MAKING PRECAST CONCRETE MIXTURES MORE SUSTAINABLE WITH BYPRODUCT FINE AGGREGATE

L. K. Crouch, Ph.D., P.E., Tennessee Technological University Department of Civil Engineering, Cookeville, Tennessee
Ben Byard, E.I., Auburn University Highway Research Center, Auburn, AL
J. D. Self, E.I., Pro2Serve, Inc., Oak Ridge, TN

ABSTRACT

Precast concrete mixtures using byproduct screenings as fine aggregate, instead of river sand, increase the use of post-industrial byproducts from approximately 4 percent by mass to 35 and 39 for conventional and self-consolidating mixtures, respectively. Both conventional and self-consolidating mixtures were developed that met Tennessee Department of Transportation precast concrete compressive strength, w/cm ratio, and minimum cement content specifications using byproduct screenings as fine aggregate. Comparing the average 28-day results of conventional and self-consolidating mixtures to a conventional precast concrete mixture with river sand fine aggregate, the screenings mixtures had 16 and 13 percent lower compressive strengths, 15 and 16 percent lower static modulus of elasticity, and 10 and 0 percent lower split tensile strength, respectively. Further, the screenings mixtures had higher average absorption and shrinkage results. Current literature was able to predict the average split tensile strength, and average static modulus of elasticity values within 11 percent for both screenings mixtures. Shrinkage was under-predicted by 9 and 21 percent for conventional and self-consolidating mixtures with screenings, respectively. In summary, sustainability was greatly increased for a moderate sacrifice in performance.

Keywords: Precast, Sustainable, SCC, Fine Aggregate, Compressive strength, Modulus, LEED, Byproduct

INTRODUCTION

Sustainable development requires that consumption of energy and natural resources be minimized to accomplish desired development. Byproduct screenings are inadvertently produced in large quantities during crushed stone production. Unfortunately, the rate of production is much greater than current demand. Therefore, byproduct screenings are in desperate need of additional applications to avoid overtaxing available quarry storage space or increasing the current waste stream. Dr. David W. Fowler, Director of the International Center for Aggregate Research (ICAR), was rumored to have said that there are no bad aggregates; the right application just needs to be found for each aggregate. Finding the "right application" for a fine aggregate which is often dusty, coarse, and is composed of angular, flat, or elongate particles is challenging to say the least. A portland cement concrete (PCC) application where cementing materials contents are typically high, to coat the large surface area and mitigate the effects of angular particles, might be a promising possibility.

RESEARCH OBJECTIVE

The objective of the project was to demonstrate that byproduct limestone screenings could be used as a fine aggregate to produce a more sustainable precast PCC bridge beam mixture. To accomplish the objective, the research team attempted to produce a non-air-entrained conventional laboratory mixture and an air-entrained self-consolidating concrete (SCC) using byproduct limestone screenings as fine aggregate that would meet constraints similar to Tennessee Department of Transportation (TDOT) Class P Concrete specification requirements. TDOT Class P concrete specifications do not currently allow SCC. Further, preliminary shrinkage, split tensile strength, static modulus of elasticity, and absorption data, not required by TDOT would be obtained and compared to a TDOT Class P mixture containing typical river sand fine aggregate. The purpose of the study was not to show that byproduct limestone screenings were superior or even equal to river sand as a fine aggregate for TDOT Class P PCC, but rather to find a viable use for byproduct screenings and thereby increase the sustainability of crushed stone aggregate and precast concrete production.

CONSTRAINTS

The 2006 TDOT Standard Specifications for Road and Bridge Construction Section 615[1] require the following for TDOT Class P PCC mixtures:

1. Compressive strengths of 27.6-MPa (4000-psi) at stress transfer and 34.5-MPa (5000-psi) at 28 days.
2. A minimum portland cement content of 390 kg/m^3 (658 lbs/CY).
3. A maximum water-cement ratio of 0.45.
4. An entrained air content of 0 to 8 percent.
5. A maximum slump of 200-mm (8-inches).

For the SCC mixture, the authors replaced requirement 5 with a slump flow of 559 to 660-mm (22 to 26-inches).

LITERATURE REVIEW

The federal government has taken a great interest in sustainable or "green" building practices. "Green" building involves using materials and practices that are more environmentally friendly. The United States Green Building Counsel (USGBC) awards Leadership in Energy and Environmental Design (LEED) green building certifications. There are four levels of certification depending on the environmentally friendliness of the structure. The certifications are given based on a point system. There is a maximum of 69 LEED points available. The minimum LEED points required to be certified green is 26. The highest LEED certification is platinum and requires 52 points. Buildings that meet LEED certification can receive tax breaks and have lower operating cost due to their energy efficiency. Using post industrial byproducts such as screenings in precast concrete sections is one way of earning points for certification. Currently LEED certification is voluntary. Eight states including California, New York, Washington, and Oregon require green building certifications for all public buildings[2]. With eight states requiring green certifications for public buildings and many states considering requiring green certification soon, green building certification will inevitably be required for all state and federal buildings. Current trends towards sustainability and environmental stewardship indicate that all structures will have to meet more rigorous environmental standards. However, performance cannot be sacrificed to achieve environmental objectives.

Quarry byproducts are being produced at a rate of 150 million tons per year in the United States and it is estimated that 4 billion tons have accumulated[3]. Unfortunately, the increased fines in screenings have been shown to decrease PCC workability. A small particle size leads to a large surface area that must be coated with paste; in turn the paste volume must be increased to maintain workability[4]. Further, rough-textured angular particles, common in screenings, require more paste to produce a workable concrete mix than smooth rounded aggregates[5]. Increasing the water-to-cementing-materials (w/cm) ratio will lower the strength and increase the concrete's susceptibility to durability problems[6]. High range water reducer (HRWR) has been shown to help mitigate the loss in workability. However, large dosages of HRWR will cause the paste and aggregate to segregate[7]. Often HRWR alone is not enough to overcome the loss in workability due to screenings[8]. It is easy to understand why river sand is usually preferred as a PCC fine aggregate. River sand is acquired through dredging rivers for navigation. Unfortunately, the river sand supply is having trouble keeping up as concrete demand is increasing. Less desirable fine aggregates such as byproduct screenings will have to be used in PCC in the future. Therefore, now is the time to find suitable PCC applications for byproduct screenings. A PCC application where cementing materials contents are typically high, such as precast PCC, might be a promising possibility.

Hiroshi has found limestone fines can aid in pozzolanic reactions producing supplementary calcium-silicate hydrate (CSH), the reaction product of primary importance for compressive strength[9]. Limestone fines have also been associated with an increased rate of hydration[10]. Celik showed that as fines increased, compressive strength increased up to 10 percent; at fines contents above 10 percent the compressive strength began to decrease[11]. Unfortunately, much of the research that showed increasing the fines resulted in an increase in compressive strength was preformed at high w/cm, around 0.7[8,12-14]. Research at realistic w/cm ratios has shown that increasing the fines content lowered the workability, requiring an increase in HRWR and w/cm ratio to restore workability. The higher w/cm ratio resulted in lower compressive strengths[8,15].

The modulus of elasticity, an important property of PCC structural members, is required for calculating deflections, prestressed losses, and transformed sections. The modulus of elasticity of concrete is dependent on the total amount of aggregate, the grading of aggregate, the modulus of aggregate, as well as the properties of the paste[5]. In general, the aggregates have a much greater effect on modulus of elasticity than the paste. Increasing the coarse aggregate content or maximum coarse aggregate size (MCAS) increases the modulus of the concrete[16]. Higher fineness modulus (FM), that is coarser, fine aggregates allow less coarse aggregate to maintain a workable mixture according to ACI 211[17]. The decrease in coarse aggregate typically results in lower modulus of elasticity. Regrettably, screenings usually have much higher FM than river sand fine aggregates.

There are several prediction equations for modulus of elasticity. ACI 318, ACI 363, and Ahmad and Shaw use unit weight and compressive strength to predict static modulus of elasticity of PCC[18-20]. The ACI 318, ACI 363, and the Ahmad and Shah equations are shown below.

ACI 318 Modulus of Elasticity Prediction Equation

$$E = W_t^{1.5} * 0.043 f'^{0.5}_c \text{ in MPa} \quad E = 33 * W_t^{1.5} * f'^{0.5}_C \text{ in FPS units} \quad (1)$$

ACI 363 Modulus of Elasticity Prediction Equation

$$E = 40000 * f'^{0.5}_C + 1000000 * \left(\frac{W_t}{145}\right)^{1.5} \text{ in FPS units} \quad (2)$$

Ahmad and Shah Modulus of Elasticity Prediction Equation

$$E = W_t^{2.5} * f'^{0.325}_C \text{ in FPS units} \quad (3)$$

where

W_t = unit weight

$f'c$ = compressive strength at 28 days

The prediction equations do not take into account aggregate amount or aggregate properties that affect the modulus of elasticity. Therefore, the prediction equations are often inaccurate[21].

Tensile strength of concrete is much lower than concrete's compressive strength. This is due to the fact that cracks can propagate much faster and easier in tension[11]. The tensile strength of concrete dictates when concrete will crack due to stresses imposed by load, environmental changes, and shrinkage. After cracking has occurred, PCC is more susceptible to durability problems. There is a strong relationship between tensile strength and compressive strength and the same factors affecting compressive strength generally affect tensile strength. Smaller MCAS and crushed aggregates will increase the tensile strength. Crushed aggregate increases PCC tensile strength more than compressive strength[11]. The interfacial transition zone (ITZ) between the cement paste and aggregate is the weakest part of the concrete matrix[11]. Fines can coat the aggregate particles and decrease the bond between the aggregate and paste further weakening the ITZ[6]. The ITZ is very important to the split tensile strength because the failure of concrete in tension is governed by micro-crack propagation particularly in the ITZ[10].

The ACI 318 and Ahmad and Shaw equations for predicting split tensile strength from compressive strength are shown below.

ACI 318 $f'_t = ((f'_c)^{0.5})/1.8$ in MPa $f'_t = 6.7 * \sqrt{f'_c}$ in FPS units (4)

Ahmad and Shah $f'_t = 4.34 * f'^{\,0.55}_c$ in FPS units (5)

where

f'_c = compressive strength
f'_t = tensile strength

Prestressed losses are the progressive losses of force in the prestressing steel over time. Shrinkage of concrete is a factor in prestressed losses[22]. According to ACI 209, "Shrinkage is the strain measured on a load free concrete specimen." As the concrete shrinks, the prestressing steel shrinks. There is a direct relationship between the loss of length in the prestressed steel and the amount of force that is lost in the prestressing steel. If the shrinkage is reduced in the concrete, prestressed losses will be minimized and the member can carry more load.

Drying shrinkage occurs because capillary pores in the concrete structure that are filled with water at a 100 percent relative humidity (RH) begin to lose water as the RH decreases. As the RH decreases the water-filled capillary pores begin to empty resulting in a tensile force on the pore walls. This tensile force results in a volumetric change referred to a drying shrinkage. Autogenous shrinkage has similar mechanisms of drying shrinkage but the loss of water in the capillary pores is due to the hydration of the cement paste[4].

The shrinkage of a given mixture is governed by the cement paste and the quantity and properties of the aggregates. The total volume of aggregates is the most important factor affecting shrinkage[23]. Shrinkage occurs in the cement paste and is restrained by the aggregates[24]. Consequently, as aggregate volumes increase drying shrinkage decreases and as the MCAS increases the shrinkage decreases[23]. The coarse aggregate restrains shrinkage more than the fine aggregate. Shrinkage increases with an increase in the fine aggregate to coarse aggregate ratio[23]. Increasing the cement content of a mixture also increases the shrinkage of a mixture[23].

The movement of moisture in the internal structure is an important factor affecting shrinkage in the paste. Increasing water's ability to move increases the rate and total shrinkage of the concrete. There are several factors affecting the moisture movement in hardened concrete. These factors include the density of the cement paste matrix and the properties of the ITZ. High fines contents can coat aggregates increasing the ITZ[6]. The increase in the ITZ causes an increased permeability. Increasing the w/cm ratio to maintain workability in high fines mixtures increases the porosity and permeability of the cement matrix[4]. However, other researchers have reported that the addition of higher fines increased the density of the paste[13] and decreased the permeability of the paste[25]. The net effect is not clear and the nature of the fines probably dictates the result in each situation.

The ACI 209 equations for predicting PCC shrinkage are shown below[26].

$$(\varepsilon_{sh})_t = \frac{t}{55+t}(\varepsilon_{sh})_u \quad (6)$$

$$(\varepsilon_{sh})_u = 780 * \gamma_{sh} * 10^{-6} \quad (7)$$

where

$(\varepsilon_{sh})_t$ = total shrinkage strain
$(\varepsilon_{sh})_u$ = ultimate shrinkage strain
t = time of shrinkage (time after wet curing period)
γ_{sh} = sum of the correction factors

The correction factors are for conditions and concrete composition other than standard. The volume of coarse aggregate is not taken into account in the correction factors. Because volume of coarse aggregate is very important, ACI 209 can be a poor estimate. Research has shown that a better prediction equation is needed to more accurately predict the shrinkage[21].

Increased absorption of concrete will lead to increased durability problems. In concretes exposed to deicing salts, increased absorption will lead to increased concentration of chlorides reaching the reinforcement. Further, decreasing the absorption decreases concrete's susceptibility to damage from freezing and thawing. Factors affecting absorption are paste permeability and the ITZ. The permeability of the paste depends on the w/cm ratio and the degree of hydration. A higher w/cm ratio increases porosity in the cement paste and therefore increases absorption. The greater the degree of hydration of the paste, the denser the paste becomes and the absorption decreases[4]. The ITZ is very permeable compared to the paste and aggregate and thus provides a path for the movement of water. Increasing the ITZ provides more paths for the water and increases the absorption of the concrete[40]. Unfortunately, the ITZ can be increased by increasing the aggregate surface area.

MATERIALS

AGGREGATES

Byproduct limestone screenings, No. 57 crushed limestone, and No. 67 crushed limestone were obtained from a local quarry[27]. The river sand was obtained from a local concrete producer. The gradation of all aggregates was determined as per ASTM C 136[28] and ASTM C 117[29]. The results are shown in Table 1. Uncompacted void contents of the fine aggregates were conducted as per ASTM C 1252[30]. Limestone screenings and river sand had Method B mean uncompacted voids contents of 48.8 and 43.5 percent, respectively. The difference in uncompacted voids indicates that, as expected, the limestone screenings are much more angular than river sand. Limestone screenings and river sand had FM values of 3.61 and 2.65, respectively. Recall, a higher FM indicates a coarser fine aggregate. Assuming spherical particle shapes, the surface area of a given quantity of fine aggregate can be estimated mathematically. For equal aggregate masses, limestone screenings have 40 percent more surface area per volume than river sand. Actually, the discrepancy in surface area is much greater than the spherical particle approximation since river sand particles are much closer to spherical than limestone screenings particles. In summary, the use of limestone screenings as fine aggregate in PCC requires a much higher paste content in PCC than the use of river sand.

Table 1 Aggregate Gradations and Fine Aggregate Specification (Percent Passing by Mass)

	No. 57	No. 67	Screenings	River Sand	ASTM C 33 Fine Aggregate
25.0-mm (1-in)	100				
19.0-mm (0.75-in)	80	100			
12.5-mm (0.5-in)	30	84			
9.5-mm (0.375-in)	10	44	100	100	100
4.75-mm (No. 4)	1	3	94	97	95 to 100
2.36-mm (No. 8)	0	1	57	90	80 to 100
1.16-mm (No. 16)			34	82	50 to 85
0.6-mm (No. 30)			24	56	25 to 60
0.3-mm (No. 50)			17	9	5 to 30
0.15-mm (No. 100)			13	1	0 to 10
0.075-mm (No. 200)			10	0.5	Varies

OTHER MATERIALS

Type I portland cement meeting ASTM C 150[31] was donated by a local concrete producer. Class C fly ash meeting ASTM C 618[32] was donated by a national supplementary cementing materials supplier. Chemical admixtures conforming to ASTM C 494[33] were donated by an international admixture supplier. The water was Cookeville, TN, municipal water.

PCC MIXTURE DESIGN

Trial batches were used to establish mixture proportions conforming to previously discussed constraints. Although no literature source specifically addressed mixture proportioning for TDOT Class P mixtures or mixtures containing byproduct screenings as fine aggregate, various ACI publications and example Class P mixtures provided by TDOT were helpful in reducing the number of trials required. The final mixture proportions and mixture design proportion ratios and percentages are shown in Table 2.

Table 2 PCC Mixture Designs and Mixture Design Proportion Ratios and Percentages

Mixture Component	River Sand PCC	Screenings PCC	Screenings SCC
Type I portland cement, kg/m^3 (lbs/CY)	415 (700)	415 (700)	427 (720)
Class C fly ash, kg/m^3 (lbs/CY)	104 (175)	104 (175)	107 (180)
No. 57 limestone SSD, kg/m^3 (lbs/CY)	1068 (1800)	917 (1546)	392 (660)
No. 67 limestone SSD, kg/m^3 (lbs/CY)	0	0	391 (659)
River sand SSD, kg/m^3 (lbs/CY)	671 (1131)	0	0
Limestone screenings SSD, kg/m^3 (lbs/CY)	0	730 (1230)	796 (1342)
Water, kg/m^3 (lbs/CY)	155 (262)	200 (337)	186 (314)
Air entrainer, mL/m^3 (oz/CY)	0	0	44 (1.1)
ASTM C 494 Type A & F, L/m^3 (oz/CY)	1 (26)	1.4 (35)	2.6 (68)
Viscosity Modifier, L/m^3 (oz/CY)	0	0	1 (27)
Water/cementing materials	0.299	0.385	0.349
Percent PC replacement with fly ash	20	20	20
Percent post industrial byproducts by mass	4.3	35.2	39.3
Percent paste by volume	34.1	38.5	41.2
Percent fine aggregate of total aggregate by volume	39.1	43.9	50

RESEARCH METHODOLOGY

For each of the three mixtures, five batches were prepared for testing of structural properties and one batch was prepared for testing of durability properties. The structural batches were tested for compressive strength as per ASTM C 39[34], modulus of elasticity as per ASTM C 469[35], and split tensile strength as per ASTM C 496[36]. The durability batches were tested for drying shrinkage as per ASTM C 157C[37] and absorption in accordance with ASTM C 642[38]. Plastic properties for the conventional PCC mixtures included slump ASTM C 143[39], temperature ASTM C 1064[40,] and unit weight ASTM C 138[41]. For the SCC mixture, the following additional plastic properties were tested: slump flow as per ASTM C 1611[42] with an inverted cone was measured instead of slump, and air content was measured by the pressure method ASTM C 231[43]. The visual stability index (VSI) was checked on each mix. The VSI of all SCC batches was considered very stable. When testing SCC for unit weight and air content, the procedure diverged from the specifications. The 0.007 m^3 (0.25 ft^3) measure was filled in one layer and not rodded or tapped. All batches were mixed in a rotary electrical mixer. The structural batch size for conventional PCC mixtures was 0.028 m^3 (1.0 ft^3). Structural batch size for the SCC mixture was 0.033 m^3 (1.15 ft^3). All durability batches were 0.014 m^3 (0.5 ft^3).

Test specimens for compressive strength, modulus of elasticity, and split tensile strength were 102-by-203-mm (4-by-8-inch) cylinders. The specimens for absorption were 76-by-152-mm (3-by-6-inch) cylinders. The specimens for drying shrinkage were 76-by-76-by-286-mm (3-by-3-by-11.25-inch) prisms. The specimens for conventional PCC were prepared per ASTM C 192[44]. The SCC test specimens did not require rodding or taping as per ASTM C 192. The SCC samples were filled to the top and struck off level with the top of the molds.

A method was developed to simulate accelerated curing similar to the curing a precast member would experience. Due to funding constraints, steam curing was unavailable. A water bath, typically used for hot mix asphalt specimens was used. The 2006 TDOT specification book was used to develop the curing method[1]. Immediately after casting, the samples were covered with plastic bags to prevent moisture loss. The plastic bags remained on the sample throughout the curing process. The TDOT specifications required beams to be held until initial set. Regular beams were to be held for 2 to 4 hours and retarded beams were to be held for 4 to 6 hours. Because the laboratory samples had 20 percent class C fly ash, the samples was treated as retarded and were held for 6 hours before heating began. After the 6 hour setting period the cylinders were placed in the water bath. The water came up to 13-mm (0.5-inch) below the top of the cylinder. The samples were placed in the bath with spacing adequate to allow the water to flow in between the samples. The samples were then heated at a rate not to exceed 28˚C/hour (50°F/hour) until they reached 66 ± 3˚C (150 ± 5°F). At lab temperatures of around 24˚C (75°F), heating the samples took approximately 2 hours. The sample remained at 66 ± 3˚C (150 ± 5°F) for 18 to 20 hours. They were then cooled at a rate not to exceed 28˚C/hour (50°F/hour). Cooling was accomplished using a fan that blew on the side of the water bath as the water continued to circulate. The entire process from mixing to end of cooling took 28 to 30 hours. A thermocouple was imbedded in a sample and in the water surrounding the sample to insure the heating criteria were met.

RESULTS

Plastic properties, average compressive strength, average split tensile strength, and average static modulus of elasticity results are shown in Table 3. Table 4 shows percent length change results. Twenty-eight day absorptions were 4.4, 5.8, and 5.9 percent for River Sand PCC, Screenings PCC, and Screenings SCC, respectively.

Table 3 PCC Properties

Property		River Sand PCC	Screenings PCC	Screenings SCC
Slump or slump flow, mm (inches)	Average	171 (6.75)	165 (6.5)	592 (23.3)
	Maximum	210 (8.25)	178 (7)	610 (24)
	Minimum	159 (6.25)	152 (6)	578 (22.75)
Temperature, C˚ (F˚)	Average	26 (79)	26 (79)	24 (76)
	Maximum	27 (81)	27 (81)	25 (77)
	Minimum	25 (77)	25 (77)	23 (74)
Air content in percent	Average	NA	NA	4
	Maximum	NA	NA	4.75
	Minimum	NA	NA	3
Unit Weight, kg/m^3 (lbs/ft^3)	Average	2448 (153)	2384 (149)	2352 (147)
	Maximum	2448 (153)	2416 (151)	2416 (151)
	Minimum	2416 (151)	2352 (147)	2304 (144)
Average Compressive strength, Mpa (psi)	Transfer	42.8 (6210)	32 (4640)	34.4 (4990)
	28-day	63.8 (9250)	53.8 (7810)	55.6 (8060)
Average Split tensile strength, Mpa (psi)	Transfer	3.3 (475)	3 (440)	3.4 (490)
	28-day	4.6 (670)	4.2 (605)	4.6 (670)
Average Static Modulus of Elasticity, GPa (ksi)	Transfer	29 (4200)	26.9 (3900)	23.1 (3350)
	28-day	34.5 (5000)	29.3 (4250)	29 (4200)

Table 4 PCC Shrinkage Data (Percent Length Change)

Time (days)	River Sand PCC	Screenings PCC	Screenings SCC
0	0	0	0
1	-0.0007	-0.0010	-0.0027
2	-0.0037	-0.0030	-0.0063
3	-0.0073	NA	-0.0080
4	-0.0120	NA	-0.0100
5	NA	-0.0150	-0.0133
7	-0.0207	-0.0163	-0.0133
14	-0.0213	-0.0270	-0.0260
21	-0.0243	-0.0293	-0.0293
28	-0.0303	-0.0397	-0.0383

ANALYSIS

All batches of the three mixtures met the target values for PC content, w/cm ratio, as well as plastic properties and compressive strengths. The use of byproduct screenings increased the percent post industrial byproduct usage from 4.3 percent to 35.2 and 39.3 percent for Screenings PCC and Screenings SCC, respectively.

EFFECT OF SCREENINGS ON STRUCTURAL PROPERTIES

Compressive Strength

Table 3 shows that both Screenings PCC and SCC have lower compressive strength than River Sand PCC. There is an average of 25 and 16 percent compressive strength reduction from River Sand PCC to Screenings PCC at transfer and 28 days, respectively. The increase in w/cm ratio from 0.299 to 0.385, shown in Table 2, is probably responsible for the compressive strength reduction. As expected, the angularity and gradation of the screenings necessitated an increase in water content to satisfy the increased paste demand and maintain workability. There is an average of 20 and 13 percent compressive strength reduction from River Sand PCC to Screenings SCC at transfer and 28 days, respectively. Screenings SCC had a higher w/cm ratio and water content than River Sand PCC and was also air entrained probably leading to the strength reduction. Standard deviations for compressive strength, split tensile strength, and static modulus of elasticity are shown in Table 5. Comparing the River Sand PCC and Screenings PCC standard deviations from Table 5 to ACI 214 standards of control, all are within the very good or excellent categories. However, it should be noted that the ACI 214 standards of control are for thirty plus batches and only five were fabricated[45]. Further, these standards of control are not applicable to SCC mixtures.

Table 5 Standard Deviations of Strengths and Static Modulus Results

Property	Time	River Sand PCC	Screenings PCC	Screenings SCC
Compressive strength, Mpa (psi)	Transfer	1.5 (218)	1.2 (172)	1.2 (179)
	28-day	1.5 (224)	0.5 (66)	3.2 (458)
Split tensile strength, Mpa (psi)	Transfer	0.3 (41)	0.2 (32)	0.2 (23)
	28-day	0.5 (69)	0.3 (43)	0.7 (103)
Static Modulus of Elasticity, GPa (ksi)	Transfer	0.9 (127)	2.7 (392)	1.8 (255)
	28-day	2 (293)	0.4 (63)	0.5 (77)

Split Tensile Strength

Table 3 also shows that Screenings PCC had a lower average split tensile strength than River Sand PCC. There is an average of 7 and 10 percent split tensile strength reduction from River Sand PCC to Screenings PCC at transfer and 28 days, respectively. The increase in w/cm ratio from 0.299 to 0.385, shown in Table 2, is probably responsible for the split tensile strength reduction. The smaller reduction in split tensile strength than compressive strength is consistent with the literature; aggregate angularity typically has a greater effect on tensile strength. There is an average of 3 and 0 percent compressive strength increase from River Sand PCC to Screenings SCC at transfer and 28 days, respectively. Table 6 shows a comparison of average measured split tensile strengths with ACI 318 and Ahmad and Shah prediction equations. The measured split tensile strength results were greater than the predicted split tensile strengths in all cases. Predicted values never differed from average measured values by more than 11 percent, indicating good agreement. Further, the standard deviations of the 28-day split tensile strength data, shown in Table 5, are all less than 16 percent of the average 28-day split tensile strength values.

Table 6 Average Differences in 28 Day Results and Predictions (Percent)

Prediction Method	River Sand PCC	Screenings PCC	Screenings SCC
ACI 318 Split Tensile	-3.9	-2.1	-10.2
Ahmad and Shah Split Tensile	-1.6	-0.8	-8.8
ACI 318 Static Modulus	19.7	25.4	25.9
ACI 363 Static Modulus	5.2	8.2	10.2
Ahmad and Shah Static Modulus	12.1	17.4	15.9

Modulus of Elasticity

The Screenings PCC and SCC have 15 and 16 percent lower 28-day average static modulus of elasticity values than River Sand PCC, respectively. Both mixtures containing screenings had lower coarse aggregate contents and higher w/cm ratios, water contents, and fine aggregate contents compared to River Sand PCC. Therefore, the static modulus of elasticity of the screenings mixtures would be expected to be lower. Table 6 shows a comparison of average measured static modulus of elasticity values with ACI 318, ACI 363, and Ahmad and Shah prediction equations. The measured static modulus of elasticity values were all lower than the results obtained from the prediction equations. ACI 363 predicted values never differed from average measured values by more than 11 percent, indicating good agreement. ACI 318 and Ahmad and Shah predicted values were not as close to the measured values. Further, the standard deviations of the 28-day static modulus of elasticity data, shown in Table 6, are all less than 6 percent of the average 28-day modulus values.

EFFECT OF SCREENINGS ON DURABILITY

Shrinkage

Table 4 shows that both mixtures that incorporated screenings as a fine aggregate had greater shrinkage than the PCC River Sand mixture for all readings after 7 days. Mixtures containing screenings contained substantially lower coarse aggregate and substantially higher water contents. Mixtures with lower coarse aggregate and higher water contents typically have greater shrinkage.

The shrinkage prediction values attained from the equations in ACI 209R-04 were -0.0303, -0.0363, and -0.0306 percent for River Sand PCC, Screenings PCC, and Screenings SCC, respectively. The shrinkage prediction values for the River Sand PCC and Screenings PCC included correction values for the relative humidity, the volume to surface area ratio, the fine aggregate to total aggregate ratio, the cement content, and slump. The air content correction factor was used for the SCC mixture. However, there is no correction specifically for an SCC mixture type. The ACI 209 prediction equation over predicted the shrinkage of the River Sand PCC by 8.1 percent and underestimated the shrinkage for the Screening PCC by 8.4 percent. ACI 209 states that the equation was developed for aggregates that meet the ASTM C 33 specifications and are "reasonably well shaped"[26]. The screenings used in this study did not meet ASTM C 33 specifications and are angular and possibly somewhat elongated. Therefore, the ACI 209 equation may not be applicable to mixtures containing screenings. Aggregate proportions for SCC mixtures are quite different from typical PCC mixtures, possibly explaining why ACI 209 under predicted the shrinkage of the SCC Screenings mixture by approximately 20 percent.

Absorption

All mixtures had absorption values below 6 percent at 28-days. The River Sand PCC had less absorption than either mixture containing screenings. For comparison, the Portland Cement Association indicates that high performance PCC has an absorption of five percent or less. The River Sand PCC mixture had a lower w/cm ratio and more coarse aggregate which has been shown to decrease the ITZ and absorption.

CONCLUSIONS

The study has shown that more sustainable precast PCC mixtures, both conventional and SCC, can be developed that meet TDOT Class P PCC compressive strength, w/cm ratio, and minimum cement content specifications using byproduct screenings as fine aggregate. The PCC mixtures using byproduct screenings as fine aggregate, instead of river sand, increase the use of post-industrial byproducts from approximately 4 percent by mass to 35 and 39 for conventional and SCC mixtures, respectively. Comparing the average 28-day results of Screenings PCC and SCC mixtures to those of River Sand PCC, the screenings mixtures had 16 and 13 percent lower compressive strengths, 15 and 16 percent lower static modulus of elasticity, and 10 and 0 percent lower split tensile strength, respectively. Further, screenings mixtures had higher average absorption and shrinkage than River Sand PCC. Current literature was able to predict the average split tensile strength and average static modulus of elasticity values within 11 percent for both screenings mixtures. Shrinkage predictions from ACI 209 were within 9 percent for Screenings PCC, but only with 21 percent for Screenings SCC. In both cases, ACI 209 under-predicted the measured shrinkage. In summary, sustainability was greatly increased for only a moderate sacrifice in performance.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the technical assistance provided Denny Lind of BASF Admixtures and Alan Sparkman of Tennessee Concrete Association and by the following TTU personnel: Dr. Benjamin Mohr, Dr. X. (Sharon) Huo, Jeff Holmes, Tim Dunn, Perry

Melton, Ryan Hewitt, Jason Phillips, and Kristen Batey. The authors sincerely appreciate the materials and supplies provided by Rogers Group, Inc., of Algood, TN; BASF Admixtures, Inc., of Tennessee; Builder's Supply of Cookeville, TN; Boral Materials Technology, Inc.; the TTU Department of Civil & Environmental Engineering; and the TTU Center for Energy Systems Research.

REFERENCES

1. TDOT Specification Section 615, " Precast/Prestressed Concrete Bridge Members," Tennessee Department of Transportation, Standard Specifications for Road and Bridge Construction, March 1, 2006, 874 pp.
2. "An Engineers Guide to: Building Green with Concrete," Portland Cement Association, Skokie, IL, 2005, 6 pp.
3. "Quarry By-Products: Material Description," *Turner-Fairbanks Highway Research Center*. Accessed Febuary 24, 2007. http://www.tfhrc.gov/hnr20/recycle/waste/qbp121.htm.
4. "Design and Control of Concrete Mixtures," 14th Ed, Portland Cement Association, Skokie, IL, 2002, 358 pp.
5. Mehta, K., and P. Monterio. Concrete: Microstructure, Properties, and Materials, 3rd Ed. McGraw-Hill, New York, NY, 2006.
6. Hewlett, P. Lea's Chemistry of Cement and Concrete, 4th Ed. Klsevier Butterworth-Heineman, Burlington, MA, 1998.
7. Ghezal, A., and K. Khayat. "Optimizing Self-Consolidating Concrete with Limestone Filler by Using Statistical Factorial Design Methods," *ACI Materials Journal*, May–June 2002, pp. 264-272.
8. Malhotra, V., and G. Carett. "Performance of Concrete Incorporating Limestone Dust as Partial Replacement for Sand," *ACI Materials Journal*, May-June 1985, pp. 363-371.
9. Uchikawa, H. "Influence of Microstructure on the Physical Properties on Concrete Prepared by Substituting Mineral Powder for Part of Fine Aggregate," *Cement and Concrete Research*, Vol. 26, No. 1, 1996, pp. 101-111.
10. Soroka, I.., and I. Stern. "Calcareous Fillers and the Compressive Strength of Portland Cement," *Cement and Concrete Research*, Vol. 6, 1976, pp. 367-376.
11. Mindess, S., J. Young, and D. Darwin. Concrete, 2nd Ed. Pearson Education, Inc., Upper Saddle River, NJ, 2003.
12. Katz, M., and H. Baum. "Effect of High Levels of Fines Content on Concrete Properties," *ACI Materials Journal*, November-December 2006, pp. 474-482.
13. Abou-Zeid, M., and M. Fakhry. "Short Term Impact of High-Aggregate of Fines Content on Concrete Incorporating Water-Reducing Admixtures," *ACI Materials Journal*, July-August 2003, pp. 280-285.
14. Quiroga, P., and N. Ahn. "Concrete Mixtures with High Microfines," *ACI Materials Journal*, July-August 2006, pp. 258-264.
15. Ahmed, A., and A. El-Kourd. "Properties of Concrete Incorporating Natural and Crushed Stone Very Fine Sand," *ACI Materials Journal*, July-August 1989, pp. 417-424.

16. Schindler, A., and R. Barnes. "Properties of Self-Consolidating Concrete for Prestressed Members," *ACI Materials Journal*, January-February 2007, pp. 53-61.
17. ACI Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete," (ACI 211.1-02), American Concrete Institute, Farmington Hills, MI, 2002.
18. ACI Committee 363, "State-of-the-Art Report on High Strength Concrete," (ACI 363R-92), American Concrete Institute, Farmington Hills, MI, 1992.
19. ACI Committee 318, "Building Code Requirements for Structural Concrete," (ACI 318R-02), American Concrete Institute, Farmington Hills, MI, 2002.
20. Ahmad, S.H., and S.P. Shah. "Structural Properties of High Strength Concrete and Its Implications for Precast Prestressed Concrete," *PCI Journal*, Vol. 30, No. 6, 1985, pp. 92-119.
21. Huo, X., and N. Al-Omaishi. "Creep, Shrink, and Modulus of Elasticity of High-Performance Concrete," *ACI Materials Journal*, November-December 2001, pp. 440-449.
22. Nawy, E. Prestressed Concrete: A Fundamental Approach, 5th Ed. Pearson Education, Inc., Upper Saddle River, NJ, 2006.
23. ACI Committee 209, "Report on Factors Affecting Shrinkage and Creep of Hardened Concrete," (ACI 209R-05), American Concrete Institute, Farmington Hills, MI, 2005.
24. Hover, K. "Much Ado About Shrinkage: Strategies for Reducing Shrinkage Cracking in Flatwork," Hanley Wood, 2005.
25. Bonavetti, V., and E. Irassar. "The Effect of Stone Dust Content in Sand," *Cement and Concrete Research*, Vol. 24, No. 3, 1994, pp. 580-590.
26. ACI Committee 209, "Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structure," (ACI 209R-92), American Concrete Institute, Farmington Hills, MI, 1992.
27. ASTM C 33-03, "Standard Specifications for Concrete Aggregates," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2004, pp. 10-20.
28. ASTM C 136-06, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2006, pp. 89-93.
29. ASTM C 117-04, "Standard Test Method for Materials Finer than 75µm (No. 200) Sieve in Mineral Aggregates by Washing," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2004, pp. 62, 63.
30. ASTM C 1252-03, "Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Perticle Shape, Surface Texture, and Grading)," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2003, pp. 671-675.
31. ASTM C 150-04a, "Standard Specification for Portland Cement," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.01, 2005, pp. 144-151.
32. ASTM C 618-03, "Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2004, pp. 319-321.

33. ASTM C 494-04, "Standard Specifications for Chemical Admixtures for Concrete," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2004, pp. 271-279.
34. ASTM C 39-01, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, October 2002, pp. 21-25.
35. ASTM C 469-94, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2004, pp. 256-260.
36. ASTM C 496-96, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2004, pp. 281-284.
37. ASTM C 157C-06, "Standard Test Method for Length Chang of Hardened Hydraulic-Cement Concrete," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2006, pp. 109-115.
38. ASTM C 642-97, "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 1997, pp. 341-343.
39. ASTM C 143C-05, "Standard Test Method for Slump of Hydraulic-Cement Concrete," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2005, pp. 100-103.
40. ASTM C 1064C-05, "Standard Test Method form Temperature of Freshly Mixed Hydraulic-Cement Concrete," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2005, pp. 557-559.
41. ASTM C 138-01, "Standard Test Method for Density, Yield, and Air Content (Gravimeteric) of Concrete," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2001, pp. 94-97.
42. ASTM C 1611-06, "Standard Test Method for Slump Flow of Self-Consolidating Concrete," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2006, pp. 835-840.
43. ASTM C 231-04, "Standard Test Method for Air content of Freshly Mixed Concrete by the Pressure Method," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2004, pp. 152-159.
44. ASTM C 192-98, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04.02, 2004, pp. 126-133.
45. ACI Committee 214, "Evaluation of Strength Tests in Concrete," (ACI 214R-02), American Concrete Institute, Farmington Hills, MI, 2002.