Evaluation of Ground Granulated Iron Blast-Furnace Slag: Grade-100

by

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ABSTRACT

Currently, the use of grade-120 Granulated Ground Blast Furnace Slag (GGBFS) is incorporated into the specifications of LA DOTD concrete mixes. This study evaluates grade-100 GGBFS and its effect on the properties of hydraulic cement concretes used in structures and pavements construction. Four mix designs were used for this study, two structural and two pavements, with varying amounts (15%, 30%, and 50%) of grade-100 GGBFS used as a by-weight substitution for cement. Additionally in order to simulate field conditions, the study used three different temperatures (50°F, 73°F and 90°F) for the components at mixing and curing conditions. This study looked at the effects of slag on workability, durability, and the compressive and flexural strengths of the concrete. How grade-100 GGBFS compared to grade-120 GGBFS in its affect on the concrete's physical properties and set times was also crucial in determining its acceptability for LA DOTD concrete structures and pavements.

Similar to the grade-120 GGBFS, test results indicate that concretes with grade-100 GGBFS substitutions exhibited delays in set times and in compressive strengths at an early age as compared to conventional concrete mixes. Permeability was reduced in those concretes that incorporated GGBFS as opposed to the conventional mixes.

Recommendations will be made from this study to incorporate grade-100 GGBFS into the specifications of Louisiana concrete mixes. It will be recommended that grade-100 GGBFS have the same allowances and restrictions that are currently specified for grade-120 GGBFS.

IMPLEMENTATION

The results of this study will assist the department in determining whether to allow the use of GGBFS grade-100 as a partial cement substitution in concrete pavements and structures. The incorporation of GGBFS grade-100 into the QPL will benefit LADOTD and the state not only with an improved concrete product but also economically and ecologically. In addition to the economical cost savings already experienced through the use of GGBFS grade-120, the economic competition of GGBFS grade-100 as an alternate cement replacement may result in a further cost savings for concrete specified by LADOTD. Furthermore, by using this otherwise waste material as a partial replacement for cement in concrete, LADOTD plays a part in the ecological recycling of these waste materials.

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INTRODUCTION

In 1999, LA DOTD approved the use of Ground Granulated Blast-Furnace Slag (GGBFS) grade-120 for use in its pavements and structures. Since this time, there have been three pavement projects (LA 14, Line Road, and U.S. 190) and two structural projects (Charenton Bridge Deck and U.S. 11 Bridge Overlay) that have used GGBFS grade-120 successfully. This research study was designed to discover whether GGBFS grade-100 performs comparatively to grade-120. Since there is currently only one provider of GGBFS grade-120, a similar performance by grade-100 would provide supply competition and present contractors with feasible supply options.

GGBFS PRODUCTION

GGBFS is a nonmetallic by-product of the steel industry simultaneously produced with iron in the blast furnace of steel mills, which consists essentially of silicates and aluminosilicates of calcium and other bases. Iron ore, limestone, and coke are crushed and blended into a mixture constituting the raw materials for molten iron, which is produced in a ±2700 °F blast furnace. The residual molten slag is chilled rapidly by immersion in water to vitrify the material into a glassy sand-like substance. This substance is then dried and ground into a very fine powder with a minimum of 80 percent less than 45 microns in size. This is the cementitious material called GGBFS. ACI 233-R classifies the range of chemical composition of GGBFS in the United States and Canada as:

Chemical Constituents (as oxides)*	Range of Composition percent by Mass
SiO_2	32-42
Al_2O_3	7-16
CaO	32-45
MgO	5-15
S	0.7-2.2
Fe_2O_3	0.1-1.5
MnO	0.2-1.0

* Except for Sulfur

PHYSICAL AND CHEMICAL PROPERTIES

ASTM C 989-99 (Standard Specification for GGBFS for use in Concrete and Mortars) and AASHTO M 302-00 (Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars) provide for three grades of GGBFS depending on their mortar strengths when blended with an equal mass of portland cement and compared to the mortar strengths of portland cement alone. Grades 120, 100 and 80 are expressed as:

SAI = (SP/P x 100)

where:

SAI = slag-activity index, %

SP = average compressive strength of slag-reference cement mortar cubes, psi

P = average compressive strength of reference cement mortar cubes, psi

Grades are determined when the mortar cube sample's SAI falls within the allowed ranges of the following table.

Slag Activity Index Min., percent	**Average of Last 5 Consecutive Samples**	**Any Individual Sample**
7-Day index		
Grade 80	-	-
Grade 100	75	70
Grade 120	95	90
28-Day index		
Grade 80	75	70
Grade 100	95	90
Grade 120	115	110

For fineness, the amount retained when wet-screened on a 45 µm (No. 325) sieve shall not exceed 20 percent. Air content of slag mortar should not exceed 12 percent. Chemical composition requirements are a maximum of 2.5 percent of sulfide sulfur (S) and a maximum of 4.0 percent of sulfate ion, reported as SO_3.

HYDRATION PROCESS

The following is a rudimentary explanation of a multifaceted chemical process that complements this report. Portland cement, when combined with water, will hydrate to form the hardened cement paste constituent of concrete. Calcium silicates, the major constituent of cement, hydrate to form calcium silicate hydrate (CSH), the beneficial property of hydrated cement, and calcium hydroxide ($Ca(OH)_2$), an unfavorable property of hydrated cement. When GGBFS is combined with portland cement, a combined interaction occurs during the hydration process. With water, GGBFS will hydrate to form calcium silicate hydrate (CSH) and silicates (SiO_2). The dissolved silicates (SiO_2) from the GGBFS hydration process, combine with the excess calcium hydroxide ($Ca(OH)_2$) from the portland cement hydration process and react with water, producing additional and beneficial calcium silicate hydrate (CSH). This combined interaction between GGBFS and portland cement during the hydration process is advantageous in that additional and beneficial (CSH) is produced at the expense of the unfavorable ($Ca(OH)_2$).

OBJECTIVE

The objective of this research is to determine whether GGBFS grade-100 performs similarly to the already approved GGBFS grade-120. If GGBFS grade-100 performs well, LA DOTD may allow its use as an alternative to GGBFS grade-120. This will further cost-efficiency and provide an alternate material for contractors. By producing concrete that is strong, durable, workable, economical, and found to be comparable to GGBFS grade-120, GGBFS grade-100 will be competitive with all the portland cement concrete LA DOTD uses.

Through a series of standard ASTM tests the effects of GGBFS grade-100 on concrete at various substitution rates and temperatures will be determined. The tests will discover the physical properties of GGBFS grade-100 concrete so that a comparison to standard concrete reference mixes and concrete with GGBFS grade-120 can be made. The minimal test procedures from the GGBFS grade-120 study will be duplicated for the GGBFS grade-100 study along with additional tests. With equal or superior results, it is expected that GGBFS grade-100 will be accepted as a qualified product for LA DOTD whereby specifications and applications for GGBFS grade-100 can be developed.

SCOPE

The LTRC Concrete Laboratory was the site of the testing program. Reference mixes (those that are standard LA DOTD mixes containing no GGBFS) and GGBFS mixes were made and tested using standard ASTM test procedures and one AASHTO test, the rapid chloride permeability test, to determine the strength, durability, and workability properties of the concrete mixes.

The scope of this research study also attempted to simulate field conditions for both the cold and hot climatic conditions experienced in Louisiana by having the concrete ingredients, mixing and curing at the temperatures of 50 ºF and 90 ºF. For these temperatures, all of the relevant tests for comparative purposes were performed while the concrete was in the plastic state: specifically set times, air content, and slump. Test specimens were made from these 50 ºF and 90 ºF concrete mixes and cured continuously at these temperatures respectively.

METHODOLOGY

All mixes were tested with their components at 50 EF, 73 EF, and 90 EF to address the set times for these temperatures since that has been a chief concern of LA DOTD's construction personnel. Any significant variations in set times would then be addressed in our specifications manual. Resistance to rapid freezing and thawing durability testing (ASTM C-666) results are all suspect due to problems encountered with the testing and recording equipment. Because of the unreliability of freeze/thaw results, they are not reported herein. Concrete mixes conformed to LADOTD Standard Specifications for Roads and Bridges. They were representative of the concrete and materials used in pavements and structures in Louisiana.

Analysis involved test results comparisons to non-GGBFS reference mixes and to test results obtained in the previous research conducted on the grade-120 GGBFS. The tests address some of the following known GGBFS qualities.

From the previous research, work experience and information that is cited by ACI, ASTM, AASHTO and others, there is general agreement that the use of all GGBFS is associated with the following effects on concrete:

- Improved workability, pumpability, slump retention, and finish ability are due in part to the smooth, dense surfaces of GGBFS particles. The slag absorbs little or no water during mixing, resulting in a reduced water demand for the mix.

- Increased time of initial setting and irregular changes in time between initial and final set are common for GGBFS concrete mixes. This is of particular concern to LA DOTD. In paving concrete, joints shall be completed in a timely manner, generally within 10 hours. The time management of the joint sawing operation could be tricky if the set is delayed or if the time window is narrowed. This is the time in between achieving the minimum strength necessary to support the joint sawing equipment and before the time when potential random cracking can occur. In addition, the minimum time requirement must be such that raveling does not occur. It is known that lower temperatures will further delay set time and strength gain, as happens with "plain pcc" and fly ash concrete at lower temperatures. Furthermore, when accelerated curing (steam) is used in the manufacture of prestressed piles and girders, high early strength development is important. Minimum strengths are usually required within twelve hours before prestressing strands can be cut. Any retardation in strength could delay the strand cutting or prevent the necessary strength from being reached in time.

- Strength Gain - Despite early strength reduction, after 7 days GGBFS grade-120 concrete shows increased strength over Portland Cement Concrete. GGBFS grade-100 should show minimal reduction in strength as compared to the reference mixes. Additionally, with higher addition percentage GGBFS concrete mixes, a reduced water content can be achieved that will give equal slump and workability resulting in a lower water to cement ratio (w/c) and higher strengths.

- GGBFS concrete mixes reduce the early rate of heat generation and the peak temperature of the concrete. This is beneficial in large mass pours where excessive heat of hydration can lead to cracking due to thermal gradients within the concrete. The reduction in generated heat is more evident with greater substitution rates of GGBFS for cement.

- GGBFS reduces permeability with its reduced absorption qualities and its smaller particle size, which results in a more consolidated mix with fewer voids within the concrete paste. The consolidated mix is also improved by GGBFS reaction with calcium hydroxides from the portland cement to form additional calcium silicate hydrates. These all contribute to a denser concrete matrix resulting in a reduced permeability.

- Sulfate resistance is improved due to the reduced permeability and the reduction of calcium hydroxide and alumina content in GGBFS concrete.

- Alkali-aggregate reactions are also diminished because GGBFS uses the culpable available alkalies during the hydration process. Also, the reduced permeability inhibits the migration of remaining alkalies within the pore structure.

- Resistance to corrosion of reinforcing steel is improved due to the reduced permeability of GGBFS concrete. The reduced permeability inhibits the migration of chemicals that attack and initiate the corrosion process in reinforcing steel, specifically chloride ions from marine environments and deicing salts.

- Freeze thaw resistance, modulus of elasticity, and scaling resistance to de-icing salts are all comparable to non-slag Type I portland cement concrete.

- Greater than normal creep and shrinkage are thought to occur with the use of GGBFS, but there are conflicting reports on this.

WORK PLAN

Tests were conducted to address some of the aforementioned GGBFS qualities. They included the following ASTM and AASHTO tests:

ASTM C 143	Slump of Fresh Concrete - 1 specimen
ASTM C 148	Air Content and Unit Weight - 1 specimen
ASTM C 403	Set Time of Fresh Concrete - 2 specimens
ASTM C 39	Compressive Strength - 3 specimens
ASTM C 78	Flexural Strength - 3 specimens
ASTM C 469	Static Modulus of Elasticity and Poisson's Ratio - 2 specimens
ASTM C 666	Resistance to Rapid Freezing and Thawing - 3 specimens
ASTM C 157	Length Change - 2 specimens
ASTM C 512-87	Creep Test of Concrete in Compression - 3 to 5 specimens
ASTM C 672-92	Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to De-icing Chemicals - 2 specimens
ASTM C 944-90a	Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating Cutter Method - 3 specimens
AASHTO C 1202	Rapid Chloride Permeability Test - 2 specimens

The following are the two mixes used in this study: a paving mix and a structural mix. Each consists of a gravel coarse aggregate mix and a crushed stone coarse aggregate mix.

Paving Mix:

The reference shall be:

- Cement content: 5.4 bags of Type I Cement per cubic yard when crushed limestone is used as the coarse aggregate; 5.8 bags of Type I Cement per cubic yard when gravel is used as the coarse aggregate
- 60/40 ratio of coarse to fine aggregate
- Coarse aggregate gradation "B"
- Water/cementitious material ratio: not to exceed 0.40 (0.40 used with HRWR)
- Same water/cementitious material ratio for similar mixes
- Use of admixtures; air entrainment and water reducers to achieve air content and slump within LA. DOTD Standard Specifications for Roads and Bridges for each mix type

Structural Mix:

The reference mix shall be:

- Cement content: 6.5 bags of Type I Cement per cubic yard when both gravel and crushed limestone are used as the coarse aggregate.
- water/cement ratio: not to exceed 0.45 (0.34 used with HRWR)
- Same water/cementitious material ratio for similar mixes
- 60/40 ratio of coarse to fine aggregate
- Coarse aggregate gradation "A"
- Use of admixtures; air entrainment and water reducers to achieve air content and slump within LA DOTD Standard Specifications for Roads and Bridges for each mix type.

Slag mixes were identical to the reference mix with the exception that various percentages (15%, 30%, and 50%) of the cement were replaced with GGBFS by weight.

The test factorial was as follows:

GRAVEL MIXES

Cement Content	Reference Mix	15 % Slag Mix	30% Slag Mix	50 % Slag Mix
5.8 bag Class B Paving Mix	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF
6.5 bag Class AA Structural Mix	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF

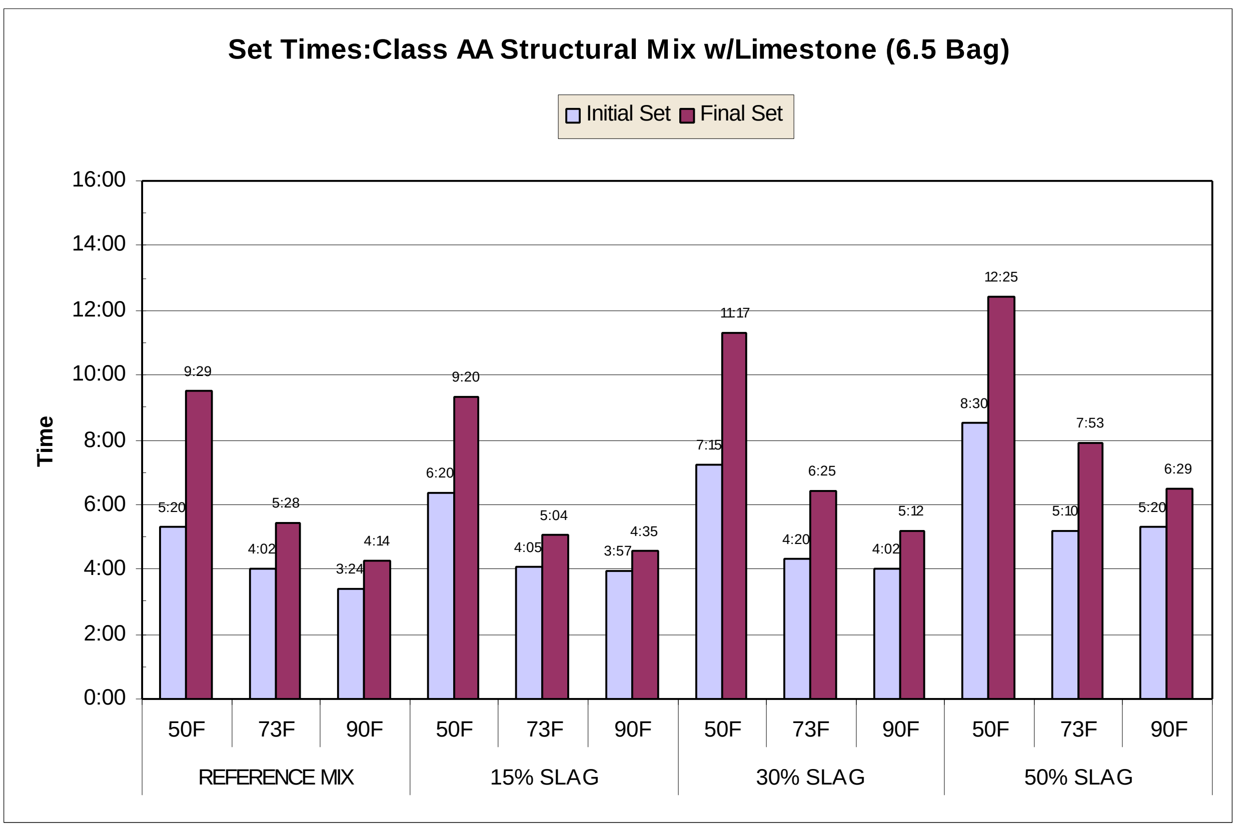
LIMESTONE MIXES

Cement Content	Reference Mix	15 % Slag Mix	30% Slag Mix	50 % Slag Mix
5.4 bag Class B Paving Mix	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF
6.0 bag Class A Structural Mix	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF	1 @ 50 EF 1 @ 73 EF 1 @ 90 EF

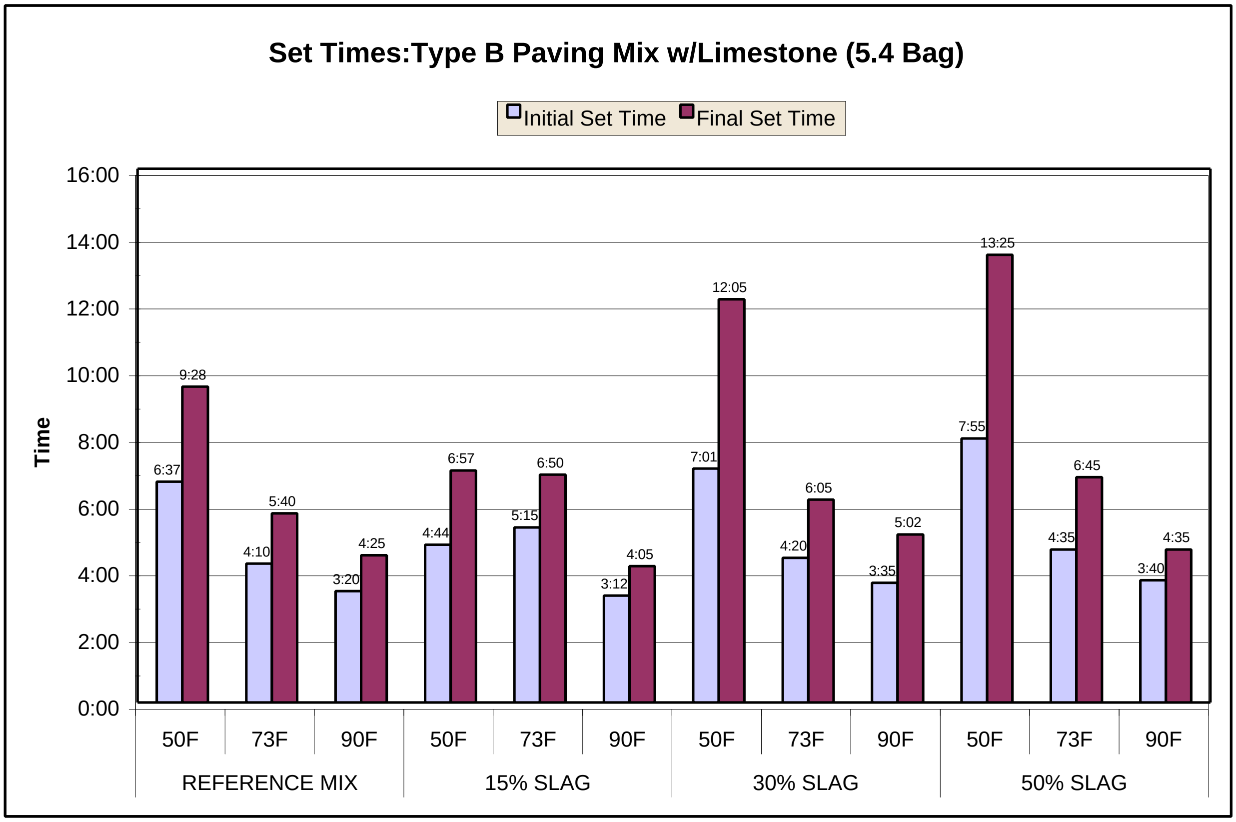
Note: Each "window" of the test factorial will be comprised of all tests previously mentioned.

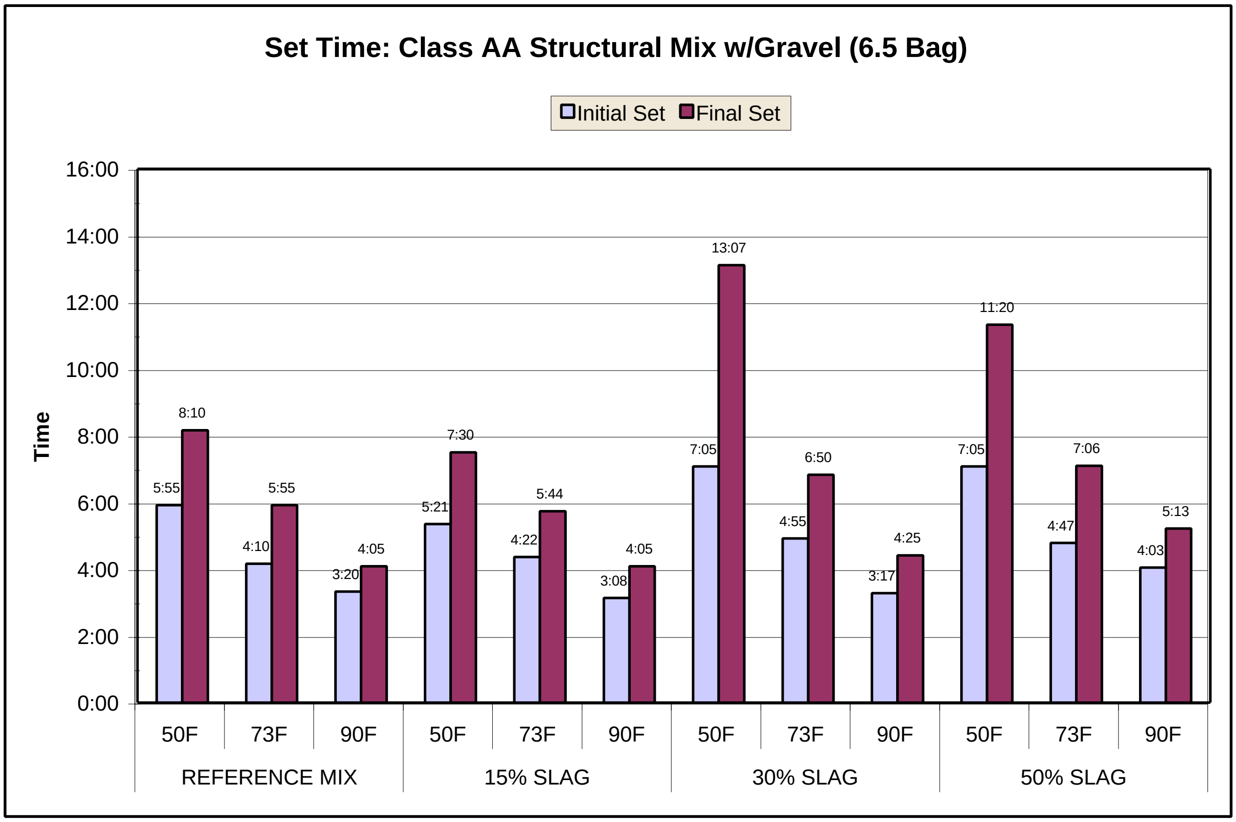
DISCUSSION OF RESULTS

Set times and strength development are the chief concerns of construction personnel concerning the use of GGBFS in LA DOTD concrete. Although GGBFS does delay set times, the major contributing factor that affects the set times, initial and final, is the curing environment, specifically temperature. This is true for both plain portland cement concrete and concrete containing GGBFS. The graph below shows a class AA structural mix that uses limestone for its coarse aggregate. Increasing set times with decreasing temperatures and increasing GGBFS addition is noticeable and evident for all four-mix variables. This trend is consistent for the other mixes in this study and reaffirms that not only the increasing addition percentage of GGBFS but also environmental factors, specifically temperature, are the primary influence on set times. From the graph below it is clear that temperature has a greater influence on set times than the substitution percentage of GGBFS.

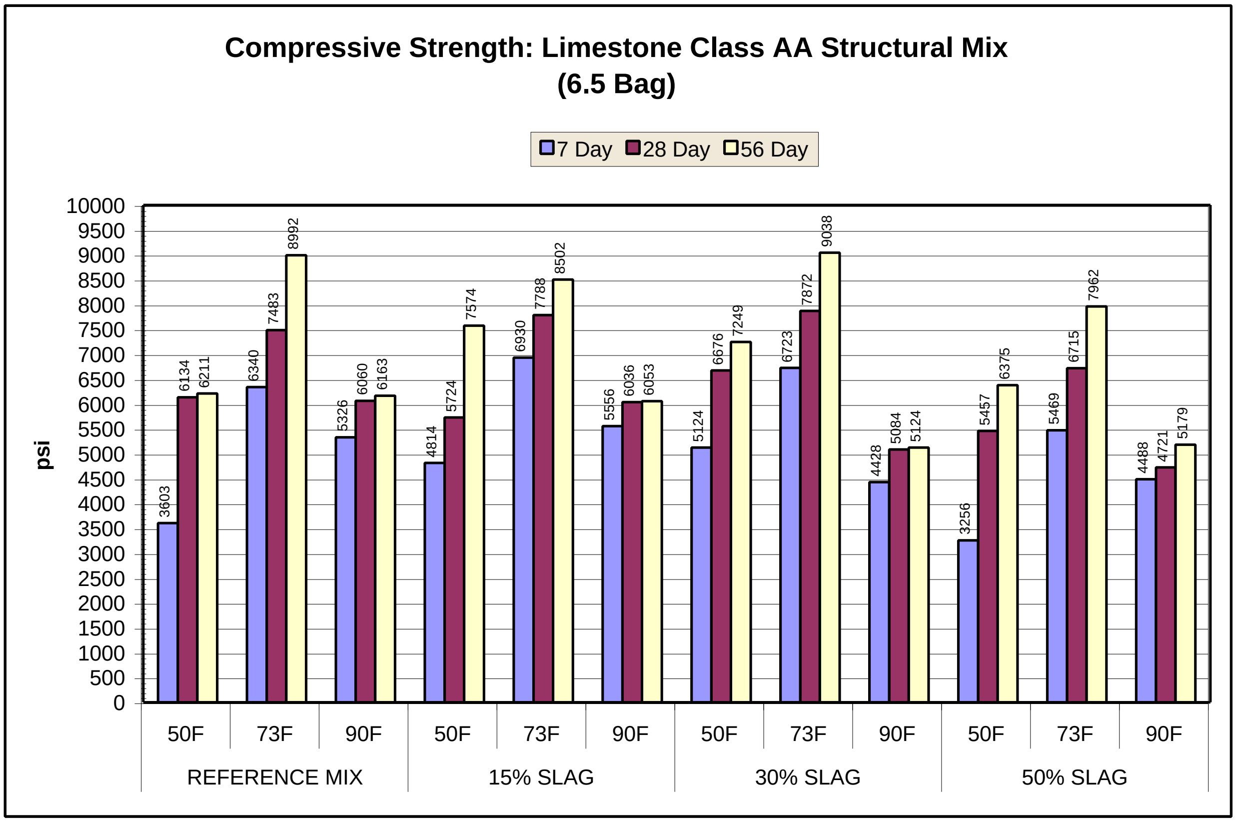


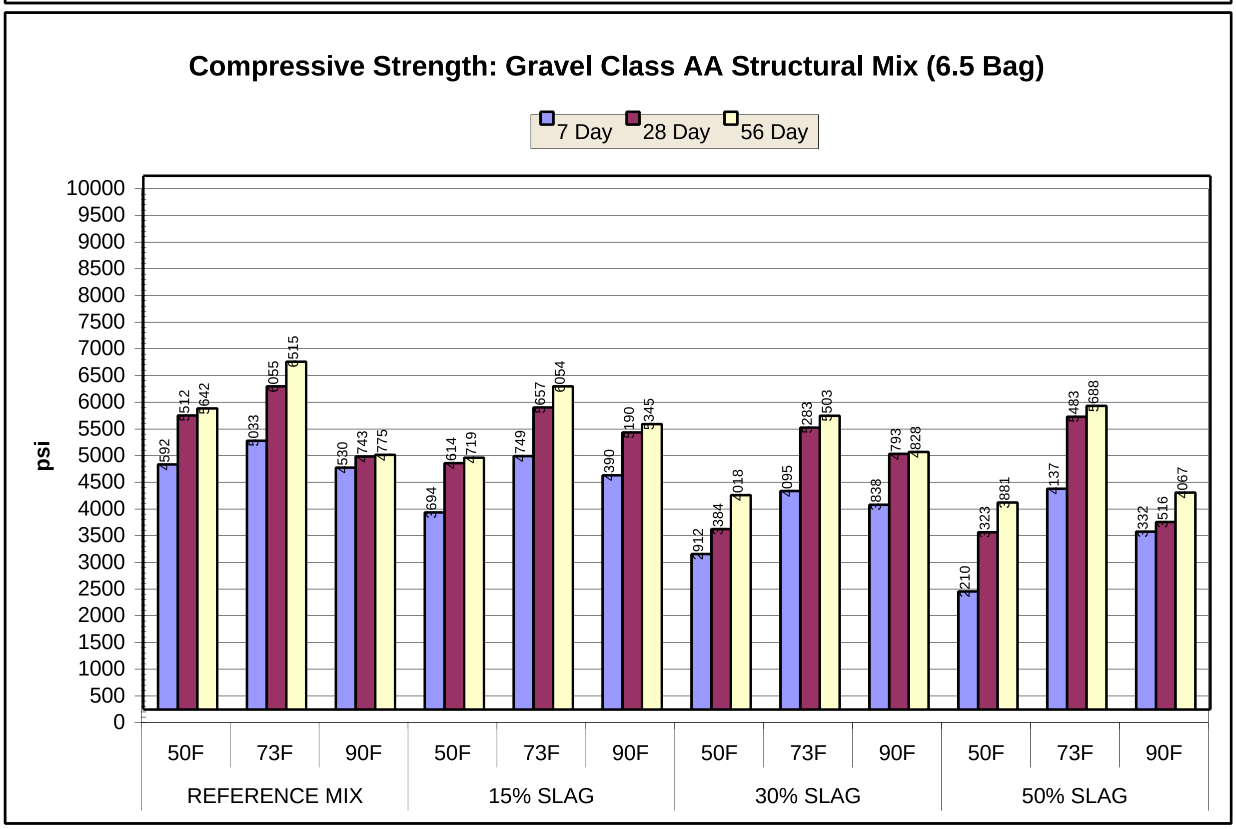
As compared to the previous study on grade-120 GGBFS, there were no distinguishable trends between the two grades of GGBFS or the substitution amounts of GGBFS relating to set times. Differences were noticed in reference mixes along with mixes containing GGBFS. As evident in the following two graphs, set times for GGBFS concrete increases in proportion to the substitution
amount.

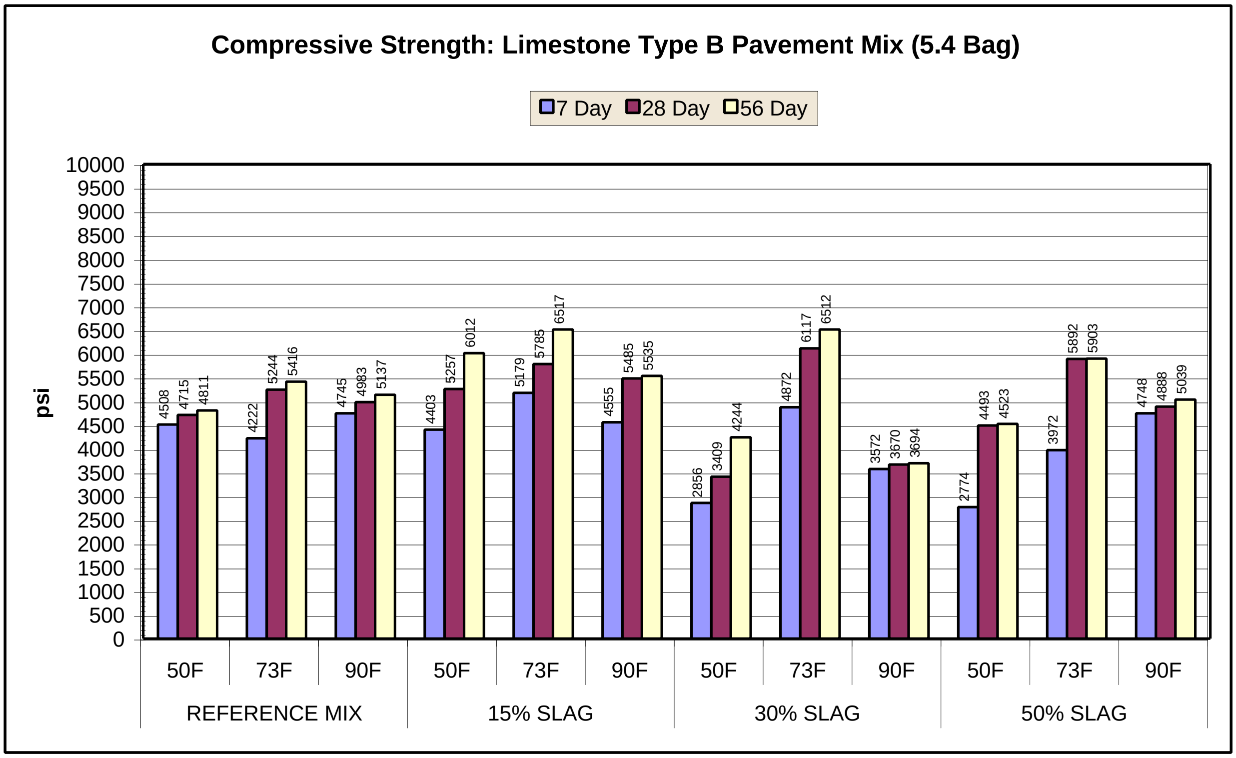


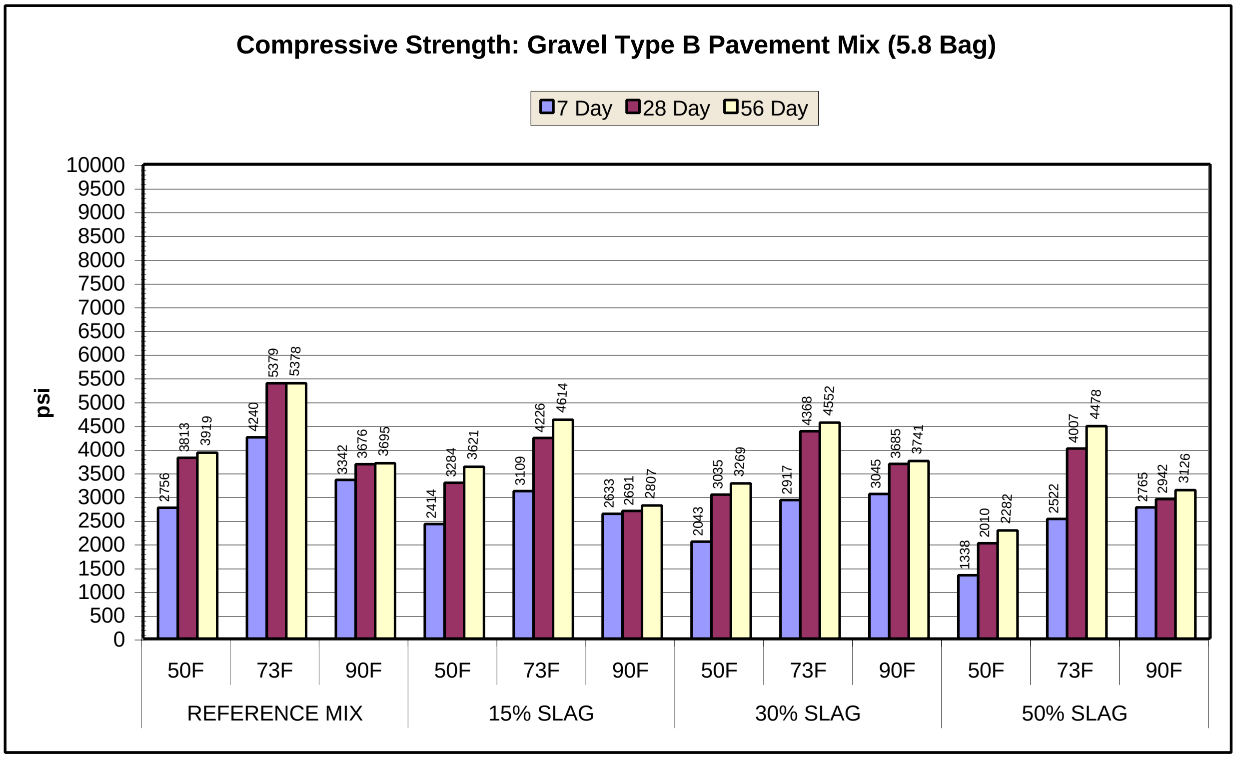


As anticipated, the grade-100 GGBFS compressive and flexural strength results were not as outstanding as those from the grade-120 GGBFS study, nor were they significantly inferior. The following four graphs illustrate these points using four different mixes with 15, 30, and 50 percent GGBFS substitution amounts. The expected difference between the limestone and gravel mixes is of particular interest. The limestone mixes exhibited greater strengths with only two (30% GGBFS at 50 ºF and 90 ºF each) of the 28-day results below LA DOTD specifications of 4000 psi and 4200 psi for pavements and structures, respectively. The gravel mixes exhibited reduced strengths with several (the 50 ºF and 90 ºF mixes) failing LA DOTD specifications. All mixes that were properly cured met LA DOTD specifications.

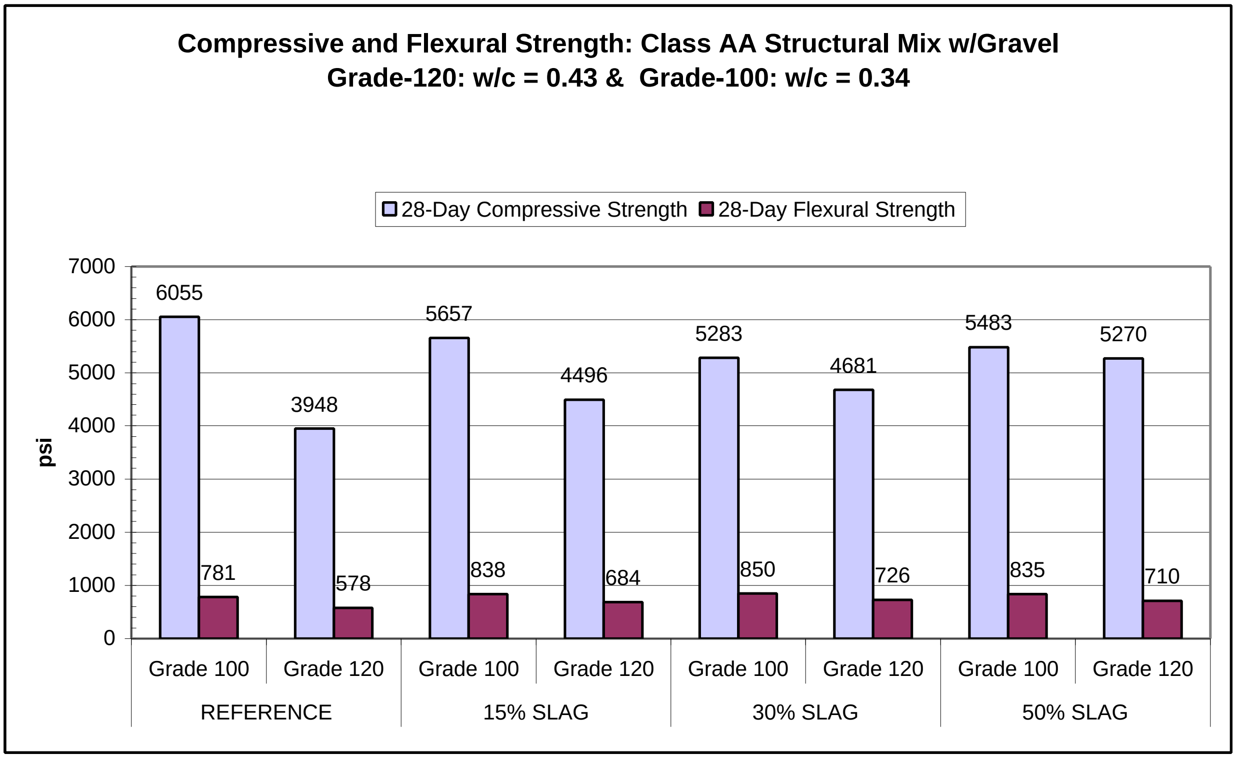

Compressive Strength: Limestone Class AA Structural Mix
(6.5 Bag)
7 Day
28 Day
56 Day
psi
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
3603
6134
6211
6340
7483
8992
5326
6060
6163
4814
5724
7574
6930
7788
8502
5556
6036
6053
5124
6676
7249
6723
7872
9038
4428
5084
5124
3256
5457
6375
5469
6715
7962
4488
4721
5179
50F
73F
90F
50F
73F
90F
50F
73F
90F
50F
73F
90F
REFERENCE MIX
15% SLAG
30% SLAG
50% SLAG

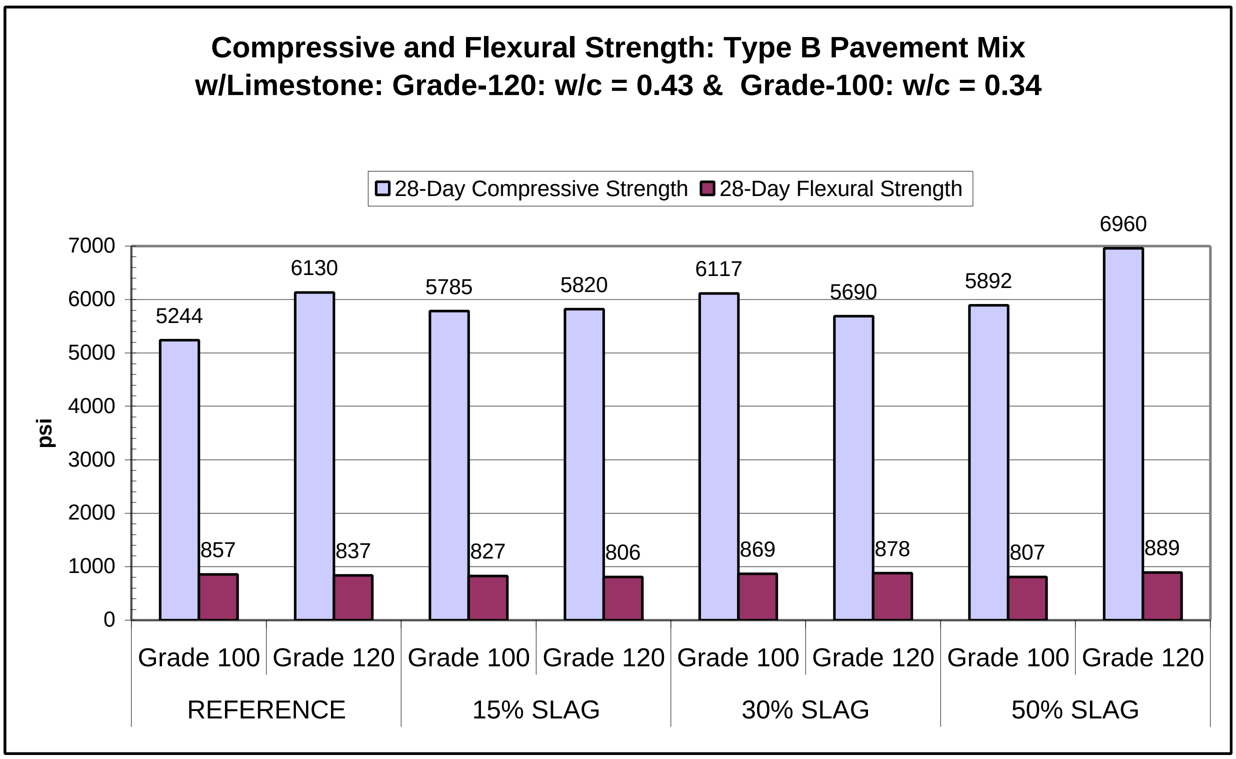

Compressive Strength: Gravel Class AA Structural Mix (6.5 Bag)
7 Day
28 Day
56 Day
psi
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
592
512
642
033
055
515
4530
4743
4775
3694
4614
4719
4749
657
054
4390
190
345
2912
3384
4018
4095
283
503
3838
793
828
2210
3323
3881
4137
483
688
3332
3516
4067
50F
73F
90F
50F
73F
90F
50F
73F
90F
50F
73F
90F
REFERENCE MIX
15% SLAG
30% SLAG
50% SLAG

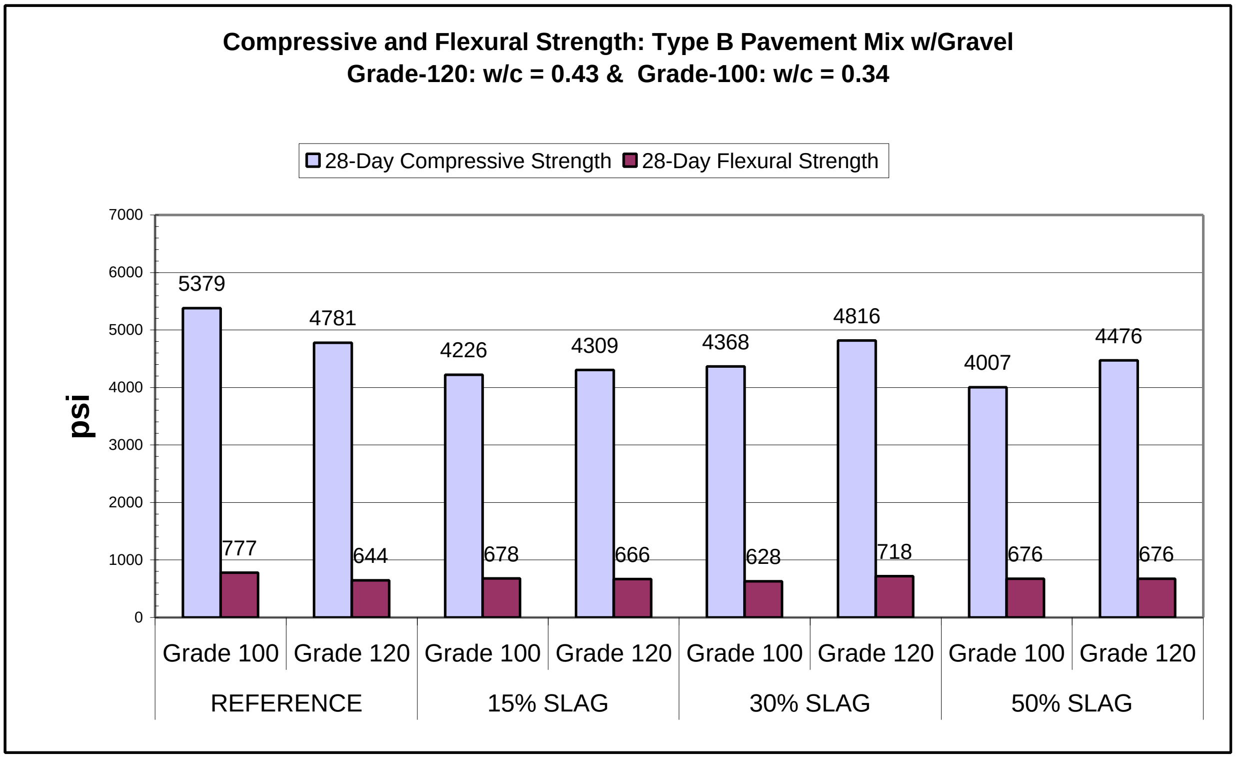

Compressive Strength: Limestone Type B Pavement Mix (5.4 Bag)
7 Day
28 Day
56 Day
psi
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
4508
4715
4811
4222
5244
5416
4745
4983
5137
4403
5257
6012
5179
5785
6517
4555
5485
5535
2856
3409
4244
4872
6117
6512
3572
3670
3694
2774
4493
4523
3972
5892
5903
4748
4888
5039
50F
73F
90F
50F
73F
90F
50F
73F
90F
50F
73F
90F
REFERENCE MIX
15% SLAG
30% SLAG
50% SLAG



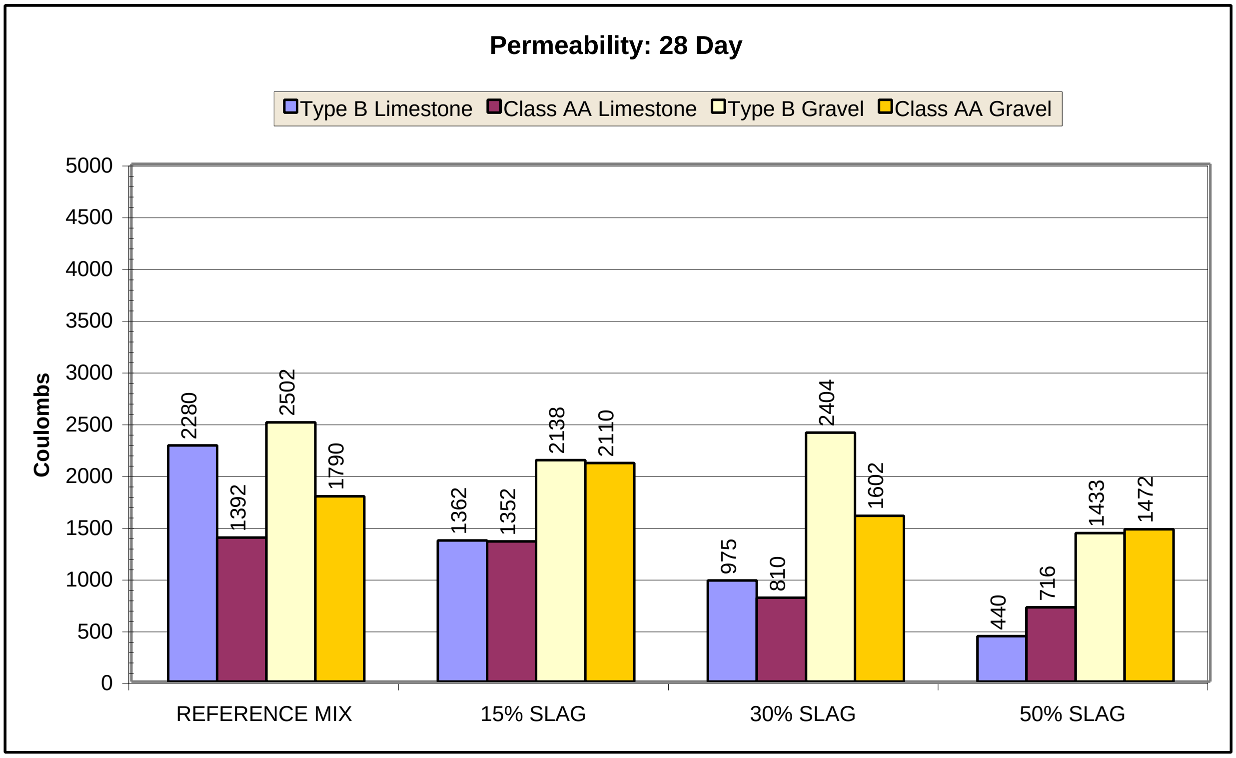
As in all concrete mix designs, the water to cement ratio (w/c) is a fundamental factor in the final strengths and durability characteristics developed by the concrete. The following graphs illustrate this obvious point by comparing a grade-120 GGBFS mix with a higher w/c of 0.43 to a comparable mix using grade-100 GGBFS with a lower w/c of 0.34. In the same mix, grade-100 GGBFS develops greater strengths than grade-120 GGBFS. A change in the w/c ratio along with the use of high range water reducers (HRWR) can overcome this difference.


Compressive and Flexural Strength: Class AA Structural Mix w/Gravel
Grade-120: w/c = 0.43 & Grade-100: w/c = 0.34
28-Day Compressive Strength
28-Day Flexural Strength
psi
7000
6000
5000
4000
3000
2000
1000
0
6055
781
3948
578
5657
838
4496
684
5283
850
4681
726
5483
835
5270
710
Grade 100
Grade 120
Grade 100
Grade 120
Grade 100
Grade 120
Grade 100
Grade 120
REFERENCE
15% SLAG
30% SLAG
50% SLAG


Compressive and Flexural Strength: Type B Pavement Mix
w/Limestone: Grade-120: w/c = 0.43 & Grade-100: w/c = 0.34
28-Day Compressive Strength
28-Day Flexural Strength
psi
7000
6000
5000
4000
3000
2000
1000
0
5244
857
6130
837
5785
827
5820
806
6117
869
5690
878
5892
807
6960
889
Grade 100
Grade 120
Grade 100
Grade 120
Grade 100
Grade 120
Grade 100
Grade 120
REFERENCE
15% SLAG
30% SLAG
50% SLAG



The rapid chloride permeability test was conducted at 28 days. Again, there was a noticeable difference between the coarse aggregates used in the mixes with the crushed limestone exhibiting superior results. In addition, it appears that the higher cement content of the structural mixes also improved permeability ratings. All mixes exhibited decreases in permeability with increasing amounts of GGBFS substitution and the lowest permeability results at the maximum 50 percent substitution rate. The type B paving mixes with gravel ranged from a moderate rating for the reference mix to a low rating at the 50 percent substitution rate. The class AA structural mixes with gravel maintained a low rating for all mixes: 0, 15, 30, and 50 percent substitution rate. The type B paving mix with limestone ranged from a moderate rating for the reference mix to a low rating at the 15 percent substitution rate and very low ratings for the 30 and 50 percent substitution rate. The class AA structural mixes with limestone ranged from a low rating for the reference and 15 percent substitution rate to very low ratings for the 30 and 50 percent substitution rate. Permeability testing was not performed on the grade-120 GGBFS study so no comparison data is available. The following graph presents the grade-100 GGBFS results.



Variations in length change were insignificant. No appreciable trend was observed between mix types, coarse aggregate used, curing temperature/environment, or substitution amounts of GGBFS even though the total cementitious paste content grew with the increasing amounts of GGBFS substitution.

Scaling resistance was mediocre for all samples, including reference mixes. The majority of samples had either moderate to severe scaling (rated 4) or severe scaling (rated 5). Only three of the samples, where limestone was the coarse aggregate, exhibited moderate scaling (rated 3).

There were no appreciable trends in abrasion resistance between mix types or substitution amounts of GGBFS. As expected, the samples that were continuously cured at 50 ºF and 90 ºF did exhibit a noticeable decrease in abrasion resistance as compared to the lab-cured samples at 73 ºF.

As part of the approval process for acceptance to the QPL, grade-100 GGBFS was utilized in a demonstration/paving project (SP. 014-03-0028). This project was a five lane urban section through the town of Oberlin on U.S. 165 in Allen parish. Plans specified that paving would proceed in two phases. The first phase would use grade-100 GGBFS in the type B paving mix where upon a successful and uneventful completion of phase one, a request to use grade-100 GGBFS would be considered for the phase two paving.

As of this writing, phase one has been successfully completed with earthwork for the phase two paving currently in progress. Concrete cylinder breaks for the phase one paving were greater than expected. A few problems have occurred on this project but none have been associated with the grade-100 GGBFS paving concrete. Since the phase one paving operation was successful with no material problems, grade-100 GGBFS has been approved for the phase two paving operation.

Recommendations

Based on the design factorial of this study, there are no reasons to restrict grade-100 GGBFS and its use in concrete mixtures provided that the existing quality control program, developed by the Materials and Testing Section, is followed and proper specification modifications are implemented.

As specified in the 2000 Edition of the Louisiana Standard Specifications for Roads and Bridges for grade-120 GGBFS the following is recommended for grade-100 GGBFS:

- The substitution rate should be limited to 45 percent and a separate hopper provided for the storage of slag when blended at the redi-mix plant.

- The maximum allowable 50/50 cement/slag blend shall be blended at the point of origin.

- Mixing of slag and fly ash or any cement containing fly ash shall not be permitted.

- Trial batches will be required to demonstrate the compatibility of the mix components before accepting the mix design.

- During trial batching, the producer should be required to demonstrate that any required physical property of the mix will be achieved when slag is included in the mix design.

- The consistency and performance of grade-100 and grade-120 GGBFS is source dependent. LA DOTD should require notification of any change in source material.