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PENNDOT RESEARCH

SUMMARY OF EVALUATION OF AAA CONCRETE MIXTURES

STATEWIDE HIGH PERFORMANCE CONCRETE INITIATIVE
Project No: 03-01 (C07)

TASK 5 SPECIAL STUDY 2 REPORT
December 1, 2005

By P. J. Tikalsky and Samrudhdi Suresh

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Prepared for
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1.INTRODUCTION

The objective of this special study is to determine the level of compliance of current bridge construction practices with the concepts of high performance concrete. The study will evaluate the AAA mixture designs used by PennDOT in terms of permeability, workability, coarseness and shrinkage. The purpose of the special study is to determine the extent in which PennDOT has already adopted High Performance Concrete (HPC) principles and practices for concrete in bridges. The results provide a platform to build additional specifications.

About five mixtures designs were received from various ditricts of PennDOT. The provided data comprises of useful details to understand the behavior of concrete and its future performance. The parameters based on which the mixtures designs are evaluated are dealt with individually. The parameters are as follows:

- Coarseness Factor
- Individual % Retained (Gradation)
- Chloride Penetration (Initiation Period)
- Life Cycle Cost
- Shrinkage

The evaluation is based on available literature and efficient mixture design analysis software. The software used to analyze the coarseness factor and Individual % retained is 'seeMIX II Design and Analysis Methods'. It is a product of Shillstone Companies, Inc. The service life and permeability of concrete were gauged using the software 'Life 365'. Life-365 is a Computer Program for Predicting the Service Life and Life-Cycle Costs of Reinforced Concrete Exposed to Chlorides. The shrinkage of the mixtures is determined by the G-Z shrinkage prediction model.

2. LITERATURE REVIEW

2.1 SeeMIX II

The properties of concrete depend on the properties of the raw materials, the proportion of the mixture, and the way they are mixed. However, how the material comes together as a mixture is more important than the individual properties of raw materials. SeeMIX II is a software which aids in analyzing the concrete mixtures, proportioning new concrete mixtures and adjustments in the mixtures to change the material characteristics. The analysis of a mixture design requires a detailed input. The software analyses the mixture on the basis of the following inputs

Setup

- General information
- Units of Measure
- Report Titles
- Aggregate Specifications

Mixture Design

- Units of Measure
- General Information
- Comments
- Water Specification
- Cement Specifications
- Mineral additives
- Admixtures
- Aggregate properties

The mixture design is analyzed considering all the above factors and the output is as follows

- Proportions
- Analysis
- Material characteristics
- Coarseness factor
- Grading
- % Passing Chart
- Individual % Retained Chart
- .45 Power Chart

2.1.1Coarseness Factor

The coarseness factor chart in SeeMIX II represents the workability of a mixture vs. its coarseness factor. A typical coarseness factor chart is as shown below:

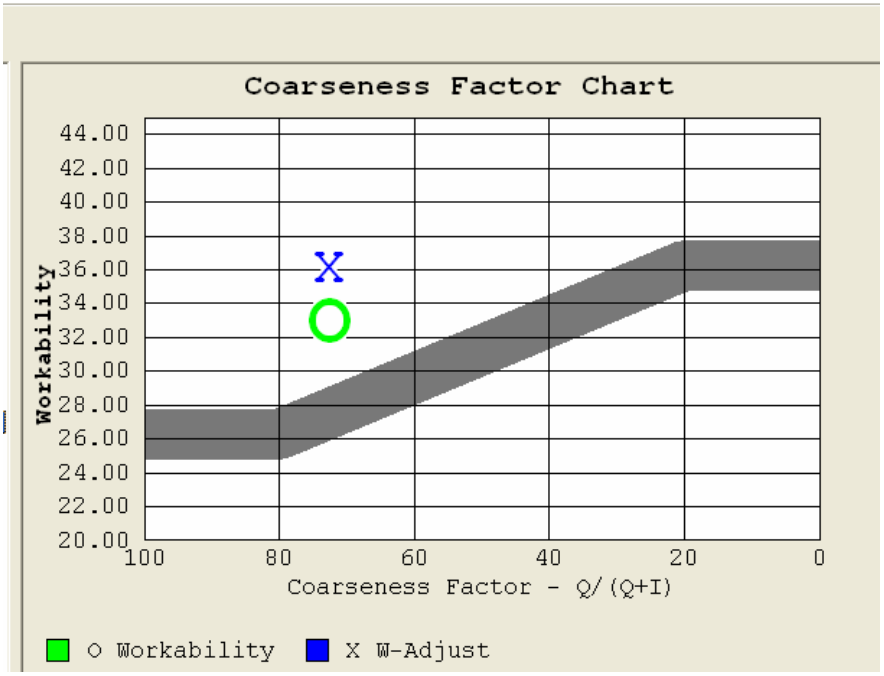

Figure 1 Coarseness Factor Chart

W: The y-axis of the chart represents the workability of the mixture. "W" is the percentage of combined aggregate that passes the #8 sieve (sieve analysis) Workability of concrete is an important property. It is the ease with which the concrete can be placed and consolidated. In ASTM C-125, workability is defined as the property determining the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity.

W-Adj: This is the workability Factor corrected for cementitious content. When water is added to cement, it forms a gel, but it does not happen immediately as the cement acts as fine sand for a while. Thus, a correction factor is applied to "W". A baseline of 6 sacks (94 pound each) of cement is considered. For each sack of cement over 6 sacks, "W" is increased by 2.5, and is decreased by 2.5 for each sack under 6 sacks. Thus, adjustments are done depending on the quantity of cement used.

Q: "Q" indicates the percentage of combined aggregate that is retained on 3/8" sieve.

I: It represents the percentage passing 3/8" sieve and retained on #8 sieve

Q/Q+I: This is the coarseness factor which is indicated on the x-axis of the coarseness factor chart. In other words, it is the ratio of % retained on 3/8" sieve to % retained on #8 sieve. This means a gravel mixture with all material passing the 3/8" sieve would have a CF of 0 (0/ (0+X)). And, a gap graded mixture where no material that passes 3/8' sieve is retained on #8 sieve will have a CF of 100 (Y/(Y+0)).

The coarseness factor chart indicates if a mixture is rocky or sandy. The shaded bar signifies the theoretically optimum concrete mixture. It should be understood that "Up" in the charts means 'more sand in the mixture', "Down" means 'more rock'. "Left" means 'fewer 3/8"-#8 particles' and "Right" means 'more 3/8"-#8 particles'

However, the band in the above chart is suitable for mass concreting applications. In the case of mixtures chosen for the analysis, they are mostly used for bridges, and other thinner sections. Thus a little higher workability is required. Hence, the chart is modified to suit our case better. A workability which is 4-5 points above the top of the band should be more appropriate for this study. The following is the modified chart for the same data-points. (W-adj and Coarseness Factor)

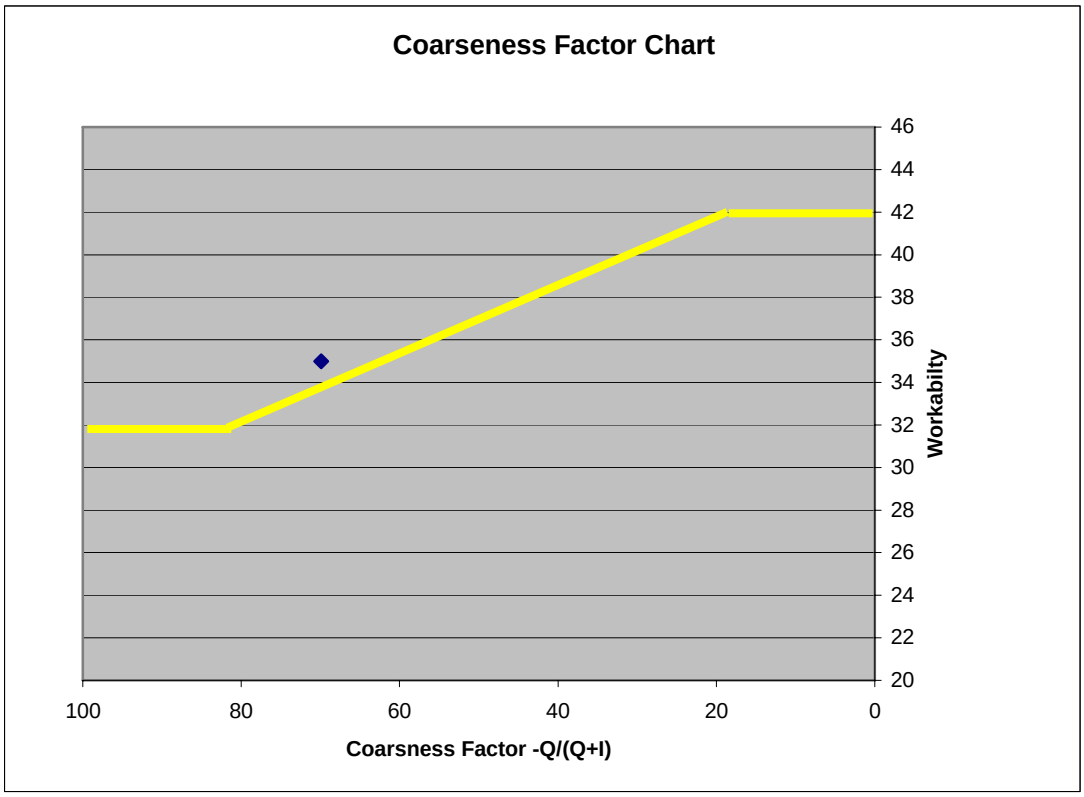

Figure2. Modified Coarseness Factor Chart

Thus, this concrete mixture, even though seemed to be more sandy according to the actual chart, is very accurate according to the modified chart. Therefore a mixture with workability and coarseness factor combination as shown above is considered a good mixture.

2.1.2Individual % Retained

The individual Percent Retained Chart shows the percentage of material that passes one sieve and is retained on the next sieve. The blue curve represents the total material including the paste and the green curve represents just the aggregate.

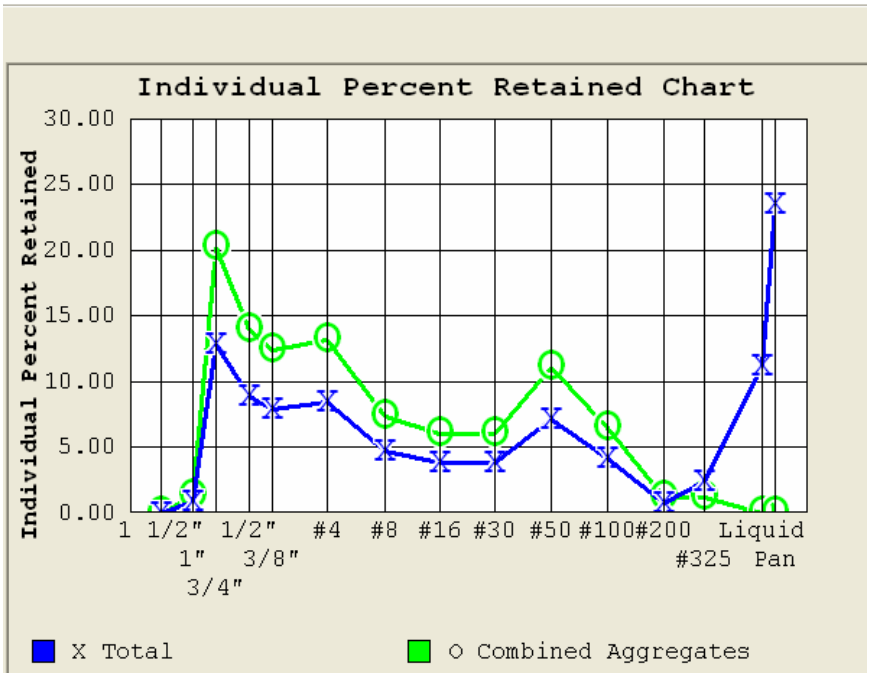

Figure 3 Individual Percent Retained Chart

Gap graded aggregates can be a major problem to a concrete mixture. Too much material retained on a sieve can cause particle interlocking resulting reduction of mobility of the mixture. On the other hand too little material retained on consecutive sieves causes increase in water demand and segregation. The "8-18 specification' is used in this case which implies that the percentage of material retained on each sieve should lie between the values of 8 % to 18%. For this specification, the green line with the circles should be referred (Combined Aggregate). It should be noted that if the amount retained on one sieve is high and the next sieve is low, then the two sieves balance each other. Therefore when considering the '8-18' specification, the average of two sieves should be considered. However, if there are three or more consecutive highs or lows, the aggregates can cause substantial problems.

The gradation of aggregate used is an important factor on which the properties of a concrete mixture depend. A well graded aggregate mixture has a number of benefits such as increased strength at a constant cement content, decreased water demand, decreased permeability, decreased shrinkage and cracking, decreases segregation, better response to vibration and pumping, better finishing and handling.

The 'Liquid' sieve is a fictitious sieve that retains particulate matter such as cement. It stops everything but liquids and air. Hence, whatever passes through it is either water or air. If this number is high, it implies decrease in strength, and increase in cracking. And the concrete mixture will not be fluid if this value is too low.

2.2Life 365

One of the major forms of concrete deterioration is corrosion of embedded reinforcement in concrete caused due to chloride penetration. The service life of reinforced concrete structures is decreased due to corrosion caused by the chlorides from deicing salts, groundwater or seawater. Various strategies such as use of low permeability concrete, non-corrosive reinforcement, chemical corrosion inhibitors, waterproofing, corrosion resistant steel, can be implied as a solution to this problem. However, to optimize the infrastructure repair and replacement cost, a complete life cycle cost analysis (LCCA) should be carried out. Thus all costs over the design life of the structure are computed by the means of LCCA.

Life 365 is comprehensive service life and life cycle cost model for reinforced concrete. This program is written by Evan Bentz & Michael Thomas and is a product of Master Builders Technologies, Grace Construction Products and Silica Fume Association.

It is advisable to analyze a mixture with user-defined scenarios to increase the accuracy of the results. The analysis is done on the basis of various parameters and user-inputs such as:

- Concrete Cost
- W/C Ratio
- % Class F Fly Ash
- % Slag
- % Silica Fume
- Type of Concrete Protection
- Type of Rebar Protection
- Type of Barrier
- Diffusion Coefficient
- m term
- Corrosion threshold
- Propagation time
- Geographic location
- Type of structure and nature of exposure; one-dimensional (e.g. parking or bridge deck) or two-dimensional (e.g. marine pile) model
- Depth of clear concrete cover to the reinforcing steel (xd)

The analysis is carried out in four separate steps as follows:

- Prediction of initiation period: t_i (time to the onset of corrosion)
- Prediction of propagation period: t_p (time to reach unacceptable corrosion levels)
- Determination of repair schedule to follow the first repair
- Estimation of life cycle costs

2.2.1 Chloride Penetration (Initiation Period)

The time taken to initiate corrosion is the initiation period. To be more precise, it is the time taken for sufficient chlorides to penetrate the concrete cover and accumulate in sufficient quantity at the depth of the embedded steel so that the corrosion is initiated.

Diffusion is assumed to be the dominant mechanism in prediction of initiation period. The governing differential equation (Fick's second law) is as follows:

$$\frac{dC}{dt} = D.\frac{d^2C}{dx^2} \qquad \text{Eqn.1}$$

Where: C = chloride content
D = apparent diffusion coefficient
x = depth (from the exposed surface)
t = time

The following relationship is used to account for time-dependent changes in diffusion:

$$D(t) = D_{ref}.\left(\frac{t_{ref}}{t}\right)^m \qquad \text{Eqn. 2}$$

Where: $D\ (t)$ = diffusion coefficient at time t
D_{ref} = diffusion coefficient at some reference time t_{ref} (= 28 days in Life-365)
m = constant (depending on mixture proportions)

The values of D_{ref} and m are either selected by Life-365 based on the mixture design details input by the user or are defined by the user (user-defined scenario)

2.2.2 Life Cycle Cost

Estimation of life cycle costs implies calculation of all costs over the whole life of the project. The model takes into consideration the various scenarios (automatic or user-defined scenarios), cost of items, cost of repairs, as well as the discount rate for calculating the costs in present worth.

Some cost information to be used in the life cycle cost analysis is to be provided by the user and the rest are assumed by the model. The user is responsible for providing the following cost information:

• Cost of concrete mixtures for the various strategies under consideration.

• Cost of repairs.
• Discount rate (i).
Life-365 assumes the following default costs for various rebar protection strategies:
• Black steel = $1.50/kg ($0.68/lb)
• Epoxy-coated rebar = $2.00/kg ($0.91/lb)
• Stainless steel = $10.00/kg ($4.54/lb)

Present Worth Value

The total life cycle costs include the initial construction costs and the discounted future repair costs over the life of the structure. The initial construction costs are the costs of materials used for the construction which comprises of the costs of concrete, steel (or other reinforcement) and surface protection (membrane or sealer). These costs are expressed as dollars per unit area of the structure (e.g. $/m2). While considering the future repair costs, the present worth of the costs is taken into consideration. The present worth is calculated using the discount rate '*i*' provided by the user and is given by the following formula:

$$PW = \frac{F}{(1+i)^t} \qquad \text{Eqn 3}$$

2.3 Shrinkage

The volume reduction that takes place in concrete as it hardens is called shrinkage. When shrinkage is restrained, it causes occurrence of cracks especially in flat structures such as bridge decks. Thus, it is a major cause of concrete deterioration and hence it is important to be able to asses the shrinkage values in order to predict the concrete behavior.

Several shrinkage prediction models such as B3 (developed at Northwestern University), ACI, Branson, GZ (developed by N.J. Gardener and J.W. Zhao) were considered for this study. B3 model is a very complex model which requires too many input parameters, which are not easily available in an ordinary mixture design details' information. After looking at the other shrinkage models and considering the data available for the given mixture designs, the shrinkage for the mixtures was calculated using the GZ model (Gardener model).

The GZ model calculates shrinkage at time t, at relative humidity at 40%, with correction factor for ambient relative humidity. Other parameters are: strength at end of moist curing, strength of concrete, duration since end of moist curing, member size. The following equations are use in calculating the shrinkage:

$$\in_{sh} = \in_{shu} .\beta(h).\beta(t) \qquad \text{Eqn.4}$$

$$\beta(h) = (1 - 1.18h^4) \qquad \text{Eqn.5}$$

$$\in_{shu} = 900.K.\left(\frac{f_{cm28}}{f_{cmtc}}\right)^{1/2}.\left(\frac{25}{f_{cm28}}\right)^{1/2}.10^{-6} \qquad \text{Eqn.6}$$

$$\beta(t) = \left[\frac{7.27 + \ln(t - t_c)}{17.18}\right].\left(\frac{t - t_c}{t - t_c + 0.015.(V/S)^2}\right) \qquad \text{Eqn.7}$$

Where: h	=	humidity expressed as decimal
t	=	age of concrete (days)
t_c	=	age drying commenced, end of moist curing (days)
t_o	=	age concrete loaded (days)
K	=	1 Type I cement, K=.70 Type II cement, K=1.33 Type III cement
V/S	=	volume/surface ratio (mm)
f_{cm28}	=	mean compressive strength at 28 days (Mpa)
f_{cmct}	=	compressive strength when drying commenced (Mpa)
f_{cmto}	=	compressive strength when loading commenced (Mpa)

In this case, some assumptions have been made based on various factors such as the area where the concrete design mixtures are being used, the average weather conditions, shrinkage patterns etc. Here we are considering the mixture designs of various districts of Pennsylvania, so the average humidity 'h', is assumed to be 70% that is 0.7 (www.ems.psu.edu). The age of concrete is taken as one year hence 365 days. For calculation of the volume and surface area of the structures, it is assumed that the average dimension of a span of concrete bridge decks where these mixtures are used is 48' X 1' and a depth of 8.5" that is .708'

3. PERFORMANCE OF AAA MIXTURES

This research evaluates the AAA mixture designs used on bridge decks by PennDOT. Each PennDOT district has provided about 5 mixture designs used by them in the past few years for evaluation. This study will help in determining the extent in which PennDOT has adopted HPC principles and practices for concrete in bridges. The mixtures are evaluated based on various parameters which are:

- Coarseness Factor
- Individual % Retained (Gradation)
- Chloride Penetration (Initiation Period)
- Life Cycle Cost
- Shrinkage (G-Z Model)

Coarseness Factor Chart

The coarseness factor chart in SeeMIX II (Shillstone Mixture Design Software) represents the workability of a mixture vs. its coarseness factor. The coarseness factor chart indicates if a mixture is rocky or sandy. The shaded bar in the chart signifies the theoretically optimum concrete mixture. It should be understood that "Up" in the charts means 'more sand in the mixture', "Down" means 'more rock'. "Left" means 'fewer 3/8"-#8 particles' and "Right" means 'more 3/8"-#8 particles. (Section 2.1.1.) A typical coarseness factor chart is as shown below:

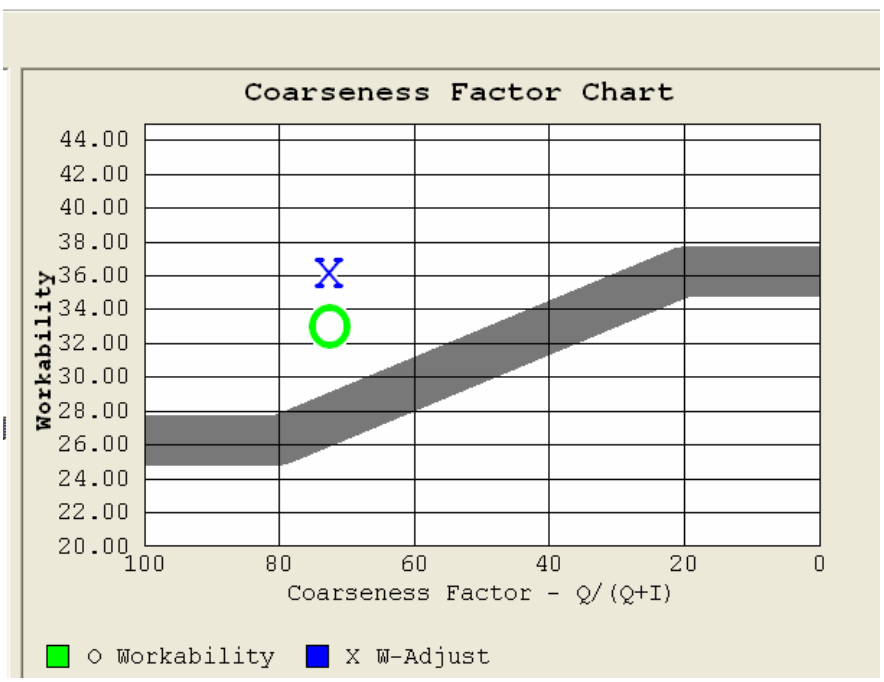

Figure 4 Coarseness Factor Chart

PennDOT provided with the AAA mixture designs used by its various districts in the bridge decks for the study and the mixture designs were analyzed and plotted for each district.

As discussed earlier, the mixture designs chosen for analysis are the mixture designs used by PennDOT in bridge decks (relatively thinner sections). However, the band in the above chart is suitable for mass concreting applications. Hence, the chart is modified to better suit this particular case. The band is required to be shifted 4-7 points upwards as higher workability is required for thinner sections. The following is the modified chart for the same data-points. (W-adj and Coarseness Factor)

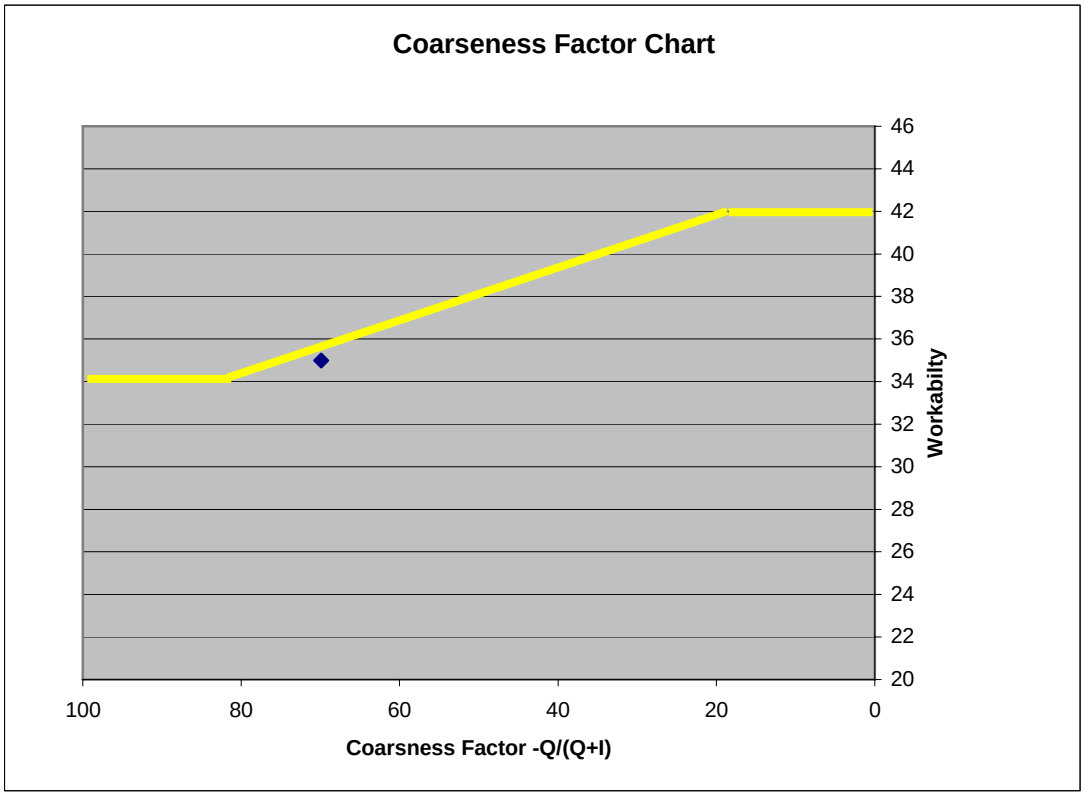

Figure 5 Coarseness Factor Chart

The coarseness factor chart for each district is given in Appendix A. The following is a chart representing AAA mixture designs used by the various districts of PennDOT. This chart enables us to have an overall idea of the type of mixtures used by PennDOT.

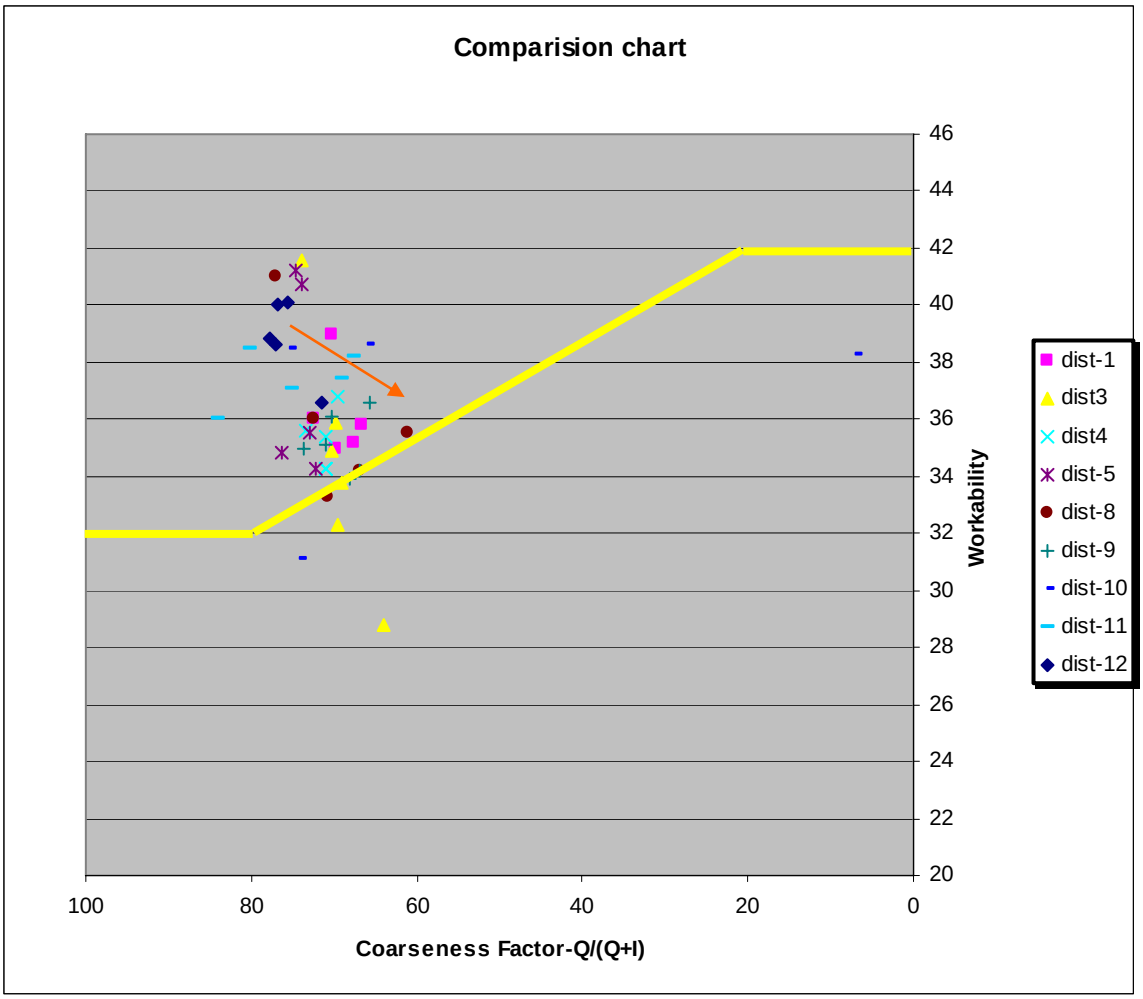

Figure 6 Coarseness Factor Comparison Chart

The above plot shows that most of the mixtures lie above the band and towards the left. As discussed earlier, "Up" in the charts means 'more sand in the mixture' and "Left" means 'fewer 3/8"-#8 particles'. Thus, the mixtures need to be shifted towards the right bottom as shown by the arrow in the above chart.

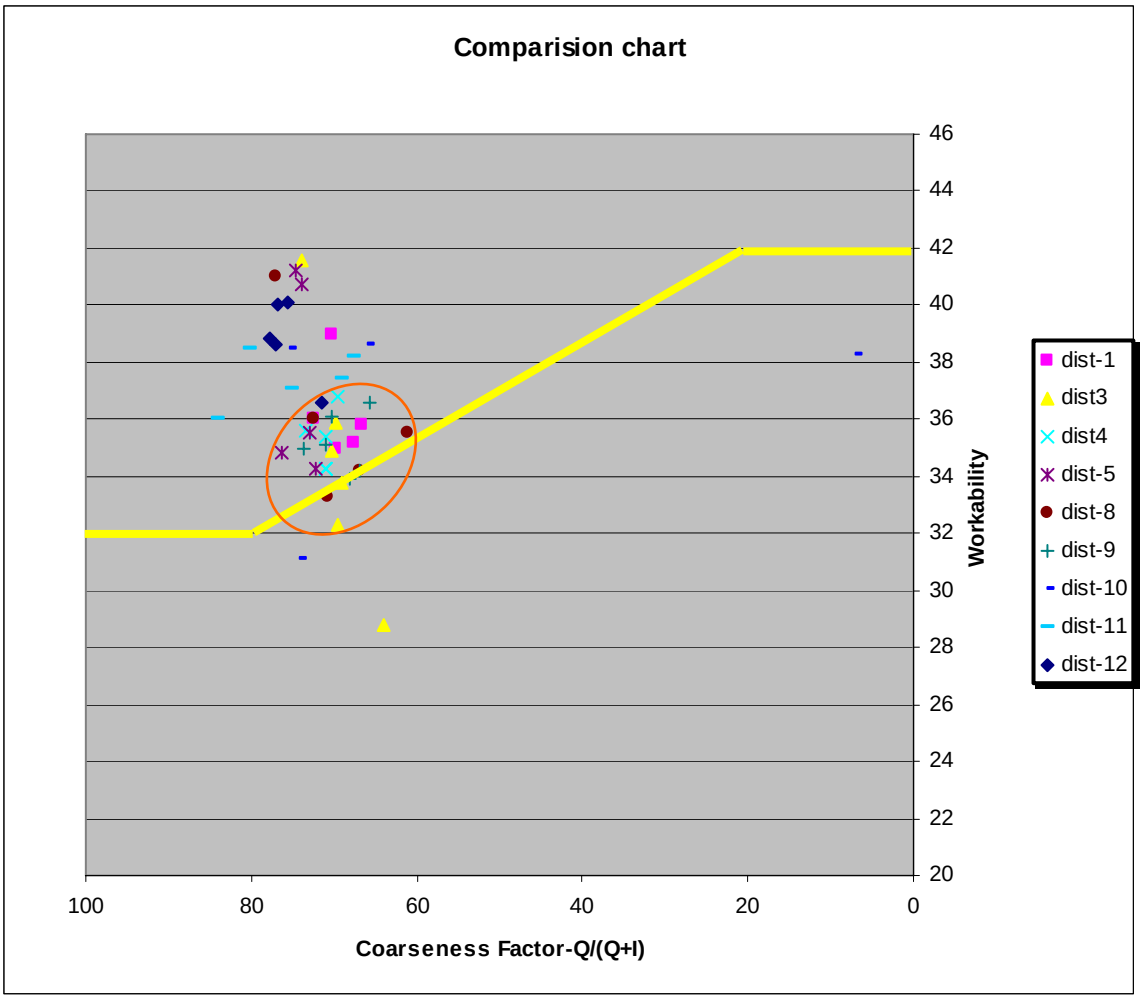

Figure 7 Coarseness Factor Comparison Chart

A number of AAA mixtures used by PennDOT for the bridge decks are in a relatively optimum zone. The data-points encircled in the above chart represent the mixtures with optimum workability and a good aggregate gradation. It can be seen from the above chart that the most of the mixture designs used by District-4, District-8 and District-9 lie close to, or on the band. Thus, these concrete mixtures have the optimum workability for the required job.

Individual % Retained

The percentage of material that passes one sieve and is retained on the next sieve is represented in the individual Percent Retained Chart. The blue curve represents the total material including the paste and the green curve represents just the aggregate.

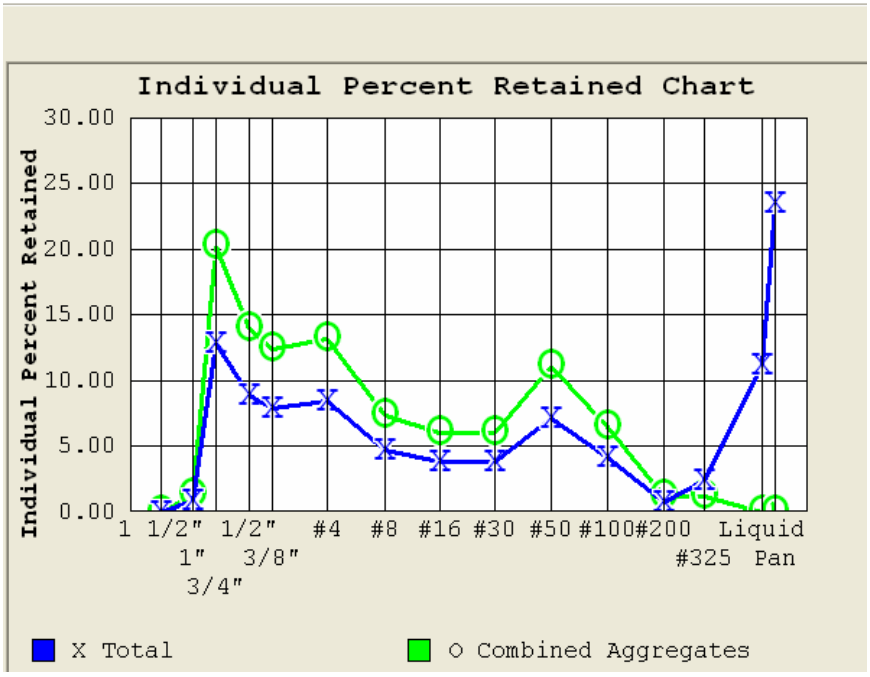

Figure 8 Individual Percent Retained Chart

The individual % retained charts for the mixtures used by various districts by PennDOT are given in Appendix B.

The “8-18 specification’ is used to evaluate the mixtures in this case, which implies that the percentage of material retained on each sieve should lie between he values of 8 % to 18%. Thus it should be checked that material retained on a sieve should neither be ‘too much’ nor ‘too little.

A better understanding would be possible if a ‘%retained chart’ for a mixture is studied with the corresponding coarseness factor chart. Let us consider the coarseness factor chart for District 3 (Appendix A)

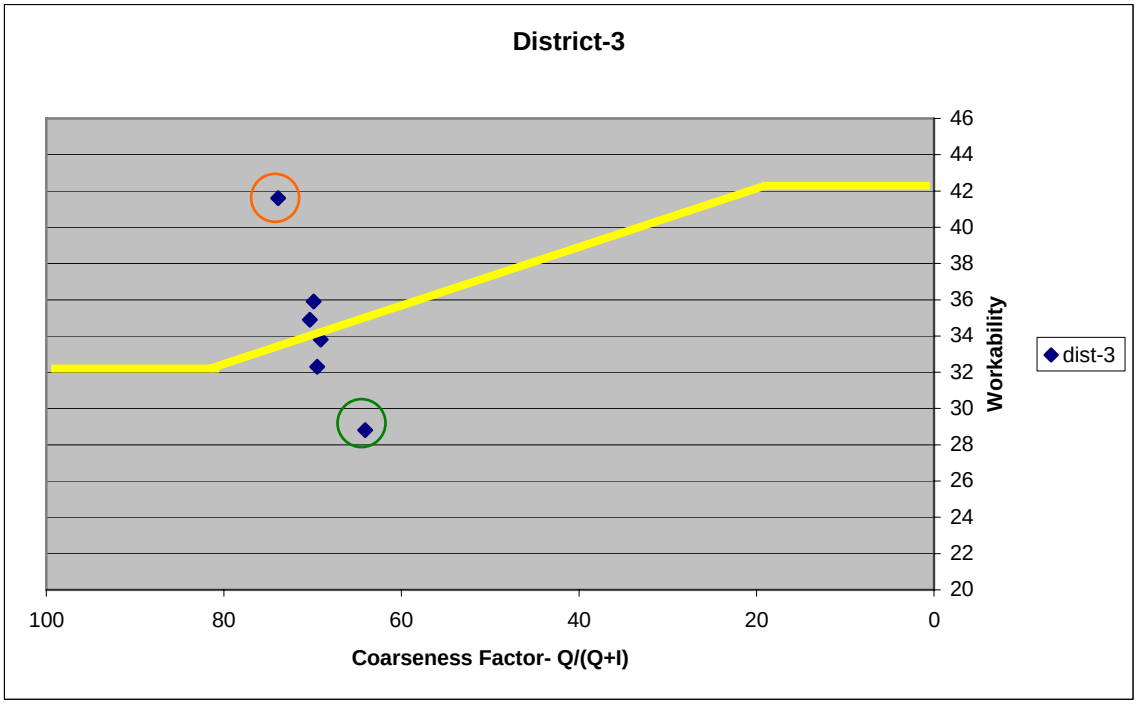

Figure 9 Coarseness Factor Chart for District 3

The % retained chart corresponding to the mixture at the top, encircled in red (say Mixture 3-1) in the above chart is shown below followed by the % retained chart corresponding to the mixture at the bottom, encircled in green (say Mixture 3-2).

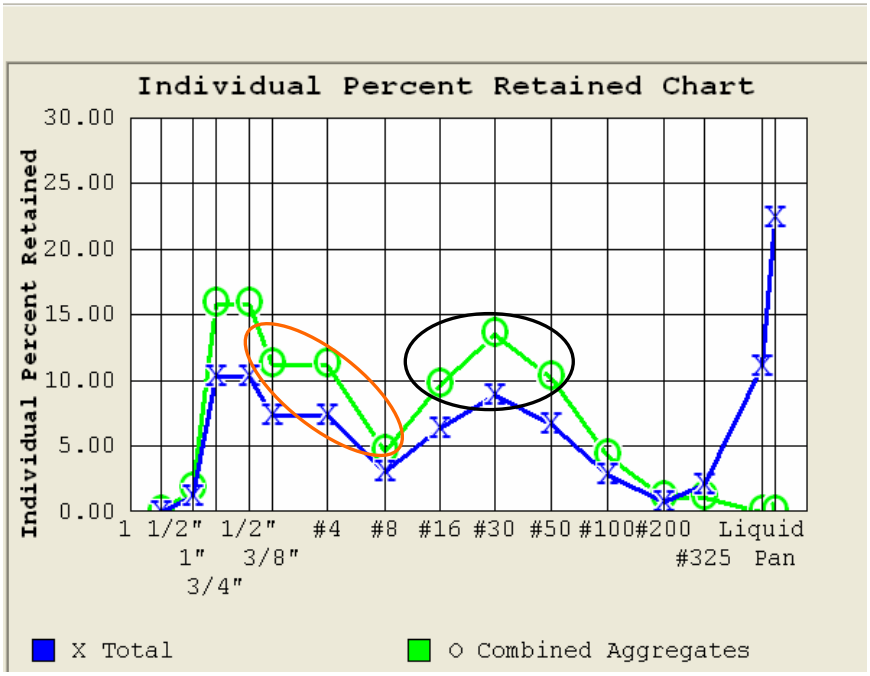

Figure 10 Individual Percent Retained Chart for Mixture 3-1

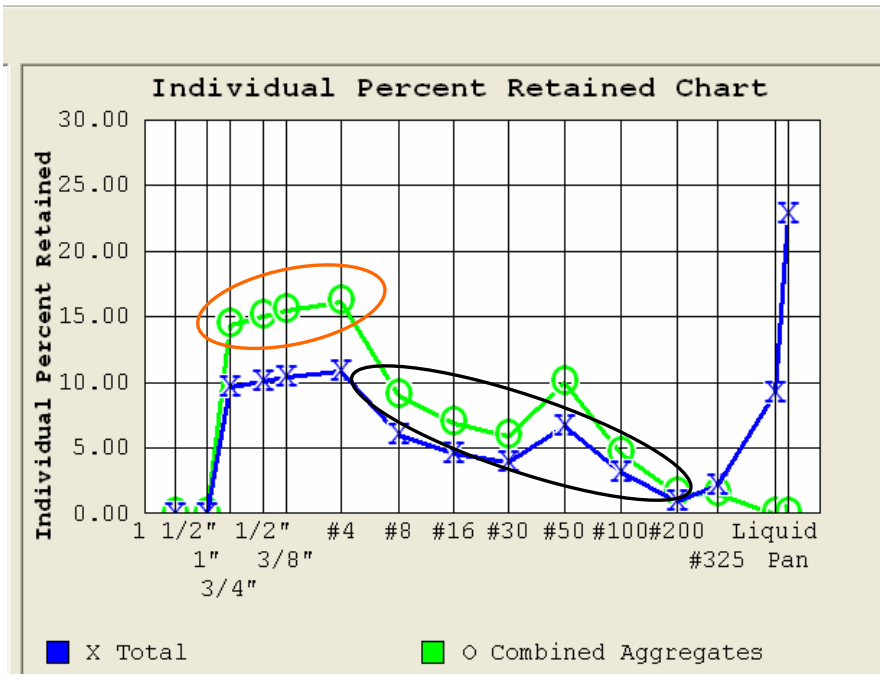

Figure 11 Individual Percent Retained Chart for Mixture 3-2

It can be seen in the % retained chart for 'Mixture 3-1' that the material retained on 3/8", #4 and #8 sieve is relatively low. Whereas the material retained in finer sieves is considerable. Thus the mixture would have less 3/8"-#8 particles and would be sandy. Thus from the % retained chart it can be inferred that the mixture would not be in an optimum workability zone but instead be above the bar and towards the left. This can be verified in the coarseness factor chart (Figure 9)

Similarly, in case of 'Mixture 3-2', it can be observed in the % retained chart that the aggregate used in the mixture is not well graded. The material retained in the sieves from 3/4" to #4 sieve is relatively high. The % retained in finer sieves is mostly 4-9 %. Thus, this mixture would tend to be rocky and hence workability would be very low for this mixture. The point corresponding to this mixture in the coarseness factor chart would thus be below the optimum workability bar. As mentioned earlier, the point encircled in green, which lies in the bottom, (Figure 9) corresponds to this mixture.

Studying the % retained charts for the mixtures used by the districts; it is observed that there is extremely less material retained in 1 ½" and 1" sieve. The data provided by the districts indicates that No. 57 coarse aggregate is used in the concrete mixtures. The concreting is to be done for bridge decks and the average thickness of the decks is taken as 8 ½". Therefore it is advisable to use larger size aggregate in the mixture. A No. 56 (AASHTO M43) Processed Aggregate would be a better gradation comparatively.

The chart also indicates that most of the mixes are too sandy. This means that the fineness modulus of the aggregate is relatively low. The mixtures using aggregate with relatively lower fineness modulus (from data provided by PennDOT), lie above the

optimum workability band in the coarseness factor chart. The allowable fineness modulus (AASHTO M6) is 2.3 to 3.1. A higher fineness modulus of aggregates used would imply greater amount of coarse aggregate. Hence, a mixture which uses aggregate with higher fineness modulus would be more suitable. The recommendations for choosing aggregate corresponding to its fineness modulus may be altered by increasing the lower limit of the range from '2.3' to '2.5'.

Chloride Penetration (Initiation Period) and Life Cycle Cost (Life 365)

Corrosion of embedded reinforcement in concrete caused due to chloride penetration is a major form of concrete deterioration. The service life of reinforced concrete structures is decreased due to corrosion caused by the chlorides from deicing salts, groundwater or seawater. Use of low permeability concrete, non-corrosive reinforcement, chemical corrosion inhibitors, waterproofing, corrosion resistant steel, are various strategies which can be implied as a solution to this problem. However, to optimize the infrastructure repair and replacement cost, a complete life cycle cost analysis should be carried out. Thus all costs over the design life of the structure are computed by the means of LCCA.

Life 365 is comprehensive service life and life cycle cost model for reinforced concrete The AAA mixture designs provided by PennDOT were analyzed using this software. The properties of scenarios are input by the user and are shown in the figure below. (Figure 12) The results were obtained in a tabular form. (Figure 13)

Properties of Scenarios

mix1-1,2,3,4,5	Mix Design : w/cm = 0.43, Cost 80 $/yd^3 D_{28} = 9.38x10^{-12} m^2/s , m = 0.20 , C_t = 0.05 %wt conc Epoxy Coated Steel (0.60 $/lb) , Propagate = 20 years
mix2-1,2,3	Mix Design : w/cm = 0.43, Cost 80 $/yd^3 Fly ash = 35 % D_{28} = 9.38x10^{-12} m^2/s , m = 0.48 , C_t = 0.05 %wt conc Epoxy Coated Steel (0.60 $/lb) , Propagate = 20 years
mix2-4,5	Mix Design : w/cm = 0.43, Cost 80 $/yd^3 D_{28} = 9.38x10^{-12} m^2/s , m = 0.20 , C_t = 0.05 %wt conc Epoxy Coated Steel (0.60 $/lb) , Propagate = 20 years
mix2-6	Mix Design : w/cm = 0.38, Cost 80 $/yd^3 Fly ash = 15 % D_{28} = 7.11x10^{-12} m^2/s , m = 0.32 , C_t = 0.05 %wt conc Epoxy Coated Steel (0.60 $/lb) , Propagate = 20 years

Figure 12 Properties of Scenarios (Input)

Project Title:	District 1,2	Date:	2005/11/22 - 7:43 am
Performed by:			
Structure:	1D slab/wall structure	Exposure:	Urban Highway Bridges
Location:	ERIE , Pennsylvania		0.85 %wt conc @ 6 years
Clear cover:	2.50 in		
Design Life:	75 years	Discount Rate:	3.0 %

Scenario Name	Initial Cost ($/ft^2)	Repair Cost ($/ft^2)	Repair Area (%)	Repair Interval (years)	Time to Initiation (years)	Time to 1st Repair (years)	Total Life Cycle Cost ($/ft^2)
mix2-1,2,3	4.61	37.20	10	10	29.5	49.5	6.59
mix2-6	4.61	37.20	10	10	17.0	37.0	7.99
mix2-4,5	4.61	37.20	10	10	8.3	28.3	9.47
mix1-1,2,3,4,5	4.61	37.20	10	10	8.3	28.3	9.47

Figure 13 Tabular Output- Life 365 Analysis for District 1 and District 2

To simplify the analysis, a common definition of Scenario and Structure was given for each case of mixture. Some assumptions are:

- Overall thickness of the slab is 8.5” with a clear cover of 2.5”
- The exposure conditions considered are for urban highway bridges located in Erie Pennsylvania
- Addition of Ipanex to the concrete mixture would increase the cost by $25/Cu.Yd.
- Only chloride diffusion considered (other types of diffusions are not considered)

The values given in the ‘Time to Initiation’ columns represent the time taken to initiate corrosion. To be more precise, it is the time taken for sufficient chlorides to penetrate the concrete cover and accumulate in sufficient quantity at the depth of the embedded steel so that the corrosion is initiated. The values in the ‘Total Life Cycle Cost’ column show all costs over the design life of the structure computed by the means of LCCA.

The tabular outputs of the AAA mixtures (Appendix C) along with their corresponding scenario properties, give a good idea of life cycle costs of the bridges and their susceptibility to chloride penetration. Let us consider the case of District 1 and 2 as shown in the above tables. The mixtures from District 1 are represented as ‘mix1-1,2,3,4,5’ and those from District 2 are represented as ‘mix2-1,2,3,4,5,6.’ Mixtures 1-1, 2,3,4,5 comprises of only portland cement as cementitious material. The steel used as re-

bar is epoxy coated. The tabular output indicates that the time for initiation for these mixtures is 8.3 years and the Life cycle cost is \$9.47/ft^2. The time to first repair is shown as 28.3 years. So is the case for Mixture2-4, 5. On the other hand, Mixture2-1, 2, 3 contains 35 % fly ash and Mixture2-6 contains 15 % fly ash. The time to initiation for Mixture2-1, 2, 3 is 29.5 years and life cycle cost is \$6.59/ft^2. The first repair would have to be done after 49.5 years in this case. Clearly, it is more beneficial to use Mixture2-1, 2, 3 in comparison with Mixture1-1, 2,3,4,5.

The mixtures containing pozzolanic material such as fly ash, slag, silica fume etc. have a better resistance to chloride penetration and hence, the time for initiation is higher. Also the total life cycle cost is significantly low. In contrast to that, mixtures containing only cement (Type I, in most of the cases) are more susceptible to chloride penetration as they have low permeability. Thus, time to initiation is very low resulting in frequent and early repairs. This in turn increases the total life cycle cost value. The life cycle cost for such a case is in order of \$9/ft^2 and above and the time to initiation can be as low as 8 years.

Another factor which is significant here is the water cement ratio of the mixture. Consider District 3. Mixtures 3-1, 3-2 and 3-3 have 15 % fly ash in them, and their water cement ratios are 0.43, 0.42 and 0.39 respectively. (Appendix C). The time to initiation and life cycle cost for the mixtures are 13.3, 14, 16.2 years and \$8.38, \$8.31, \$8.07 per square feet respectively. Thus for same scenario and a lower water cement ration, a mixture would have a relatively lower total life cycle cost and a time for chloride penetration to initiate would be high. However, a very low water cement ratio may not be suitable for workability of concrete.

Shrinkage

Several shrinkage prediction models such as B3 (developed at Northwestern University), ACI, Branson, GZ (developed by N.J. Gardener and J.W. Zhao) were considered for shrinkage calculation of these mixtures. Considering the data available for the given mixture designs and studying the level of accuracy of the shrinkage models, the GZ model (Gardener model) was chosen to calculate the shrinkage for the mixtures. (Eqn. 4)

Some assumptions have been made for shrinkage calculations in this study. The assumptions are based on various factors such as the area where the concrete design mixtures are being used, the average weather conditions, shrinkage patterns etc. Here we are considering the mixture designs of various districts of Pennsylvania, so the average humidity 'h', is assumed to be 70% that is 0.7 (www.ems.psu.edu). Shrinkage is calculated for concrete at 365 days. For calculation of the volume and surface area of the structures, it is assumed that the average dimension of a span of concrete bridge decks where these mixtures are used is 48' X 1' and a depth of 8.5" that is .708'

The shrinkage calculated for the mixtures using the GZ model are shown in Appendix D. The shrinkage value in this model depends on various factors such as humidity, age of concrete, end of moist curing (days), type of cement, volume/surface ratio, mean compressive strength at 28 days, compressive strength when drying commenced.

However, some of these values, such as compressive strength at 28 days and compressive strength when drying commenced, also depend on the mixture design.

Studying the shrinkage values along with the mixture designs, a particular pattern can be observed. Mixtures with lower water cement ratio have lower shrinkage when other constituents are similar. Hence, for similar properties of scenario, a mixture will have greater shrinkage if its water cement ratio is greater. This can be understood by taking the example of ‘mixture3-7’ and ‘mixture6-4’. ‘Mixture3-7’ has a water cement ratio of ‘0.47’ and the shrinkage corresponding to this value is 178.79 microstrains, whereas ‘mixture6-4’ has a water cement ration of ‘0.36’ and has estimated shrinkage of 152.32 microstrain.

Shrinkage also depends on the total cementitious material present in the mixture. For instance, consider ‘mixture4-2’ which contains 799 pounds of total cementitious material. The shrinkage of this mixture is calculated to be 174.12 microstrains which is relatively a higher value when compared to that of mixtures with lower amounts of cementitious material. The cementitious material should be confined to about 650 pounds to control the shrinkage. The presence of pozzolanic material also affects the shrinkage

4. PERFORMANCE OF HPC

In order to determine the level of compliance of current bridge construction practices with the concepts of high performance concrete, it is important to study the performance of HPC. The proposed HPC mixtures for bridge deck structures have been put to use on I-99 bridges. The proposed HPC mixture designs are as follows:

	Percentage of constituent					
Mixture No.	Portland Cement	GGBFS	Class F Fly Ash	Silica Fume	Specified Chemical Admixture	Cost $/yd^3
HPC-101	50	50	-	-	-	90
HPC-102	70		30	-	-	85
HPC-103	55	40	-	5	-	140
HPC-105	55	42	-	3	-	120
HPC-106	70	-	30	-	Ipanex	110
HPC-107	50	50	-	-	Ipanex	115
HPC-108	70	-	27	3	-	115
HPC-109	65	-	30	5	-	135
HPC-110	95	-	-	5	-	140

Figure14 HPC Mixtures

This section mainly deals with analysis of HPC mixtures using ‘Life 365’. It has been emphasized to bring out the cost differences between AAA and HPC mixtures. Although the initial costs of use of HPC mixtures may be relatively high, the eventual cost including the repair costs and the total life cycle cost turns out to be extremely low for HPC mixtures. The AAA mixtures have been evaluated using ‘Life 365' assuming the cost of the mixture to be $80/yd$^{3.}$ The above table shows the estimated costs of the HPC mixtures. These values are used in the software ‘Life 365’ for the analysis. The tabular output of the analysis for HPC mixtures by ‘Life 365’ is as shown:

Project Title:	hpc-mixtures 1	Date:	2005/11/22 - 8:05 am
Performed by:			
Structure:	1D slab/wall structure	Exposure:	Urban Highway Bridges
Location:	ERIE , Pennsylvania		0.85 %wt conc @ 6 years
Clear cover:	2.50 in		
Design Life:	75 years	Discount Rate:	3.0 %

Scenario Name	Initial Cost ($/ft^2)	Repair Cost ($/ft^2)	Repair Area (%)	Repair Interval (years)	Time to Initiation (years)	Time to 1st Repair (years)	Total Life Cycle Cost ($/ft^2)
hpc-106	5.40	37.20	10	10	47.9	67.9	5.90
hpc-103	6.19	37.20	10	10	51.6	71.5	6.19
hpc-101	4.87	37.20	10	10	30.5	50.5	6.33
hpc-105	5.66	37.20	10	10	39.3	59.3	6.78
hpc-102	4.74	37.20	10	10	23.8	43.7	7.09

Figure15 Tabular Output-Life 365 Analysis for HPC Mixtures (1)

Project Title:	HPC mixtures (2)	Date:	2005/11/22 - 8:06 am
Performed by:			
Structure:	1D slab/wall structure	Exposure:	Urban Highway Bridges
Location:	ERIE , Pennsylvania		0.85 %wt conc @ 6 years
Clear cover:	2.50 in		
Design Life:	75 years	Discount Rate:	3.0 %

Scenario Name	Initial Cost ($/ft^2)	Repair Cost ($/ft^2)	Repair Area (%)	Repair Interval (years)	Time to Initiation (years)	Time to 1st Repair (years)	Total Life Cycle Cost ($/ft^2)
hpc-107	5.53	37.20	10	10	55.5	75.5	5.53
hpc-109	6.05	37.20	10	10	55.0	75.0	6.05
hpc-108	5.53	37.20	10	10	34.5	54.5	6.83
hpc-110	6.19	37.20	10	10	15.8	35.8	9.68

Figure16 Tabular Output-Life 365 Analysis for HPC Mixtures (2)

It can be observed that the total life cycle cost per square feet for most of these mixtures is $7 or less as compared to $7-10 for most of the AAA mixtures. Also, the time for initiation for HPC is quite high mostly more than 20 years. According to the analysis, HPC mixtures can prevent corrosion due to chloride penetration for as long as 50 years. In the case of AAA mixtures, the time to initiation mostly lies between 8 to 20 years. Hence, the concrete in the bridge decks starts deteriorating quite early which calls for early and frequent repairs. This in turn increases the overall money spent on the bridges over its complete life, hence increasing the total life cycle cost.

Thus the cost-effectiveness of use of HPC mixtures can be clearly understood. Some of the mixtures used by PennDOT which comply with the HPC standards can be recognized to have lower life cycle costs and hence a better performance.

5. SUMMARY AND CONCLUSIONS

The AAA mixtures used by PennDOT have been analyzed using various softwares and models in this report. The study aims to determine the compliance of these AAA mixtures with HPC principles. The results provide a platform to build additional specifications.
About five mixtures designs were received from various districts of PennDOT. The data provided comprises of useful details to understand the behavior of concrete and its future performance. The parameters based on which the mixtures designs are evaluated are dealt with individually. The parameters are as follows:

- Coarseness Factor
- Individual % Retained (Gradation)
- Chloride Penetration (Initiation Period)
- Life Cycle Cost
- Shrinkage

A number of AAA mixtures used by PennDOT for the bridge decks are in a relatively optimum zone of workability in the coarseness factor chart. The data-points encircled in the coarseness factor comparison chart (Figure 7) represent the mixtures with optimum workability and a good aggregate gradation. Although several AAA mixtures lie in the optimum workability zone, the chart indicates that most of the mixtures lie above the band and towards the left. Thus, the mixtures need to be shifted towards the right bottom as shown by the arrow in Figure 6. As the mixtures are sandy, the total coarse aggregate content of the mixtures can be increased so that the gradation is balanced and the mixtures lie in the optimum workability area. Also the percentage of aggregate between the 3/8” and the #8 sieve should be increased.

Studying the individual percentage retained charts for the mixtures used by the districts; it is observed that there is extremely less material retained in 1 ½” and 1” sieve. The data provided by the districts indicates that No. 57 coarse aggregate is used in the concrete mixtures. The concreting is to be done for bridge decks and the average thickness of the decks is taken as 8 ½”. Therefore it is advisable to use larger size aggregate in the mixture. A No. 56 (AASHTO M43) Processed Aggregate would be a better gradation comparatively.

The chart also indicates that most of the mixes are too sandy. This means that the fineness modulus of the aggregate is relatively low. The mixtures using aggregate with relatively lower fineness modulus, (from data provided by PennDOT), lie above the optimum workability band in the coarseness factor chart. The allowable fineness modulus (AASHTO M6) is 2.3 to 3.1. A higher fineness modulus of aggregates used would imply greater amount of coarse aggregate. Hence, a mixture which uses aggregate with higher fineness modulus would be more suitable. The recommendations for choosing aggregate

corresponding to its fineness modulus may be altered by increasing the lower limit of the range from ‘2.3’ to ‘2.5’.

Life 365 is comprehensive service life and life cycle cost model for reinforced concrete The AAA mixture designs provided by PennDOT and the proposed HPC mixtures for use at the bridge decks were analyzed using this software. The effects of: addition of pozzolanic material, percentage of pozzolanic material added and the water to cement ratio used for the mixture can be understood in this analysis. It has also been emphasized to bring out the cost differences between AAA and HPC mixtures.

The mixtures containing pozzolanic material such as fly ash, slag, silica fume etc. have a better resistance to chloride penetration and hence, the time for initiation is higher. Also the total life cycle cost is significantly low. In contrast to that, mixtures containing only cement (Type I, in most of the cases) are more susceptible to chloride penetration as they have low permeability. Thus, time to initiation is very low resulting in frequent and early repairs. This, in turn increases the total life cycle cost value. The life cycle cost for such a case is in order of $\$9/ft^2$ and above and the time to initiation can be as low as 8 years.

Another factor which is significant here is the water cement ratio of the mixture. It can be observed that for same scenario properties and lower water cement ratio, a mixture would have a relatively lower total life cycle cost and the time for chloride penetration to initiate would be high. However, a very low water cement ratio may not be suitable for workability of concrete.

Although the initial costs of use of HPC mixtures may be relatively high, the eventual cost including the repair costs and the total life cycle cost turns out to be extremely low for HPC mixtures. It can be observed that the total life cycle cost per square feet for most of these mixtures is $7 or less as compared to $7-10 for most of the AAA mixtures. Also, the time for initiation for HPC mixtures is quite high mostly more than 20 years. Some of the HPC mixtures prevent corrosion due to chloride penetration for as long as 50 years. In the case of AAA mixtures, the time to initiation mostly lies between 8 to 20 years. Thus, the cost-effectiveness of use of HPC mixtures can be clearly understood. Some of the mixtures used by PennDOT which comply with the HPC standards can be recognized to have lower life cycle costs and hence a better performance.

Studying the shrinkage values along with the mixture designs, a particular pattern can be observed. Mixtures with lower water cement ratio have lower shrinkage when other constituents are similar. Hence, for similar properties of scenario, a mixture will have greater shrinkage if its water cement ratio is greater. Shrinkage also depends on the total cementitious material present in the mixture. The mixtures with high amounts of cementitious material tend to have a higher value of shrinkage. The total cementitious material should be confined to about 650 pounds to control the shrinkage. The presence of pozzolanic material also affects the shrinkage

The overall study and analysis of AAA mixtures and comparing it with HPC mixtures, the following suggestions can be made to build additional specifications

- total coarse aggregate content of the mixtures can be increased
- A No. 56 (AASHTO M43) Processed Aggregate: a better aggregate gradation
- Aggregates with higher fineness modulus to be used. (Recommended FM 2.5 - 3.1).
- Use of pozzolanic material (proposed HPC mixture designs)
- Optimum water/cement ratio.
- Limiting the total cementitious content of the mixture.

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