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Universal and Excavatable Controlled Low Strength Material Using High Loss on Ignition Fly Ash and Limestone Screenings†

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A B S T R A C T

Limestone screenings and high loss on ignition (LOI) fly ash are by-products that are stockpiling because of their unintentional production and the negative effects when utilized in portland cement concretes. The research objective was to investigate whether these by-products could produce controlled low strength materials (CLSMs) meeting the three types of Tennessee Department of Transportation (TDOT) 204.06 flowable fill specifications. TDOT defines these CLSMs as the following: general use, excavatable, and early strength. Each type is required to have an inverted slump flow of not less than 15 inches (38.1 cm) while meeting ASTM International D6024 at 24 hours. Because of trench unavailability, a 10-psi minimum compressive strength requirement was substituted for the ASTM D6024 ball drop. Early strength flowable fills must meet ASTM D6024 at 6 hours and provide a 30-psi minimum compressive strength at 24 hours. Excavatable flowable fills (EFFs) must also provide a 30-psi minimum at 28 days and a 140-psi maximum at 98 days. A universal flowable fill was produced without portland cement (PC), but by using an 11.1% LOI fly ash, class C fly ash, and limestone screenings. The EFF was produced using 92% high LOI fly ash and 7% PC by weight of the cementing materials. The results indicated that high LOI fly ash and limestone screenings can be combined to produce an excavatable CLSM satisfying TDOT CLSM requirements, and an universal CLSM can be produced that satisfies the requirements for general use, excavatable, and early strength TDOT CLSMs.

A R T I C L E I N F O

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1. Introduction and Research Significance

In 2013, of the approximately 48.4 million metric tons of fly ash produced in the United States, only 21.1 million metric tons was utilized (American Coal Ash Association, 2015). Fly ash is produced unintentionally every year through the combustion of coal in electric power plants throughout the United States. Fly ashes whose loss on ignition (LOI) exceeds the limits set forth by ASTM C618 have proven problematic (ASTM International, 2016c). LOI is defined as the percentage of unburned carbon, or coal, remaining in the fly ash (American Coal Ash Association, 2003). LOIs exceeding these limits have been known to cause air entrainment issues in portland cement concretes (PCCs) (American Coal Ash Association, 2015). This air entrainment issue makes the possibility of recycling efforts difficult and expensive because of the increased amount of chemical admixtures required to offset the air-entraining admixture absorption effect of the high carbon content remaining in the ash (American Coal Ash Association, 2003). Thus, the unusable ash is regulated in retention ponds and landfills indefinitely (Tennessee Valley Authority [TVA], 2016). Long-term storage of fly ash requires continual upkeep, which is costly. Long-term storage can also, in some cases, result in pollution (U.S. Environmental Protection Agency [US EPA], 2016). Additional utilization of fly ash could help reduce future fly ash spills such as the TVA Kingston Fossil fly ash spill in 2008

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(US EPA, 2016). These facts make non–air-entrained controlled low strength materials (CLSMs) a great candidate for the utilization of high-LOI fly ash by-products. CLSMs incorporating these high-LOI fly ashes could reduce the efforts required to retain and maintain the landfills of the massive quantities produced yearly (TVA, 2016).

In 2015, 1.32 billion metric tons of crushed stone was produced throughout the United States (U.S. Geological Survey, 2016). Approximately 70% of this crushed stone was limestone and dolomite, totaling 924 million metric tons (U.S. Geological Survey, 2016). The production of crushed stone consists of drilling and blasting, loading, hauling, crushing, screening, washing, and further handling (Federal Highway Administration [FHWA], 2016). During the primary and secondary crushing stages, a quarry by-product called screenings are produced (FHWA, 2016). Screenings generally violate ASTM C33 grading specifications for concrete aggregates because of the high fines content and are therefore not approved for PCCs (ASTM International, 2016a). Limestone screening utilization in CLSMs could provide a source of utilization for this accumulating quarry by-product (Kumar and Hudson, 1992).

The Tennessee Department of Transportation (TDOT) 204.06 specifications pertain to three types of CLSM requirements (TDOT, 2015). TDOT specifies three type of CLSMs or flowable fills as general use, excavatable (EFF), and early strength (ESFF), in which none have a minimum required air content (TDOT, 2015). The lack of a minimum air content for all three CLSMs makes them a promising candidate for high-LOI fly ash utilization because of the air-entraining difficulties associated with the ash (American Coal Ash Association, 2003). A universal flowable fill (UFF) that satisfies the requirements of all three CLSM types and an EFF were produced and investigated for the use of high-LOI fly ash and limestone screenings incorporation (TDOT, 2015).

2. Research Objectives

Because of the massive amounts of accumulating high-LOI fly ash and limestone screenings, any application that consumes these by-products could help alleviate the endeavor of managing them. Mainly, it could reduce the undertaking of safely storing and monitoring high-LOI fly ash for the possibility of leaching heavy metals into the groundwater system. Hence, in an effort to reduce storage efforts, the formulated objective of this research was to utilize high-LOI fly ash and limestone screenings in producing a UFF that meets all TDOT 204.06 specifications for general use, EFF, and ESFF CLSMs (TDOT, 2015) and an EFF meeting all TDOT 204.06 specifications for EFF. If these CLSMs meet TDOT criteria, it could generate a statewide, applicable area for approved utilization for these accumulating by-products. The EFF and UFF were produced utilizing limestone screenings and an 11.1% LOI fly ash supplementary cementing material (SCM) substitution rate of 92% and 67% by weight of the cementing materials, respectively (TDOT, 2015). Furthermore, the UFF was produced without portland cement (PC) but, rather, class C fly ash. To comply with TDOT CLSM requirements, both were required to achieve certain inverted slump flows and compressive strengths at the assigned ages. Both CLSMs were required to meet TDOT 204.06 specifications for inverted slump, in which an inverted slump of 15 inches (38.1 cm) or greater is required (TDOT, 2015). The TDOT 204.06 specifications for compressive strength for EFF indicated it must provide a minimum compressive strength at 24 hours and 28 days, and it must not exceed a maximum compressive strength at 98 days to be considered excavatable. The three combined TDOT 204.06 CLSM specifications indicated that a UFF was required to meet minimum compressive strength requirements at 6 hours and 24 hours and a maximum compressive strength requirement at 98 days (ASTM International, 2012a; TDOT, 2015).

3. Literature Review

3.1. Fly ash

Fly ash is the most widely used SCM and has been used in the United States since the 1930s (American Concrete Institute [ACI], 2001). 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 (ACI, 2000; ASTM International, 2016c). The main sources of fly ash production originate from coal-powered electric power plants (ACI, 2001). ASTM classifies fly ash based on its pozzolanic or pozzolanic and cementitious properties, as well as the chemical composition (ASTM International, 2016c). Fly ash is classified as either class F, class C, or class N (ASTM International, 2016c). Fly ash not meeting the requirements for these three classes is deemed unsatisfactory for use in concrete (ASTM International, 2016c).

The properties affecting fly ash quality consist of LOI, fineness, chemical composition, and uniformity (American Coal Ash Association, 2003; ASTM International, 2016c). The maximum allowable LOI for ASTM C618 is set at 10% for class N fly ash and 6% for class F and class C fly ashes (ASTM International, 2016c). LOIs exceeding these limits can result in air entrainment complications from the absorptive effect of the unburned carbon to the chemical air-entraining admixture (American Coal Ash Association, 2003). ASTM C618 continues to state that class F fly ash may be used with an LOI up to 12% "if either the acceptable performance records or laboratory test results are made available" (ASTM International, 2016c). The fineness of the ash contributes to the rate of reactivity (American Coal Ash Association, 2003). Coarser gradations lessen reactivity and tend to contain higher carbon contents, whereas finer gradations produce greater reactivities with smaller carbon contents (American Coal Ash Association, 2003). The uniformity of the ash refers to the consistency between shipments (American Coal Ash Association, 2003).

Fly ash has many applications including, but not limited to, PCCs, stabilized base courses, flowable fills, structural fills, and soil modifications (American Coal Ash Association, 2003). When fly ash is supplemented in PC applications, the fly ash reacts with the PC's hydration by-product calcium hydroxide to form additional calcium silicate hydrate (CSH) (ACI, 2001; American Coal Ash Association, 2003). This reaction allows near complete utilization of PC and its by-products (ACI, 2001). The additional CSH produced using fly ash can therefore improve the long-term hardening properties while reducing the cost of the material produced (ACI, 2001; American Coal Ash Association, 2003).

3.2. Limestone screenings

Limestone screenings or quarry fines are a by-product of the production of crushed stone (Kumar and Hudson, 1992). Screenings are a low-cost, fine aggregate filler with typically a large, 10% to 20% by weight, amount of material passing the No. 200 sieve (Kumar and Hudson, 1992; Halmen and Shah, 2015). As stated earlier, approximately 1.32 billion metric tons of crushed stone was produced throughout the United States in 2015 (U.S. Geological Survey, 2016). Approximately 70% of this crushed stone, 924 million metric tons, was limestone and dolomite (U.S. Geological Survey, 2016). The production of these crushed stones produce mass amounts of screenings annually (U.S. Geological Survey, 2016).

Because screenings are generated in multiple crushing stages of crushed stone production, they are often angular with a rough surface texture (Kosmatka and Wilson, 2012). The particles tend to be cubical and elongate in shape (Kosmatka and Wilson, 2012). Usually, the gradation of limestone screenings are uniform but vary between quarries (Kumar and Hudson, 1992). Gradation uniformity from individual quarries permit consistent mixture production (Kumar and Hudson, 1992).

When high fines materials such as screenings are used in PCCs, the water demand dramatically increases from the increased surface area exposure (Kumar and Hudson, 1992). This results in a reduction in slump (Kumar and Hudson, 1992). The compressive strength of most PCCs incorporating a small substitution of limestone dust or high fines material increase because of fines possibly filling the air voids while reacting with the PC to produce carboaluminates (Kumar and Hudson, 1992). The compressive and flexural strength decline with further increased substitution (Kumar and Hudson, 1992).

Limestone screenings or quarry fines used in CLSMs have been shown to reduce the cost of screenings storage while reducing the cost of CLSMs (Halmen and Shah, 2015). Performance-related screenings have proven able to produce CLSMs meeting National Ready Mix Concrete Association performance criteria (Crouch et al., 1998).

3.3. *Controlled low-strength materials (flowable fills)*

CLSMs are a flowable, self-leveling, low-strength material commonly used as an economical backfill material as a substitute for compacted fills (National Ready Mixed Concrete Association [NRMCA], 2000; ACI, 2005). The self-leveling characteristic of CLSMs reduce labor, equipment needed, and time required for placement (NRMCA, 2000), which makes CLSMs more economical compared with compacted fills (NRMCA, 2000; ACI, 2005). CLSM, or flowable fill, applications include utility trenches, bridge abutments, pile excavations, retaining walls, road cuts, and others (NRMCA, 2000).

The components selected for the majority of CLSMs include fine aggregate, PC, fly ash, water, and occasionally admixtures (ACI, 2005). The spherical shape and ball-bearing effect of fly ash helps improve the flowability of CLSMs (ACI, 2001, 2005; American Coal Ash Association, 2003). Fly ashes not meeting ASTM C618 are commonly used in CLSMs because of the stringent hardened property requirements (ACI, 2005). Fine aggregates consist of the majority of CLSM volume, and aggregates conforming to ASTM C33 are commonly used (ACI, 2005; ASTM International, 2016a). Aggregates not conforming to ASTM C33 have also been proven suitable (ACI, 2005). These inferior aggregates include quarry waste products, sandy soils, pea gravel with sand, and $^3/_4$-inch (1.905-cm) minus aggregates with sand (ACI, 2005). Aggregates containing up to 20% by weight of components passing the No. 200 sieve have also been proven sufficient (ACI, 2005). Admixtures occasionally incorporated in CLSMs mainly consist of air entrainers to improve the mixture's flowability (ACI, 2005).

CLSMs are ideal for applications requiring mixture properties that lie between soil and PCC (ACI, 2005). 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 (Kumar and Hudson, 1992). The flowability of CLSMs is a unique and desired property that eliminates the use of compaction efforts (ACI, 2005). The various flowability tests consist of ASTM D6103, C143, and C939 (ASTM International, 2012c, 2016b,d). The method selected for this research conforms to the TDOT 204.06B specification (TDOT, 2015). This method requires a minimum diameter of 15 inches for the inverted slump flow (TDOT, 2015). Generally, the compressive strength of CLSMs range from 50 to 100 psi (ACI, 2005). The range allows users to use excavatable or higher strength flowable fills (ACI, 2005). This research aimed to produce an EFF CLSM conforming to the TDOT 204.06B EFF requirements and a UFF CLSM conforming to the TDOT 204.06B general, EFF, and ESFF requirements (TDOT, 2015). Each was required to meet the ball drop test, ASTM D6024, at 24 hours (ASTM International, 2012b). Because of trench unavailability, a 10-psi minimum compressive strength requirement was substituted for the ASTM D6024 ball drop test (ASTM International, 2012a,b). The EFF was additionally required to provide compressive strengths of 30 psi minimum at 28 days and 140 psi maximum at 98 days (ASTM International, 2012a; TDOT, 2015). ESFFs are 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 (ASTM International, 2012a,b; TDOT, 2015) Thus, the requirements for the UFF to satisfy all three types include compressive strength requirements of a minimum 10 psi at 6 hours, of 30 psi at 24 hours, and a maximum of 140 psi at 98 days (TDOT, 2015).

4. Materials

TDOT CLSM specification 204.06B requires Type I PCs to conform to AASHTO M85 (AASHTO, 2009f; TDOT, 2015). The specification allows SCM substitutions with class C, class F, and ground granulated blast furnace slag (GGBFS), which are required to conform to AASHTO M295 and M302, respectively (AASHTO, 2009c,d). Instead of using an approved class F, class N fly ash, or GGBFS, a high-LOI fly ash and class C fly ash were used to investigate the research goal. The chemical compositions of the high-LOI fly ash and class C fly ash used in the research are compared with AASHTO M295 requirements for class F, class C, and class N in Table 1 (AASHTO, 2009c). Fine aggregates to be used in TDOT CLSMs are required to meet 903.01-3 grading specifications (TDOT, 2015). Limestone screenings were selected for the fine aggregate and were obtained from a local quarry. The gradation results of the limestone screenings compared with TDOT 903.01-3, ASTM C33, and AASHTO M6 requirements are shown in Table 2 (AASHTO, 2009e; TDOT, 2015; ASTM International, 2016a). Even though the limestone screenings gradation did not comply with the specifications, they were still used to address the secondary objective of the research. The water used conformed to AASHTO T26 requirements (AASHTO,

Table 1
Fly ash properties compared with AASHTO M 295 requirements[1]

Property	High LOI	Class C	Class F	Class C	Class N
Silicon dioxide (%)	47.8	38.9	–	–	–
Aluminum oxide (%)	21.5	19.6	–	–	–
Iron oxide (%)	8.7	6.1	–	–	–
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	78	64.6	70.0 min.	50.0 min.	70.0 min.
Calcium oxide (%)	7.9	21.7	–	–	–
Magnesium oxide (%)	1.7	–	–	–	–
Sulfur trioxide (%)	0.0	1.8	5.0 max.	5.0 max.	4.0 max.
Loss on ignition (%)	11.1	0.4	5.0 max.	5.0 max.	5.0 max.
Moisture content (%)	25	0.1	3.0 max.	3.0 max.	3.0 max.
Alkalis as Na_2O (%)	1.1	1.4	1.5 max.	1.5 max.	1.5 max.

[1] American Association of State Highway and Transportation Officials, 2009c. LOI = loss on ignition; min. = minimum; max. = maximum.

Table 2
Limestone screenings percent passing specification comparison[1]

Sieve size	Limestone screenings	ASTM C33 (%)	AASHTO M6 (%)	TDOT 903.01-3 (%)
1/2 inch (1.27 mm)	–	–	–	100
3/8 inch (9.5 mm)	100	100	100	–
No. 4 (4.75 mm)	95.0	95–100	95–100	–
No. 8 (2.36 mm)	52.8	80–100	80–100	–
No. 16 (1.18 mm)	31.1	50–85	50–85	–
No. 30 (600 μm)	24.7	25–60	25–60	–
No. 50 (300 μm)	22.9	5–30	10–30	–
No. 100 (150 μm)	22.9	0–10	2–10	–
No. 200 (75 μm)	22.6	0–3	–	0–20

[1] American Association of State Highway and Transportation Officials, 2009e; Tennessee Department of Transportation, 2015; ASTM International, 2016a.

2009g). No chemical admixtures were used, but if they were, they would have been required to comply with AASHTO M194 and M154, respectively (AASHTO, 2009a,b).

5. Procedure

5.1. Mixture trialing

To market these high-LOI fly ash CLSMs, the mixtures were trialed and tested until they met TDOT plastic and hardened property requirements. The TDOT 204.06B requirements for plastic properties state that all flowable fills must have an inverted slump of not less than 15 inches (TDOT, 2015). This specification's hardened property requirements state that all flowable fills must meet the ASTM D6024 ball drop test at 24 hours (ASTM International, 2012b; TDOT, 2015). Because of trench unavailability, a 10-psi minimum compressive strength requirement was substituted for the ASTM D6024 ball drop (ASTM International, 2012a,b; TDOT, 2015). TDOT requires an ESFF to instead meet ASTM D6024 or the 10-psi substituted compressive strength at 6 hours and provide a 30-psi minimum compressive strength at 24 hours (ASTM International, 2012a,b; TDOT, 2015). An EFF is required to provide compressive strengths of 30 psi minimum at 28 days and 140 psi maximum at 98 days (ASTM International, 2012a,b). The EFF and UFF mixtures were trialed and altered until the inverted slump and compressive strengths complied with TDOT 204.06B requirements at the respective testing dates, so the mixtures could be applicable for TDOT utilization (ASTM International, 2012a; TDOT, 2015).

5.2. Mixture designs

The mixtures were produced according to ASTM C4832, and the final mixture design for the UFF and EFF are compared with the TDOT 204.06-1 suggested general use flowable fill mixture design in Table 3 (TDOT, 2015). The final UFF mixture was produced using class C and high-LOI fly ash with no PC, and the final EFF mixture was produced with PC and high-LOI fly ash (ASTM International, 2012a). These mixtures were altered and obtained after several trials until they met all TDOT 204.06 plastic and hardened property requirements (ASTM International, 2012a; TDOT, 2015).

5.3. Testing procedure

After obtaining the final mixture designs, 10 batches were produced after calculating the required sample size based on the initial compressive strength results. To comply with TDOT criteria, both CLSMs were measured for inverted slump and tested at the corresponding compressive strength date requirements (ASTM International, 2012a; TDOT, 2015). Six 4 × 8-inch (10.16 × 20.32-cm) cylinders were produced per batch according to ASTM D4832 (ASTM International, 2012a). For compressive strength testing, two cylinders were tested at 6 hours, 24 hours, and 98 days for the UFF, and two cylinders were tested at 24 hours, 28 days, and 98 days for the EFF according to ASTM D4832 (ASTM International, 2012a).

6. Results and Analysis

The inverted slump and compressive strength results at the various ages were recorded as each batch of the UFF and EFF was

Table 3
Controlled low-strength material mixture designs compared with Tennessee Department of Transportation (TDOT) general use[1]

Component	UFF	EFF	TDOT general use
Type I PC, lb/yd^3 (kg/m^3)	–	40 (23.7)	100 (59.3)
Class C fly ash, lb/yd^3 (kg/m^3)	570 (338)	–	250 (148.3)[2]
High-LOI fly ash, lb/yd^3 (kg/m^3)	281 (166)	440 (261.0)	–
Limestone screenings, lb/yd^3 (kg/m^3)	2251 (1336)	2494 (1479.6)	2800 (1661.2)[3]
Water, lb/yd^3 (kg/m^3)	475 (282)	581 (344.7)	500 (296.6)

[1] PC = portland cement; LOI = loss on ignition; UFF = universal flowable fill; EFF = excavatable flowable fill.
[2] TDOT suggestion for all combined fly ashes, not specifically class C.
[3] TDOT suggestion for fine aggregate, not specifically limestone screenings.

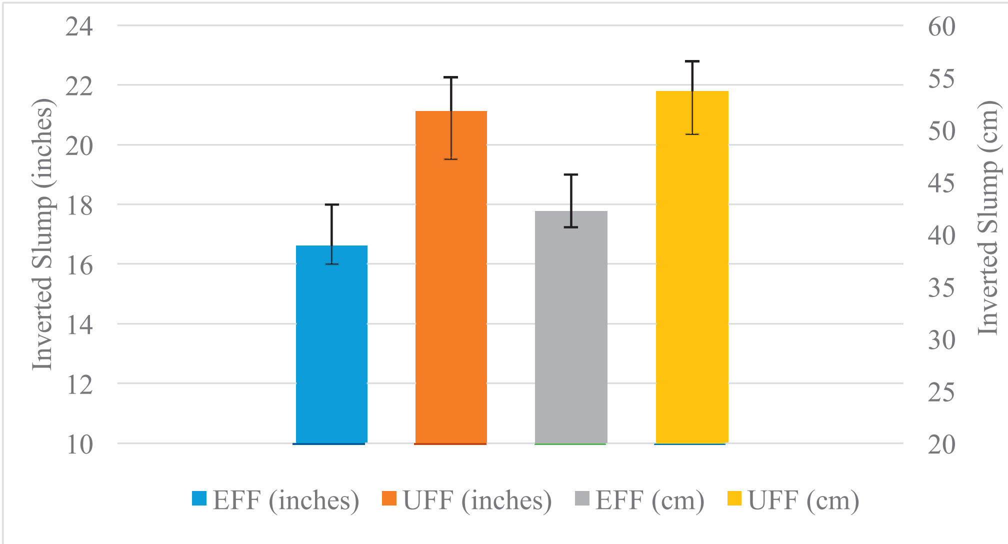

Fig. 1. Excavatable flowable fill (EFF) and universal flowable fill (UFF) inverted slump results.

produced. The inverted slump results for both CLSMs are shown in Figure 1, in which every individual batch complies with TDOT 204.06 requirements (TDOT, 2015). The UFF compressive strength results at 6 hours, 24 hours, and 98 days are shown in Figure 2. The EFF compressive strength results at 24 hours, 28 days, and 98 days are shown in Figure 3. Figures 2 and 3 compare both mixtures with TDOT requirements at the various ages to ensure that compressive strength compliance is deemed applicable in the field. All individual batch averages for the UFF and EFF met TDOT 204.06 specifications for inverted slump and compressive strength (ASTM International, 2012a; TDOT, 2015).

Once the results were gathered, an analysis was performed on the data to ensure dependable and consistent results. Currently, there are no variability standards for compression testing of CLSM cylinders according to ASTM D4832 (ASTM International, 2012a). Also, TDOT 204.06B contains no variability standards for the inverted slump test (TDOT, 2015). 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 4. The UFF and EFF compressive strength statistical parameter results are shown in Tables 5 and 6, respectively.

Despite substituting 91.7% high-LOI fly ash in the EFF and 33% high-LOI fly ash content in the UFF with no PC, by weight, of the cementing materials, every individual batch of each CLSM met all TDOT 204.06B criteria for inverted slump and compressive strength (TDOT, 2015).

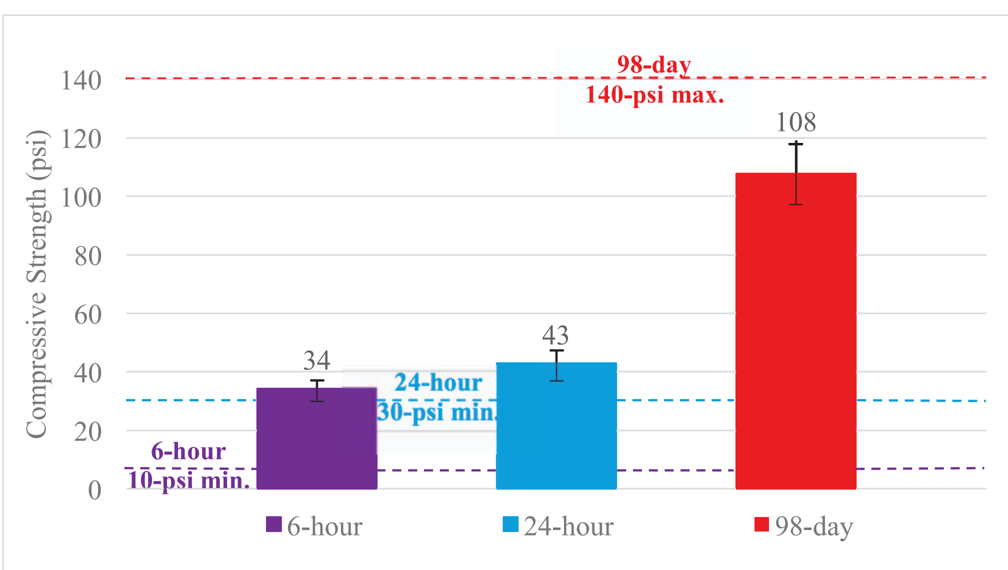

Fig. 2. Universal flowable fill compressive strength results compared with the combined Tennessee Department of Transportation controlled low-strength material requirements. min. = minimum; max. = maximum.

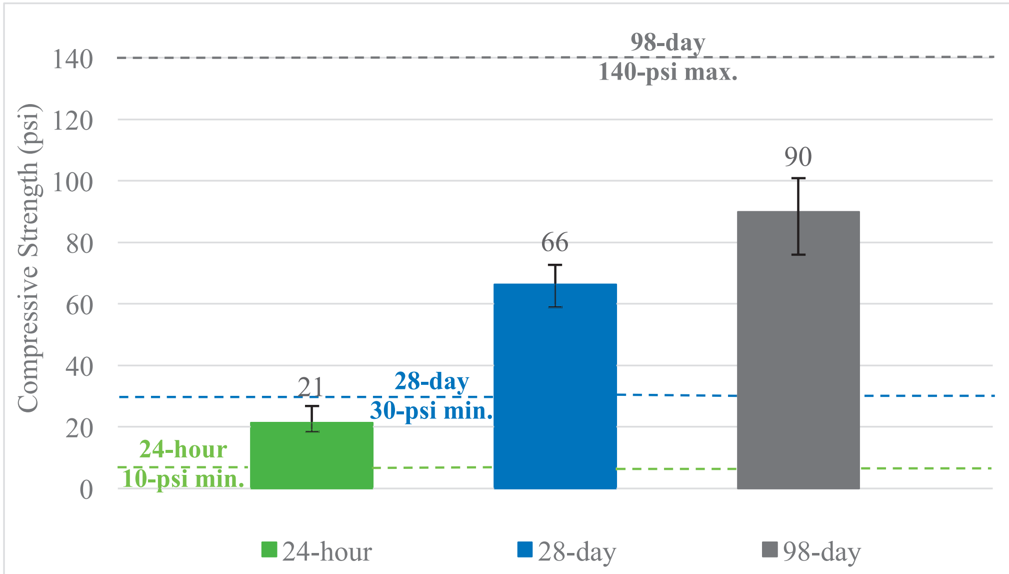

Fig. 3. Excavatable flowable fill (EFF) compressive strength results compared with EFF Tennessee Department of Transportation requirements. min. = minimum; max. = maximum.

Table 4
Universal flowable fill (UFF) and excavatable flowable fill (EFF) inverted slump statistical parameters

Parameter	UFF	EFF
Mean, in. (cm)	21.1 (117.1)	16.6 (42.2)
Standard deviation, in. (cm)	0.95 (2.40)	0.63 (1.59)
Coefficient of variation, %	4.5	3.8
Mean within test range, in. (cm)	2.75 (6.99)	2.0 (5.08)

Table 5
Universal flowable fill compressive strength statistical parameters

Parameter	6 h	24 h	98 days
Mean, psi (kPa)	34.3 (236.6)	42.9 (295.8)	107.7 (742.7)
Standard deviation, psi (kPa)	2.60 (17.9)	3.26 (22.5)	7.92 (54.6)
Coefficient of variation, %	7.6	7.6	7.4
Mean within test range, psi (kPa)	9.15 (63.1)	11.9 (82.3)	27.0 (186.0)

7. Conclusions

The results from the utilization of the high-LOI fly ash and limestone screenings in these CLSM mixtures indicate the following:

1. Large percentages of high-LOI fly ash can definitely be used to produce effective EFFs and UFFs that comply with TDOT 204.06B specifications (TDOT, 2015).
2. Limestone screenings also can be used to produce TDOT 204.06B–approved flowable fills (TDOT, 2015).
3. Flowable fills provide a practical outlet for the use of high-LOI fly ash and limestone screenings with the proviso of a limited market volume for flowable fills.
4. Because the high-LOI fly ash and limestone screenings are both by-products, the cost of these mixtures could be considerably less than conventional CLSMs.

Table 6
Excavatable flowable fill compressive strength statistical parameters

Parameter	24 h	28 days	98 days
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, %	13.9	7.8	9.1
Mean within test range, psi (kPa)	9.23 (63.6)	16.6 (114.7)	32.7 (225.5)

8. Future Research

Repeating this research with a different source of high-LOI fly ash could provide one area of possible future research. This research could also be repeated using a different fine aggregate by-product source. Another possible area could be to analyze the effects of various environmental factors during field placement of the mixtures produced herein. Finally, investigating the use of high-LOI fly ash utilization in other materials having no minimum air content, such as pervious PCCs, certain precast PCCs, and precast self-consolidating concretes, could provide additional topics for future research. These applications could provide dependable and practical outlets for high-LOI fly ash utilization and could also provide an opportunity to consume high-LOI fly ash instead of having to worry about fly ash slurry spills into the environment, such as the Kingston Springs spill. Furthermore, it could reduce efforts required to store the ash in various ways such as ash ponds, silos, and landfills that demand continual monitoring because of the threat of heavy metal leaching into the groundwater system.

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