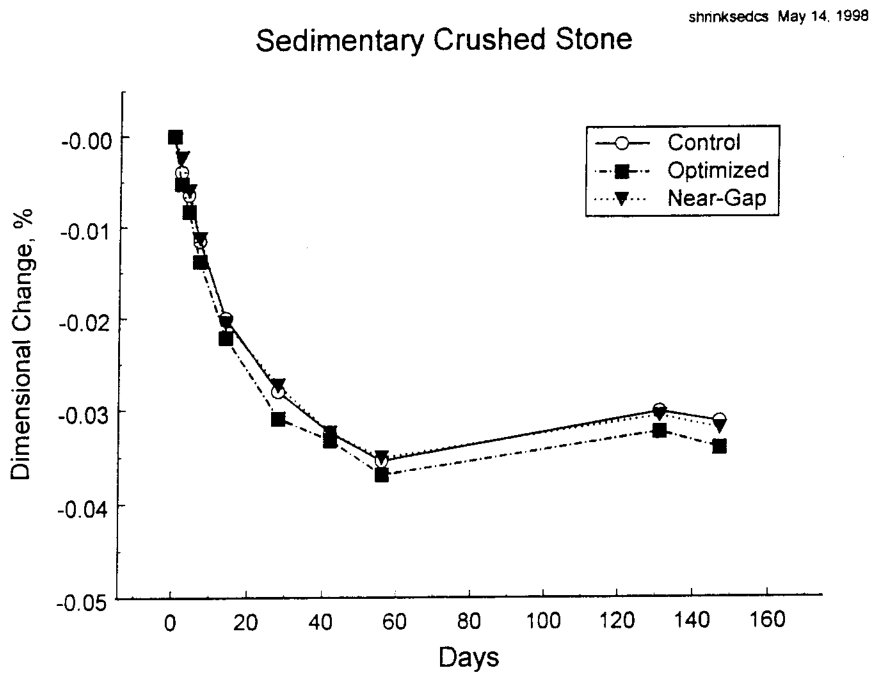

Figure 9. Air-dry Shrinkage Results for Sedimentary Crushed Stone

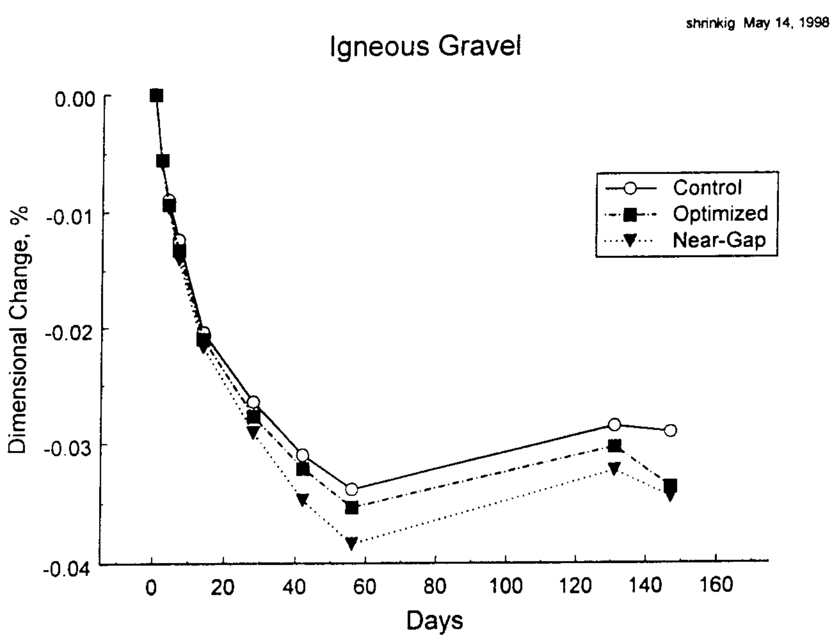

Figure 10. Air-dry Shrinkage Results for Igneous Gravel

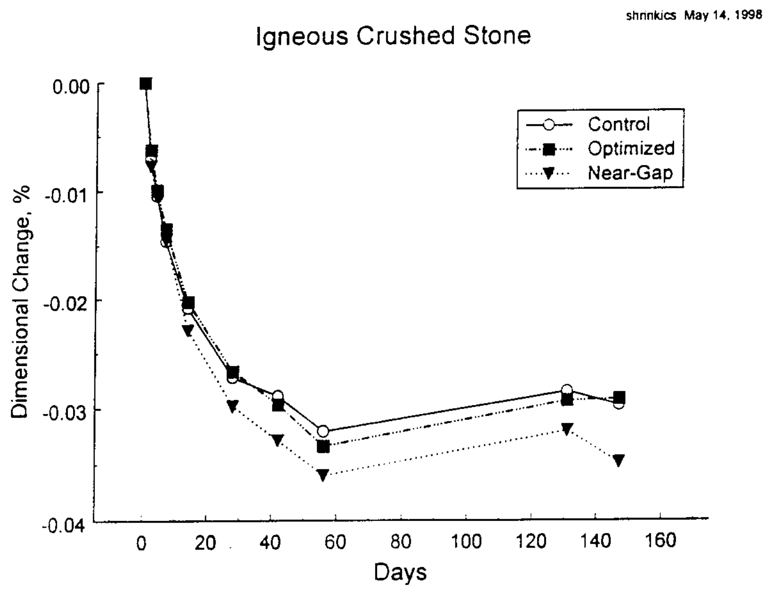

Figure 11. Air-dry Shrinkage Results for Igneous Crushed Stone

5.4 Permeability

Average permeability test results are shown in Fig. 12. It is assumed that lower permeability leads to greater durability by inhibiting the diffusion of water and water-borne chemicals into the concrete matrix. In Fig. 12, water permeability data are shown for comparison with the chloride ion permeability results. As mentioned earlier, the water permeability testing was abandoned after great difficulty was encountered in obtaining reliable data for these mixes with low water-cement ratios. Despite our general lack of confidence in obtaining repeatable water permeability results, the data that were collected tend to follow the trends observed in the chloride ion testing. Of most interest, Fig. 12 shows that the optimized mixes yielded the lowest water permeabilities. The sedimentary mixes showed low to very low chloride ion permeabilities with the igneous aggregates in the moderate to low range. Particularly in the igneous aggregates, the near-gap mixes showed significantly higher mean permeabilities. Table 6 reveals the analysis of variance results and indicates the differences in mean chloride ion permeabilities were significant in only half the comparisons. In all cases where mean permeabilities were significantly different, the near-gap mixes displayed higher permeabilities (Table 6).

Permeable May 14, 1998

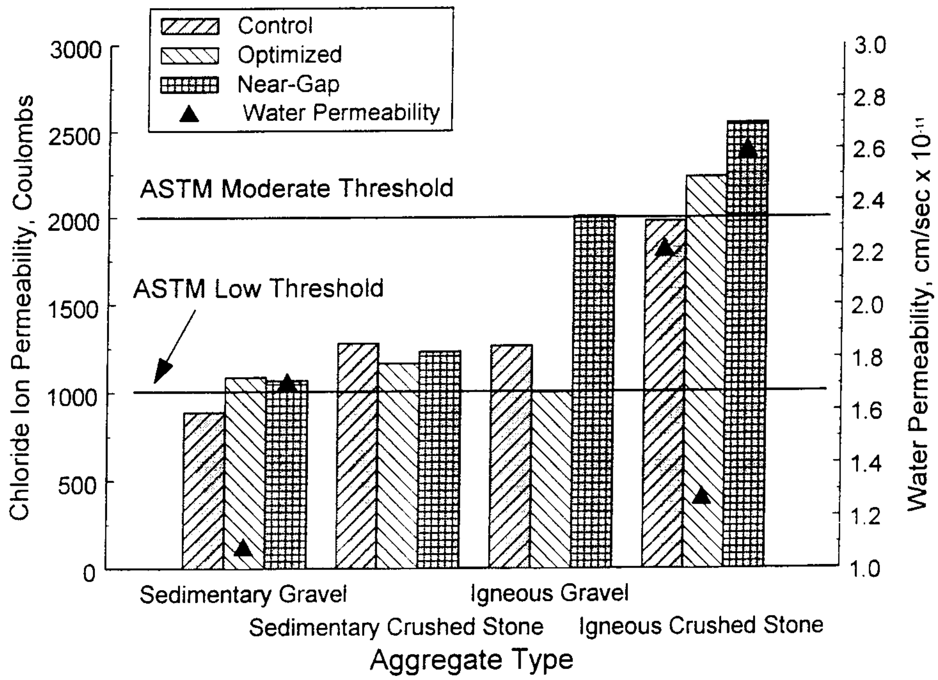

Figure 12. Chloride Ion and Water Permeability Test Results for Each Aggregate/Mix Type

Table 6. Summary of Mean Permeability Test Results

Aggregate Type	**RCP Permeability (Coulombs) Mixes Compared**		**Percent Difference in Mean Permeability**	**Confidence Level**	**Means are significantly different**
Sedimentary Gravel	**Control** (891)	Near-gap (1070)	20%	80%	Yes
	Optimized (1090)	Near-gap (1070)	-2%	50%	No
Sedimentary Crushed Stone	**Control** (1283)	Near-gap (1235)	-4%	50%	No
	Optimized (1166)	Near-gap (1235)	6%	50%	No
Igneous Gravel	**Control** (1267)	Near-gap (2007)	58%	85%	Yes
	Optimized (1004)	Near-gap (2007)	100%	95%	Yes
Igneous Crushed Stone	**Control** (1981)	Near-gap (2552)	29%	80%	Yes
	Optimized (2237)	Near-gap (2552)	14%	50%	No

5.5 Freeze-Thaw Tests

All test specimens proved to be extremely freeze-thaw durable. As indicated in Figs. 13 through 16, specimens showed little degradation when subject to 1000 cycles in water with the exception of sedimentary gravel mixes. Although a strict failure criterion for ASTM C666 test has not been established, a relative modulus of 60 percent or less after 300 cycles is generally considered failure.

It was observed during mixing, that the sedimentary gravel contained significant quantities of chert. Samples of 500 particles per size fraction of sedimentary gravel and sedimentary crushed stone were analyzed lithologically by a geologist for chert. Table 7 shows the occurrence of chert particles by size for the sedimentary aggregates. Subsequent analysis of the chert revealed a specific gravity of 2.37 and absorption of 4.1%. The WisDOT Standard Specifications (State of Wisconsin DOT 1996) limit the amount of chert to 5% by mass with a specific gravity of less than 2.45 of the material retained on the 9.5-mm sieve. During freeze-thaw testing, popouts and actual specimen fracture were repeatedly observed to occur at locations of chert. Within the precision of the data available, we found no evidence to suggest the less durable near-gap specimens (Fig. 13) had more chert particles than other specimens containing sedimentary gravel.

Following the 1000 cycles of testing in water, specimens were air dried and testing was restarted with the 3 percent sodium chloride solution. The drying and restarting process explains the jump at 1000 cycles displayed in Figs. 14-16.

The sedimentary crushed stone specimens began to fail after the additional 1000 cycles of testing in the sodium chloride solution. The igneous gravel specimens began to show some degrade after the additional 1000 cycles but did not fail. The igneous crushed stone specimens showed little degrade after 1000 cycles in water and the additional 1000 cycles in sodium chloride solution.

In all cases, the near-gap mixes showed the lowest durability. In the tests of the sedimentary mixes (Figs. 13 and 14), the decreased durability of the near-gap mixes was clearly displayed and, from a practical viewpoint, significant. For the igneous aggregate specimens, trends were less clear but again the near-gap mixes displayed lower durability.

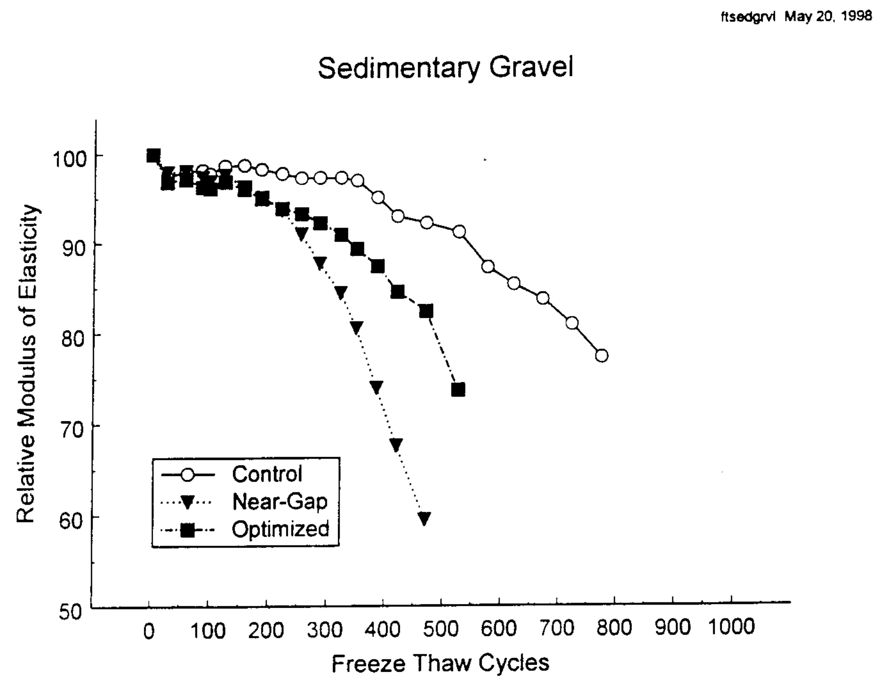

Figure 13. Relative Modulus Degrade From ASTM C666 Acelerated Freeze-Thaw Testing in Water for Sedimentary Gravel Specimens

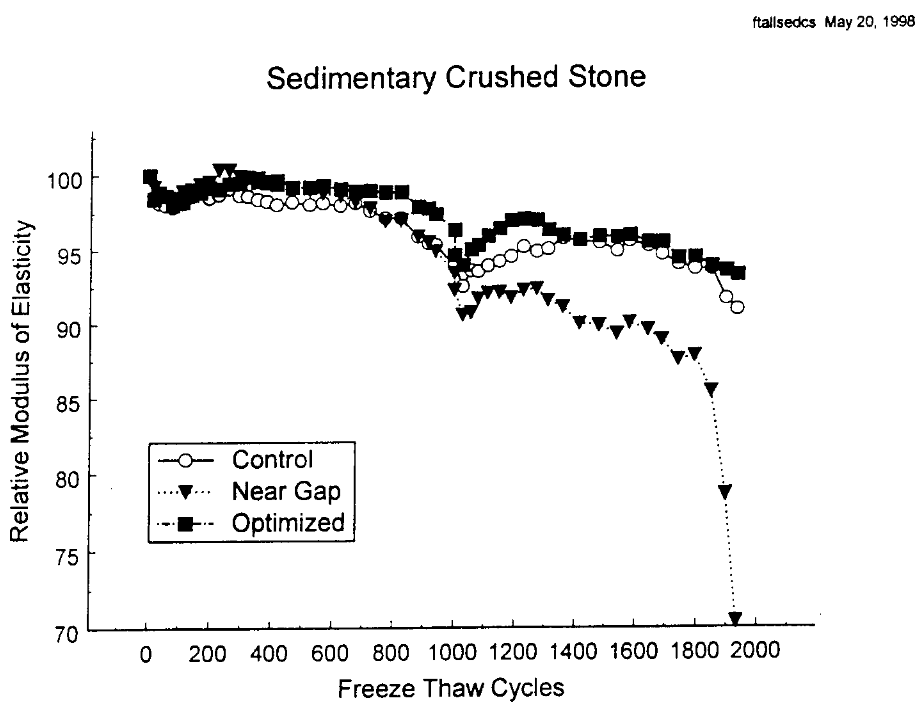

Figure 14. Relative Modulus Degrade From ASTM C666 Acelerated Freeze-Thaw Testing in Water for Sedimentary Crushed Stone Specimens

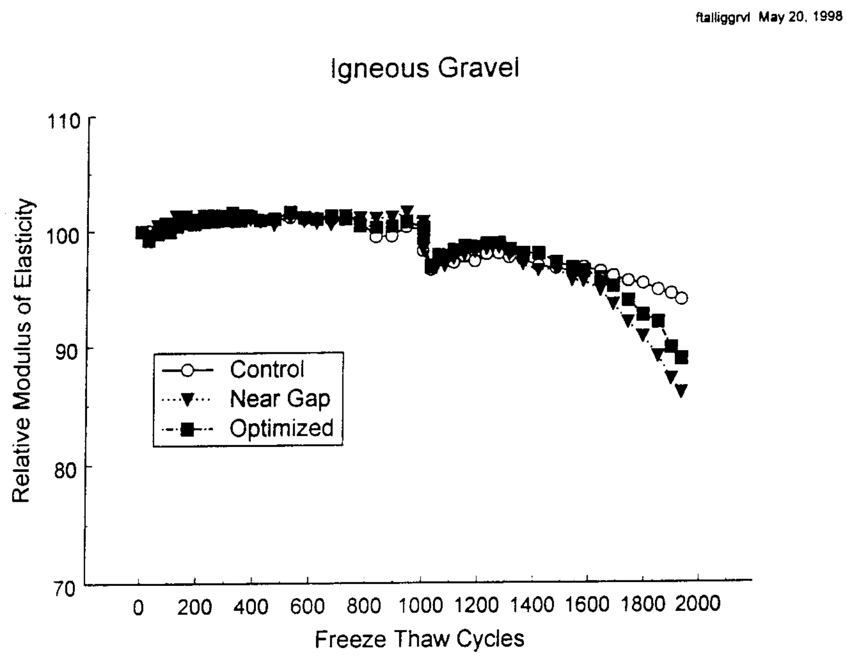

Figure 15. Relative Modulus Degrade From ASTM C666 Acelerated Freeze-Thaw Testing in Water for Igneous Gravel Specimens

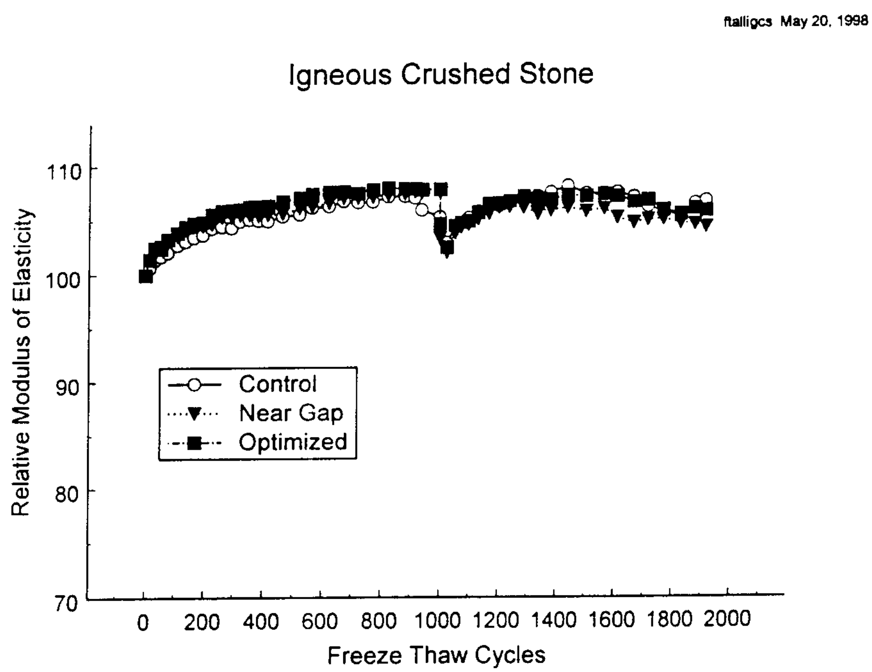

Figure 16. Relative Modulus Degrade From ASTM C666 Acelerated Freeze-Thaw Testing in Water for Igneous Crushed Stone Specimens

Table 7. Chert Content of Sedimentary Aggregates

Size Fraction	Gravel (percent of particles)	Crushed Stone (percent of particles)
37.5 mm	11%	0%
25.0 mm	12%	0%
19.0 mm	12%	0%
12.5 mm	9%	0%
9.5 mm	14%	2%
4.75 mm	12%	3%

6. Conclusions

The objective of this research was to identify the durability-related differences between concrete paving mixtures that have different aggregate gradations. We examined the influence of aggregate gradation on strength, shrinkage, permeability and freeze-thaw durability on gravel and crushed-stone aggregates derived from sedimentary and igneous sources. Control gradations consisted of a 40%-60% blend of fine and coarse aggregates as they occur in different locations of Wisconsin. Various techniques have been proposed in the past that optimize concrete performance based on aggregate gradation. These techniques were reviewed and considered in the identification of the optimized gradation used in this study. Optimized and near-gap gradations were fabricated by sieving and recombining particle sizes to create gradations that had the potential to be used in practice. This practical consideration meant that extreme gradations that did not meet state specifications, but would probe the extremes of potential gradation-induced influences were not tested.

As extreme gradations were not considered, the differences in the performance measures for the different mixtures tended to be small as expected. In many of the cases, clear advantages of one gradation type over another were not found. The observed differences were not random either. Optimized gradations and control gradations tended to perform about the same across the study and near-gap mixes tended to perform worse. We did not establish an optimized gradation that offered a consistent performance benefit compared to control gradations across the complete range of concrete strength and durability measures. Isolated advantages of the optimized gradation were indicated but not in a consistent form across the study variables.

The near-gap mixes tended to perform measurably worse than comparable control and optimized mixes. While the differences were not always large, the differences in the gradations also were not large – confirming that minor adjustments in gradations of quality concrete will not yield dramatic results. The strengths of near-gap mixes were 2 to 14 percent less than comparable control or optimized mixes. Mean shrinkage was 8 percent greater in the near-gap mixes compared to the control mixes. On average, permeabilities were more than 25 percent greater in the near-gap mixes compared to control and optimized mixes. In all cases, the near-gap mixes showed the lowest freeze-thaw durabilities. Although failure was accelerated by the occurrence of chert in the sedimentary gravel specimens, the near-gap specimens of this type degraded in approximately half the number of cycles to achieve comparable degrade in the control specimens.

7. References

Abrams, D.A. , *Design of Concrete Mixtures*, Bulletin No. 1, Structural Materials Research Laboratory, Lewis Institute, Chicago, IL 1918.

Basri, B. *Evaluation of Optimized Gradation Concepts Using the Fineness Modulus Theory*, Independent Study Report, University of Wisconsin-Madison, August 1996, Madison, WI, 58 pgs.

Cramer, S., M. Hall, and J. Parry. Effect of Optimized Total Aggregate Gradation on Portland Cement Concrete for Wisconsin Pavements. *Transportation Research Record No. 1478 – Concrete and Concrete Pavement Construction.* TRB, National Research Council, Washington, D.C., 1995, pp. 100-106.

Fuller, W.B., and S.E. Thompson. The Laws of Proportioning Concrete. *Transactions*, Vol. 59, ASCE, 1907, pp. 67-143.

Laplin, L.L. *Probability and Statistics for Modern Engineering,* 2nd Edition, PWS-Kent Publishing, 1990, 810 pgs.

Minnesota Dept. of Transportation Modifications to Specification 2301, Nov. 11, 1996. Obtained through personal communication with D. Schwartz, Minnesota DOT.

Shilstone, James M., "Concrete Pavement-Specification by Modeling" *Servicability and Durability of Construction Materials,* Proceedings, First Material Engineering Congress, ASCE, 1990, pp. 932-952.

Shilstone, James M., "Concrete Mixture Optimization" *Concrete International*, June 1990, p 33-39.

Soongswang, P., Tia, M., Bloomquist, D., Meletiou, C. and Session, L. Efficient Test Setup for Determining the Water-Permeability of Concrete, *Transportation Research Record 1204*, 1988.

United States Air Force. *Proportioning Concrete Mixtures with Graded Aggregates for Rigid Airfield Pavements*, AFI 32-1028, 1997

Walker, S. and Bartels, F. "Discussion of Concrete Mix Design – A Modification of the Fineness Modulus Method" *ACI Journal*, 19(4), Dec. 1947.

State of Wisconsin Department of Transportation. *Standard Specifications for Highway and Structure Construction.* Wisconsin Department of Transportation, 1996.

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Appendix A – Concrete Batch Data

Table Appendix-1. Batch Quantities and Mix Parameters for Sedimentary Aggregate Mixes

	Sedimentary Gravel						Sedimentary Crushed Stone						
Mix	opt1w	opt2w	gap1w	gap2w	con1w	con2w	opt2y	opt3y	gap1y	gap2y	gap3y	con1y	con3y
Batch Size (m^3)	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052
Cement, kg	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47
Fly Ash, kg	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27
Water, kg	7.98	7.98	8.35	8.35	7.98	7.98	8.36	8.36	8.36	8.36	8.16	8.16	8.16
Air Entraining Agent, oz	30	30	28	28	30	30	30	30	30	30	28	28	28
Aggregate, kg													
38-mm	0.00	0.00	0.00	0.00	0.95	0.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25-mm	17.10	17.10	13.29	13.29	19.96	19.96	17.10	17.10	13.29	13.29	13.29	11.39	11.39
19-mm	9.48	9.48	15.20	15.20	8.53	8.53	9.48	9.48	15.20	15.20	15.20	16.15	16.15
13-mm	11.39	11.39	16.15	16.15	9.48	9.48	11.39	11.39	16.15	16.15	16.15	16.15	16.15
10-mm	7.12	7.12	4.76	4.76	6.67	6.67	7.12	7.12	4.76	4.76	4.76	6.67	6.67
No. 4	13.29	13.29	3.81	3.81	8.53	8.53	13.29	13.29	3.81	3.81	3.81	7.12	7.12
No. 8	9.48	9.48	3.81	3.81	8.53	8.53	9.48	9.48	3.81	3.81	3.81	4.76	4.76
No. 16	8.53	8.53	3.81	3.81	8.53	8.53	8.53	8.53	3.81	3.81	3.81	8.53	8.53
No. 30	7.12	7.12	11.88	11.88	7.58	7.58	7.12	7.12	11.88	11.88	11.88	7.58	7.58
No. 50	5.72	5.72	15.20	15.20	9.48	9.48	5.72	5.72	15.20	15.20	15.20	9.98	9.98
No. 100	4.76	4.76	6.94	6.94	5.72	5.72	4.76	4.76	6.94	6.94	6.94	5.72	5.72
No. 200	0.95	0.95	0.18	0.18	0.95	0.95	0.95	0.95	0.18	0.18	0.18	0.95	0.95
Slump, mm	51	51	57	70	57	51	70	70	51	70	51	70	38
Air Content, %	6.7	5.6	6.6	7.8	6.3	6.3	6.7	5.9	6.6	7.7	6.4	5.9	5.1

Table Appendix-2. Batch Quantities and Mix Parameters for Igneous Aggregate Mixes

	Igneous Gravel						Igneous Crushed Stone					
Mix	opt1e	opt2e	gap1e	gap2e	con1e	con2e	opt1h	opt2h	gap1h	gap2h	con1h	con2h
Batch Size (m^3)	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052
Cement, kg	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47
Fly Ash, kg	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27
Water, kg	6.44	6.52	7.58	7.35	6.49	6.49	6.63	6.72	7.28	7.28	6.80	6.71
Air Entraining Agent, oz	35	60	25	30	50	50	30	30	25	25	30	30
Aggregate, kg												
38-mm	0.00	0.00	0.00	0.00	2.59	2.59	0.00	0.00	0.00	0.00	1.91	1.91
25-mm	17.10	17.10	13.29	13.29	19.01	19.01	17.10	17.10	13.29	13.29	16.15	16.15
19-mm	9.48	9.48	15.20	15.20	8.53	8.53	9.48	9.48	15.20	15.20	9.48	9.48
13-mm	11.39	11.39	16.15	16.15	13.29	13.29	11.39	11.39	16.15	16.15	14.24	14.24
10-mm	7.12	7.12	4.76	4.76	7.30	7.30	7.12	7.12	4.76	4.76	6.67	6.67
No. 4	13.29	13.29	3.81	3.81	8.16	8.16	13.29	13.29	3.81	3.81	9.48	9.48
No. 8	9.48	9.48	3.81	3.81	4.76	4.76	9.48	9.48	3.81	3.81	5.49	5.49
No. 16	8.85	8.85	3.81	3.81	6.67	6.67	8.85	8.85	3.81	3.81	6.67	6.67
No. 30	8.07	8.07	11.88	11.88	13.11	13.11	8.07	8.07	11.88	11.88	13.29	13.29
No. 50	7.12	7.12	15.20	15.20	9.48	9.48	7.12	7.12	15.20	15.20	9.48	9.48
No. 100	2.86	2.86	6.94	6.94	1.91	1.91	2.86	2.86	6.94	6.94	1.91	1.91
No. 200	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Slump, mm	51	64	76	76	57	64	25	38	57	44	64	57
Air Content, %	4.9	6.1	6.5	7.2	6.7	6.4	5.1	5.0	6.4	6.3	6.2	6.8