Excavatable and Early Strength CLSM using High LOI Fly Ash and Limestone Screenings

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ABSTRACT

Limestone screenings and high loss on ignition (LOI) fly ash stockpile because of their unintentional production and negative effects when used in portland cement concretes (PCCs). The research objective was to investigate whether these byproducts could produce controlled low strength materials (CLSMs) meeting Tennessee Department of Transportation (TDOT) 204.06 specifications. This specification requires an inverted slump flow of not less than 15 inches while meeting ASTM D6024 at 24 hours. Due to trench unavailability, a 10 psi minimum compressive strength requirement was substituted for the ASTM D6024 ball drop. Early strength flowable fill (ESFF) must meet ASTM D6024 at 6 hours and provide a 30 psi minimum compressive strength at 24 hours. The ESFF was produced without portland cement (PC) but instead using an 11.1% LOI fly ash, class C fly ash, and limestone screenings. It provided a ten batch average strength of 34 psi at 6 hours and 43 psi at 24 hours with an average inverted slump of 21 inches. Excavatable flowable fill (EFF) is required to provide compressive strengths of 30 psi minimum at 28 days and 140 psi maximum at 98 days. The EFF produced using 93% high LOI fly ash and 7% PC provided a ten batch average strength of 21 psi at 24 hours, 66 psi at 28 days, and 90 psi at 98 days, with an average inverted slump of 16.5 inches. The results indicated high LOI fly ash and limestone screenings, when used simultaneously, can produce quality excavatable and early strength CLSMs.

INTRODUCTION AND RESEARCH SIGNIFICANCE

In 2013, of the approximately 53.4 million tons of fly ash produced in the United States (U.S.), only 23.3 million tons were utilized.[1] Fly ash is produced unintentionally every year through the combustion of coal in electric power plants throughout the U.S. Fly ashes whose loss on ignition (LOI) exceeds the limits set forth by ASTM C618 have proven problematic.[2] LOI is defined as the percentage of unburned carbon, or coal, remaining in the fly ash.[3] LOIs exceeding the limits have been known to cause air-entrainment issues in portland cement concretes (PCCs).[1] This air-entrainment issue makes the possibility of recycling efforts difficult and expensive due to the increased amount of chemical admixtures required to offset the air-entraining admixture absorption effect of the high carbon content remaining in the ash.[3] Thus, the unusable ash is regulated in retention ponds and landfills indefinitely.[4] Long-term storage of fly ash requires continual upkeep, which is costly. Long-term storage can also in some cases result in pollution.[5] Additional utilization of fly ash could help reduce future fly ash spills such as the TVA Kingston Fossil fly ash spill in 2008.[5] These facts make non-air-entrained CLSMs a great candidate for the utilization of high LOI fly ash byproducts. CLSMs incorporating these high LOI fly ashes could reduce the efforts required to retain and maintain the landfills of the massive quantities produced yearly.[4]

1.32 billion metric tons of crushed stone were produced throughout the U.S. in 2015.[6] Approximately 70% of this crushed stone was limestone and dolomite, totaling to 9.24 million metric tons.[6] The production of crushed stone consists of drilling and blasting, loading, hauling, crushing, screening, washing, and further handling.[7] During the primary and secondary crushing stages, a quarry byproduct called screenings are produced.[7] Due to the high fines content, screenings generally violate ASTM C 33 grading specifications for concrete aggregates and are therefore not approved for PCCs.[8] Limestone screening utilization in CLSMs could provide a source of utilization for this accumulating quarry byproduct.[9]

The Tennessee Department of Transportation (TDOT) 204.06 specifications pertains to TDOT's requirements for CLSMs.[10] TDOT specifies three type of CLSMs or flowable fills: general use, excavatable (EFF), and early strength (ESFF) in which none have a minimum required air content.[10] The lack of a minimum air content makes these CLSMs promising for high LOI fly ash utilization because of the air-entraining difficulties associated with the ash.[3] EFF and ESFFs were selected for the investigation of high LOI fly ash and limestone screenings incorporation for this research.[10]

RESEARCH OBJECTIVES

The objectives of this research were to utilize high LOI fly ash and limestone screenings in the production of two types of controlled low strength materials (CLSMs) meeting TDOT 204.06 specifications.[10] The two TDOT 204.06 CLSMs selected were EFF and ESFF.[10] The CLSMs produced were to meet TDOT 204.06 specifications for an inverted slump of no less than 15 inches.[10] They were also required to meet TDOT 204.06 specifications for compressive strength at every required testing age.[10, 11]

LITERATURE REVIEW

Fly Ash

Fly ash is the most widely used supplementary cementing material (SCM) and has been used in the U.S. since the 1930s.[12] Fly ash is a finely divided residue formed from the combustion of pulverized coal that is transported by flue gases and filtered by a particle removal system.[2, 13] The main sources of fly ash production originate from coal powered electric power plants.[12] ASTM classifies fly ash based on pozzolanic or pozzolanic and cementitious properties as well as their chemical composition.[2] They are classified as either Class F, Class C, or Class N.[2] Any fly ash not meeting the requirements for these three classes is deemed unsatisfactory for use in concrete.[2]

The properties affecting fly ash quality consists of the LOI, fineness, chemical composition, and uniformity.[2, 3] ASTM C618's maximum allowable LOI is set at 10% for Class N fly ash and 6% for Class F and Class C fly ashes.[2] LOIs exceeding these limits can result in air-entrainment complications due to the absorptive effect of the unburned carbon to the chemical air-entraining admixture.[3] ASTM C618 goes on to state that Class F fly ash may be used with a LOI of up to 12% "if either the acceptable performance records or laboratory test results are made available".[2] The fineness of the ash contributes to the rate of reactivity.[3] Coarser gradations lessen reactivity and tend to contain higher carbon contents, whereas finer gradations produce greater reactivity's with smaller carbon contents.[3] The uniformity of the ash refers to the consistency between shipments.[3]

Fly ash has many applications which include but are not limited to: PCCs, stabilized base courses, flowable fills, structural fills, and soil modifications.[3] When fly ash is supplemented in portland cement (PC) applications, the fly ash reacts with the PCs byproduct calcium hydroxide to form additional calcium silicate hydrate (CSH).[3, 12] This reaction allows near complete utilization of PC and its byproducts.[12] The additional CSH produced using fly ash can therefore improve the long-term hardened properties while reducing the cost of the material produced.[3, 12]

Limestone Screenings

Limestone screenings or quarry fines are a byproduct from the production of crushed stone.[9] Screenings are a low-cost filler fine aggregate with typically a large, 10 to 20%, amount of material passing the No. 200 sieve.[9, 14] As stated earlier, approximately 1.32 billion metric tons of crushed stone was produced throughout the US in 2015.[6] Approximately 70% of this crushed stone was limestone and dolomite, 9.24 million metric tons.[6] The production of these crushed stones produce mass amounts of screenings annually.[6]

Since screenings are generated in the multiple crushing stages of crushed stone production, they are often angular with a rough surface texture.[15] The particles tend to be cubical and elongated in shape.[15] Usually, the gradation of limestone screenings are uniform, but vary between quarries.[9] Gradation uniformity from individual quarries permit consistent mixture production.[9]

When high fines materials such as screenings are used in PCCs, the water demand dramatically increases due to the increased surface area exposure.[9] This results in a reduction in slump.[9] The compressive strength of most PCCs incorporating a small substitution of limestone dust or high fines material increases due to the fines possibly filling the air voids while reacting with the PC to produce carboaluminates.[9] The compressive strength as well as the flexural strength declines with further increased substitution.[9]

Limestone screenings or quarry fines used in CLSMs have been shown to reduce the cost of screenings storage while reducing the cost of CLSMs.[14] Performance wise, screenings have proven able to produce CLSMs meeting National Ready Mix Concrete Association (NRMCA) performance criteria.[16]

Controlled Low Strength Materials (Flowable Fill)

CLSM is a flowable, self-leveling low strength material commonly used as an economical backfill material as a substitute for compacted fills.[17, 18] The self-leveling characteristic of CLSMs reduces labor, equipment needed, and time for placement.[18] This makes CLSMs more economical when compared to compacted fills.[17, 18] CLSMs or flowable fills applications include utility trenches, bridge abutments, pile excavations, retaining walls, road cuts, and others.[18]

The components selected for the majority of CLSMs include fine aggregate, PC, fly ash, water, and occasionally admixtures.[17] The spherical shape and ball-bearing effect of fly ash helps improve the flowability of CLSMs.[3, 12, 17] Fly ashes not meeting ASTM C618 are commonly used in CLSMs due to the stringent hardened property requirements.[17] Fine aggregates consist of the majority of CLSM volume and aggregates conforming to ASTM C33 are commonly used.[8, 17] Aggregates not conforming to ASTM C33 have also been proven suitable.[17] These inferior aggregates include quarry waste products, sandy soils, pea gravel with sand, and 3/4 inch minus aggregates with sand.[17] Aggregates containing up to 20% passing the No. 200 sieve have also been proven sufficient.[17] Admixtures occasionally incorporated in CLSMs mainly consist of air-entrainers to improve the mixture's flowability.[17]

CLSMs are ideal for applications requiring mixture properties that lie between soil and PCC.[17] Their strengths tend to be greater than most compacted soils but not as strong as PCCs, whereas some CLSMs can still be excavated if needed.[9] The flowability of CLSMs is a unique and desired property which eliminates the use of compactive efforts.[17] The various flowability tests consist of ASTM D 6103, C 143, and C 939.[19, 20, 21] The method selected for this research conforms to TDOT's 204.06B.[10] This method requires a minimum diameter of 15 inches for the inverted slump flow.[10] Generally, the compressive strength of CLSMs range from 50 to 100 psi.[17] The range allows users to use excavatable or higher strength flowable fills.[17] This research aimed to produce CLSMs conforming to TDOT's 204.06B EFF and ESFFs.[10] Each was required to meet the ball drop test, ASTM D6024 at 24 hours.[22] Due to trench unavailability, a 10 psi minimum compressive strength requirement was substituted for the ASTM D6024 ball drop test.[11, 22] The EFF was additionally required to provide compressive strengths of 30 psi minimum at 28 days and 140 psi maximum at 98 days.[10, 11] The ESFF was additionally required to meet ASTM D6024 or the 10-psi minimum at 6 hours and provide a 30 psi minimum compressive strength at 24 hours.[10, 11, 22]

MATERIALS

TDOT CLSM specification 204.06B requires Type I PCs used to conform with AASHTO M 85.[10, 23] The specification allows SCM substitutions from Class C, Class F, and Ground Granulated Blast Furnace Slag (GGBFS) which were required to conform with AASHTO M 295 and AASHTO M 302, respectively.[24, 25] Instead of using an approved Class F, Class C, Class N fly ash, or GGBFS, a high LOI fly ash was used to investigate the research goal for the EFF. A Class C fly ash along with the high LOI fly ash with no PC was used to produce the ESFF. The high LOI fly ash properties compared to AASHTO M 295 requirements for Class F, Class C, and Class N requirements are shown in Table 1.[24] Fine aggregates to be used in TDOT CLSMs are required to meet 903.01-3 grading specifications.[26] Limestone screenings were selected for the fine aggregate and were obtained from a local quarry. The gradation results of the limestone screenings compared to TDOT 903.01-3, ASTM C 33, and AASHTO M 6 requirements are shown in Table 2.[8. 26, 27] Even though the limestone screenings gradation did not comply with the specifications, they were still used in order to address the secondary objective of the research. The water used conformed with AASHTO T 26 requirements.[28] No chemical admixtures were used but were they to have been used, they would have been required to conform with AASHTO M 194 and AASHTO M 154, respectively.[29, 30]

Table 1: Fly Ash Properties Compared to AASHTO M 295 Requirements[24]

Property	High LOI	Class F	Class C	Class N
Silicon Dioxide (%)	47.8	-	-	-
Aluminum Oxide (%)	21.5	-	-	-
Iron Oxide (%)	8.7	-	-	-
SiO_2 + Al_2O_3 + Fe_2O_3 (%)	78	70.0 min.	50.0 min.	70.0 min.
Calcium Oxide (%)	7.9	-	-	-
Magnesium Oxide (%)	1.7	-	-	-
Sulfur Trioxide (%)	0.0	5.0 max.	5.0 max.	4.0 max
Loss on Ignition (%)	11.1	5.0 max.	5.0 max.	5.0 max.
Moisture Content (%)	25	3.0 max	3.0 max	3.0 max
Alkalies as Na_2O (%)	1.1	1.5 max	1.5 max	1.5 max

Table 2: Limestone Screenings Percent Passing Specification Comparison[8, 26, 27]

Sieve Size	Limestone Screenings	ASTM C 33	AASHTO M 6	TDOT 903.01-3
½" (1.27-.mm)	-	-	-	100
3/8" (9.5-mm)	100	100	100	-
No. 4 (4.75-mm)	95.0	95 to 100	95 to 100	-
No. 8 (2.36-mm)	52.8	80 to 100	80 to 100	-
No. 16 (1.18-mm)	31.1	50 to 85	50 to 85	-
No. 30 (600-µm)	24.7	25 to 60	25 to 60	-
No. 50 (300-µm)	22.9	5 to 30	10 to 30	-
No. 100 (150-µm)	22.9	0 to 10	2 to 10	-
No. 200 (75-µm)	22.6	0 to 3	-	0 to 20

PROCEDURE

Mixture Trialing

TDOT 204.06B requires CLSMs to have an inverted slump of not less than 15 inches for any EFF or ESFF.[10] The CLSMs must then meet ASTM D6024 at 24 hours.[10, 22] Due to trench unavailability, a 10 psi minimum compressive strength requirement was substituted for the ASTM D6024 ball drop.[10, 11, 22] ESFF must additionally meet ASTM D6024 or the 10 psi substituted compressive strength at 6 hours and provide a 30 psi minimum compressive strength at 24 hours.[10, 11, 22] EFF is required to provide compressive strengths of 30 psi minimum at 28 days and 140 psi maximum at 98 days.[11, 22] The EFF and ESFF mixtures were trialed and altered until the inverted slump and the compressive strengths complied with TDOT 204.06B requirements at the respective testing dates.[10, 11]

Mixture Designs

The final mixture designs for the EFF and the ESFF are shown in Table 3. The ESFF CLSM was produced according to ASTM C4832 using no PC but rather Class C fly ash to meet all TDOT 204.06 plastic and hardened property requirements.[10, 11]

Table 3: CLSM Mixture Designs

Component	EFF	ESFF
Type I PC, lbs/CY (kg/m³)	40 (23.7)	-
Class C Fly Ash, lbs/CY (kg/m³)	-	569.5 (337.9)
High LOI Fly Ash, lbs/CY (kg/m³)	440 (261.0)	280.5 (166.4)
Limestone Screenings, lbs/CY (kg/m³)	2494 (1479.6)	2251 (1335.5)
Water, lbs/CY (kg/m³)	581 (344.7)	475 (281.8)

Testing Procedure

After each mixture was trialed and altered until compliance, ten batches of each mixture were produced, measured for their inverted slump, and tested at the corresponding compressive strength date requirements.[10, 11] Six 4x8-inch cylinders were produced per batch per mixture according to ASTM D4832.[11] For the EFF compressive strength testing, two cylinders were tested at 24 hours, two at 28 days, and two at 98 days according to ASTM D 4832.[11] For the ESFF, two cylinders were tested at 6 hours and two at 24 hours.[11]

RESULTS AND ANALYSIS

The inverted slump results for the EFF and ESFF mixtures are shown in Table 4 and Table 5, respectively. The EFF compressive strength results at 24 hours, 28 days, and 98 days are shown in Table 6, Table 7, and Table 8, respectively. The ESFF compressive strength results at 6 hours and 24 hours are shown in Table 9 and Table 10, respectively. All individual batch averages for the EFF and ESFF met TDOT 204.06 specifications for inverted slump and compressive strength.[10, 11] A summary of the average results compared to TDOT requirements for the EFF and ESFF mixtures are shown in Table 11 and Table 12, respectively.

Table 4: EFF Inverted Slump

Batch Number	Inverted Slump, in. (cm)	Mean, in. (cm)	Range, in. (cm)
1	16.5 (41.9)	16.6 (42.2)	2.0 (5.1)
2	16.0 (40.6)		
3	16.25 (41.3)		
4	17.0 (43.2)		
5	18.0 (45.7)		
6	16.0 (40.6)		
7	16.5 (41.9)		
8	16.75 (42.5)		
9	16.0 (40.6)		
10	17.0 (43.2)		

Table 5: ESFF Inverted Slump Results

Batch Number	Inverted Slump, in. (cm)	Mean, in. (cm)	Range, in. (cm)
1	20.0 (50.8)	21.1 (53.6)	2.75 (7.0)
2	20.75 (52.7)		
3	20.5 (52.1)		
4	19.5 (49.5)		
5	22.0 (55.9)		
6	22.0 (55.9)		
7	21.0 (53.3)		
8	21.25 (54.0)		

9	22.0 (55.9)		
10	22.25 (56.5)		

Table 6: EFF 24-hour Compressive Strength Results

Batch Number	Cylinder 1, psi (kPa)	Cylinder 2, psi (kPa)	Mean, psi (kPa)	Range, psi (kPa)
1	19.1 (131.7)	19.1 (131.7)	19.1 (131.7)	0.0 (0.0)
2	17.9 (123.4)	19.8 (136.5)	18.9 (130.3)	1.9 (13.1)
3	20.2 (139.3)	19.8 (136.5)	20.0 (137.9)	0.4 (2.8)
4	18.1 (124.8)	18.8 (129.6)	18.4 (126.9)	0.7 (4.8)
5	18.0 (124.1)	18.8 (129.6)	18.4 (126.9)	0.7 (4.8)
6	25.5 (175.8)	23.7 (163.4)	24.6 (169.6)	1.8 (12.4)
7	19.9 (137.2)	23.8 (164.1)	21.8 (150.3)	3.9 (26.9)
8	26.3 (181.3)	27.1 (186.8)	26.7 (184.1)	0.8 (5.5)
9	24.0 (165.5)	20.4 (140.7)	22.2 (153.1)	3.7 (25.5)
10	23.8 (164.1)	22.5 (155.1)	23.2 (160.0)	1.3 (9.0)

Table 7: EFF 28-day Compressive Strength Results

Batch Number	Cylinder 1, psi (kPa)	Cylinder 2, psi (kPa)	Mean, psi (kPa)	Range, psi (kPa)
1	62.6 (431.6)	62.5 (430.9)	62.5 (430.9)	0.1 (0.7)
2	57.0 (393.0)	61.2 (422.0)	59.1 (407.5)	4.2 (29.0)
3	62.6 (431.6)	73.1 (504.0)	67.8 (467.5)	10.6 (73.1)
4	61.5 (424.0)	67.1 (462.6)	64.3 (443.3)	5.6 (38.6)
5	57.1 (393.7)	63.2 (435.7)	60.1 (414.4)	6.1 (42.1)
6	70.4 (485.4)	70.0 (482.6)	70.2 (484.0)	0.4 (2.8)
7	71.9 (495.7)	66.0 (455.1)	68.9 (475.0)	5.9 (40.7)
8	67.1 (462.6)	68.0 (468.8)	67.6 (466.1)	1.0 (6.9)
9	71.8 (495.0)	73.6 (507.5)	72.7 (501.2)	1.8 (12.4)
10	66.4 (457.8)	71.9 (495.7)	69.1 (476.4)	5.5 (37.9)

Table 8: EFF 98-day Compressive Strength Results

Batch Number	Cylinder 1, psi (kPa)	Cylinder 2, psi (kPa)	Mean, psi (kPa)	Range, psi (kPa)
1	79.0 (544.7)	72.8 (501.9)	75.9 (523.3)	6.2 (42.7)
2	Damaged	80.8 (557.1)	80.8 (557.1)	0.0 (0.0)
3	91.6 (631.6)	89.9 (619.8)	90.8 (626.0)	1.7 (11.7)
4	87.7 (604.7)	83.0 (572.3)	85.3 (588.1)	4.7 (32.4)
5	88.7 (611.6)	82.3 (567.4)	85.5 (589.5)	6.4 (44.1)
6	89.4 (616.4)	99.5 (686.0)	94.4 (650.9)	10.1 (69.6)
7	89.5 (617.1)	94.0 (648.1)	91.8 (632.9)	4.5 (31.0)
8	96.1 (662.6)	105.5 (727.4)	100.8 (695.0)	9.4 (64.8)
9	98.1 (676.4)	95.7 (659.8)	96.9 (668.1)	2.4 (16.5)
10	94.5 (651.6)	99.9 (688.8)	97.2 (670.2)	5.4 (37.2)

Table 9: ESFF 6-hour Compressive Strength Results

Batch Number	Cylinder 1, psi (kPa)	Cylinder 2, psi (kPa)	Mean, psi (kPa)	Range, psi (kPa)
1	34.2 (235.9)	30.8 (212.3)	32.5 (224.1)	3.4 (23.6)
2	32.9 (227.1)	34.3 (236.5)	33.6 (231.8)	1.4 (9.3)
3	32.1 (221.1)	32.1 (221.7)	32.1 (221.4)	0.1 (0.5)
4	30.3 (209.0)	29.7 (204.7)	30.0 (206.8)	0.6 (4.4)
5	32.1 (221.1)	32.9 (226.6)	32.5 (223.9)	0.8 (5.5)
6	35.3 (243.6)	38.8 (267.7)	37.1 (255.7)	3.5 (24.1)
7	35.0 (241.4)	35.3 (243.6)	35.2 (242.5)	0.3 (2.2)
8	37.1 (255.7)	37.2 (256.8)	37.2 (256.2)	0.2 (1.1)
9	35.7 (246.4)	36.8 (254.0)	36.3 (250.2)	1.1 (7.7)
10	36.8 (254.0)	36.7 (252.9)	36.8 (253.5)	0.2 (1.1)

Table 10: ESFF 24-hour Compressive Strength Results

Batch Number	Cylinder 1, psi (kPa)	Cylinder 2, psi (kPa)	Mean, psi (kPa)	Range, psi (kPa)
1	44.5 (306.8)	41.5 (286.1)	43.0 (296.5)	3.0 (20.7)
2	41.5 (286.1)	40.9 (282.0)	41.2 (284.1)	0.6 (4.1)
3	40.3 (277.9)	41.1 (283.4)	40.7 (280.6)	0.8 (5.5)
4	38.0 (262.0)	35.7 (246.1)	36.8 (253.7)	2.2 (15.2)
5	42.3 (291.6)	38.5 (265.4)	40.4 (278.5)	3.7 (25.5)
6	45.3 (312.3)	46.0 (317.2)	45.6 (314.4)	0.7 (4.8)
7	43.6 (300.6)	43.8 (302.0)	43.7 (301.3)	0.2 (1.4)
8	47.2 (325.4)	47.7 (328.9)	47.4 (326.8)	0.5 (3.4)
9	45.4 (313.0)	45.0 (310.3)	45.2 (311.6)	0.4 (2.8)
10	43.1 (297.2)	47.0 (324.1)	45.0 (310.3)	4.0 (27.6)

Table 11: 10 Batch Average EFF Properties Compared to TDOT 204.06B[10]

Property	EFF	TDOT EFF
Inverted Slump, in. (cm)	16.6 (42.2)	≥ 15 (38.1)
24-hour Compressive Strength, psi (kPa)	21.3 (147.1)	≥ 10 (68.9)
28-day Compressive Strength, psi (kPa)	66.2 (456.7)	≥ 30 (206.8)
98-day Compressive Strength, psi (kPa)	90.4 (632.5)	≤ 140 (965.3)

Table 12: 10 Batch Average ESFF Properties Compared to TDOT 204.06B[10]

Property	EFSS	TDOT ESFF
Inverted Slump, in. (cm)	21.1 (53.6)	≥ 15 (38.1)
6-hour Compressive Strength, psi (kPa)	34.3 (236.6)	≥ 10 (68.9)
24-hour Compressive Strength, psi (kPa)	42.9 (295.8)	≥ 30 (206.8)

Currently, there are no variability standards for the compression testing of CLSM cylinders according to ASTM D4832.[11] Also, TDOT 204.06B contains no variability standards for their inverted slump test.[10] Even so, a statistical analysis was performed on the results obtained for the inverted slump and compressive strengths. The inverted slump statistical parameter results are shown in Table 13. The compressive strength statistical parameter results are shown in Table 14 and Table 15 for the EFF and ESFF, respectively.

Table 13: EFF and ESFF Inverted Slump Statistical Parameters

Parameter	EFF	ESFF
Mean, in. (cm)	16.6 (42.2)	21.1 (117.1)
Standard Deviation, in. (cm)	0.63 (1.59)	0.95 (2.40)
Coefficient of Variation (COV), %	3.8	4.5
Mean Range of within Test, in. (cm)	2.0 (5.08)	2.75 (6.99)

Table 14: EFF Compressive Strength Statistical Parameters

Parameter	24-hour	28-day	98-day
Mean, psi (kPa)	21.3 (147.1)	66.2 (456.7)	89.9 (620.2)
Standard Deviation, psi (kPa)	2.97 (20.5)	5.13 (35.4)	8.23 (56.7)
Coefficient of Variation (COV), %	13.9	7.8	9.1
Mean Range of within Test, psi (kPa)	9.23 (63.6)	16.6 (114.7)	32.7 (225.5)

Table 15: ESFF Compressive Strength Statistical Parameters

Parameter	6-hour	24-hour
Mean, psi (kPa)	34 (236.6)	43 (295.8)
Standard Deviation, psi (kPa)	2.60 (17.9)	3.26 (22.5)
Coefficient of Variation (COV), %	7.6	7.6
Mean Range of within Test, psi (kPa)	9.15 (63.1)	11.9 (82.3)

Despite substituting a 91.7% high LOI fly ash, the EFF met all TDOT 204.06B criteria for inverted slump and compressive strength.[10] The ESFF also met TDOT 204.06B criteria for inverted slump and compressive strength while using no PC, but rather Class C fly ash and a 33% high LOI fly ash substitution.[10]

CONCLUSIONS

The results from the utilization of the high LOI fly ash and limestone screenings in the EFF and ESFF mixtures indicate the following:

1. High LOI fly ash can definitely be used to produce effective CLSMs that comply with TDOT 204.06B specifications.[10]
2. Limestone screenings can also be used to produce TDOT 204.06B approved CLSMs.[10]
3. CLSMs provide a practical outlet for high LOI fly ash and limestone screenings utilization.

FUTURE RESEARCH

1. Repeat this research using a different source of high LOI fly ash;
2. Analyze the effects of various environmental factors during field placement of the mixtures produced herein;
3. Investigate the use of the high LOI fly ash in other materials having no minimum air content such as pervious PCC, certain precast PCC, and precast self-consolidating concretes.

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