Tennessee Stabilized Base Using Substandard Fly Ash and Byproduct Limestone Screenings

June 19, 2012

Word Count: 250 (Abstract) + 4,735 (Text) + 9 * 250 (Tables) + 1 * 250 (Figure) = 7,485 Words

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ABSTRACT

Substandard fly ash (high carbon/loss-on-ignition (LOI)) and byproduct limestone screenings are plentiful materials in Tennessee. Utilization of these materials could result in both economic and environmental benefits. The Tennessee Department of Transportation (TDOT) Specification 312 for an Aggregate-Lime-Fly Ash Stabilized Base Course includes hydrated lime, fly ash, and TDOT Grading C limestone. The specification requires an average compressive strength of 950-psi (6.5-MPa) for three specimens, with no individual compressive strength less than 800-psi (5.5-MPa), after 28-days of curing at 100 °F (37.8 °C).

The use of substandard fly ash and limestone screenings was compared to the use of standard materials. The control set consisted of the control fly ash with an aggregate blend, while the variable sets consisted of the control and variable fly ashes, respectively, with limestone screenings. The average compressive strength and coefficient of variation were 1,263-psi (8.71-MPa) and 5.8% for the control set, 1,416-psi (9.76-MPa) and 4.9% for the first variable set, and 966-psi (6.65-MPa) and 3.2% for the second variable set, respectively. The average static modulus of elasticity and coefficient of variation were 3,000-ksi (20.68-GPa) and 7.8% for the control set, 2,650-ksi (18.27-GPa) and 5.2% for the first variable set, and 1,400-ksi (9.65-GPa) and 8.7% for the second variable set, respectively.

Analysis of these results indicates that a high LOI fly ash can be useful as a stabilizing agent when used in combination with hydrated lime. These results also suggest that byproduct limestone screenings can be used effectively as a significant part of the aggregate.

INTRODUCTION AND RESEARCH SIGNIFICANCE

The focus of this research is on use of substandard fly ash (not meeting ASTM C 618 (*1*)) and byproduct limestone screenings, both of which are abundantly available in Tennessee and the Southeast region. Accumulation of substandard and byproduct materials has become an issue in many areas due to lack of viable uses. Fly ash is either piled in large retention ponds at the generation plant or shipped to a landfill, buried, and continuously monitored. Limestone screenings are typically amassed in large quantities at the quarry during production of crushed stone. Therefore, viable uses for these materials are necessary.

Interest in use of underutilized materials, particularly fly ash, was motivated by the tragic ash spill at the TVA Kingston Fossil Plant in late December of 2008 where more than 5-million-yd^3 (3.8-million-m^3) of the stored ash was released over the surrounding area, nearly 300-acres (121-ha) of land and water (*2, 3, 4*). As part of the recovery process, the spilled ash was shipped by rail to a lined landfill in West Central Alabama (*3, 4*). Burying the ash, however, requires continuous monitoring for leakage of heavy metals, such as arsenic, lead, and selenium, into nearby watersheds (*5*). Hence, other methods of disposal, or use, for the fly ash are of interest. Past experience, however, has shown that substandard fly ash could present problems in obtaining the desired air contents in concrete. In addition, prior experience with substandard fly ash in controlled low strength materials has also not been promising (*6*).

The Tennessee Department of Transportation (TDOT) has a specification (Specification 312) for Aggregate-Lime-Fly Ash Stabilized Base Course (ALFASB) which includes hydrated lime, fly ash, and TDOT Grading C limestone in percentages by dry weight of the total mixture of 3.5, 11, and 85.5, respectively (*7*). This base course method, however, is rarely used due to the higher costs of materials compared to that of other highway base alternatives. Therefore, use of substandard fly ash and byproduct limestone screenings (which can be used in TDOT Grading C Limestone) in ALFASB could result in economic and environmental benefits.

RESEARCH OBJECTIVES AND OVERVIEW

Given that substandard fly ash is an abundant material that is currently underutilized, some method of consumption is necessary for the material. Therefore, the primary objective for this research project was to determine if substandard fly ash could be used successfully in a TDOT ALFASB. The success of its use was determined by whether the current compressive strength requirements for TDOT ALFASB were met using a substandard fly ash. In addition, the loss in estimated static modulus of elasticity due to use of a substandard fly ash was also determined.

As mentioned previously, limestone screenings are also an abundant material with little utility. Thus, a secondary objective of the research project was to determine if byproduct limestone screenings could be used as the sole aggregate (rather than the TDOT Grading C limestone) for a TDOT ALFASB. The success of its use was also determined by whether the current compressive strength requirements for TDOT ALFASB were met.

The research was separated as to compare one control sample set with two variable sample sets. The control set consisted of 40 test specimens which examined use of the control fly ash in ALFASB using an aggregate blend to produce TDOT Grading C limestone. The variable sets consisted of a total of 80 test specimens which examined use of the control and variable fly ashes, respectively, in ALFASB using only limestone screenings as the aggregate.

LITERATURE REVIEW

Base Stabilization

A pavement base layer provides an increased capacity for the load bearing and structural aspects of the pavement, both flexible and rigid (*8, 9*). Therefore, the base commonly consists of high quality aggregate capable of resisting the recurrent loads the pavement may experience (*9*). A stabilized base, according to the Federal Highway Administration (FHWA), is a combination of aggregate, cementitious material, and water that can be compacted to produce a dense mass that will gain strength over time (*10*). As a result, a stabilized base can often utilize substandard and lower quality aggregate or soil, those of which are usually present at the application site (*11*). Stabilization modifies the engineering properties of a material, allowing applied loads to be distributed over a larger area, which can potentially reduce the layer thickness, due to improved strength and stability (*12, 13, 14*). In this respect, additives like lime and fly ash can be mixed in with the soil or aggregate to chemically alter the material, through pozzolanic reactions, to obtain the desired long term effects (*14, 15*). Similarly, compaction efforts can be used to mechanically modify the soil to a denser state to improve its load bearing capacity (*14*).

Modification and Stabilization

Fly Ash

Fly ash is a common additive used in stabilization (*10, 14, 15*). It is a byproduct resulting from coal combustion processes used for electric power generation (*15, 19*). Therefore, depending on the type of coal and the process in which it was burned, the properties of fly ash vary, as well as the applications in which it can be used (*15*). Class C (a self cementing fly ash) and Class F (a non-self cementing fly ash) are the two most common fly ashes available, as specified in ASTM C 618, and are more commonly used with coarse-grained soils and aggregates for stabilization (*1, 14, 15*). Fly ash is useful in reducing the shrink and swell potential of a soil by bonding the soil particles together, thereby improving soil strength and durability (*19*).

Lime-Fly Ash

A typical option for use in stabilizing soils and aggregate is a combination of lime and fly ash (*10*). Lime, a common chemical additive used in stabilization, is produced through the calcination of limestone, a process that chemically changes the material to calcium oxide (quicklime) (*15, 16, 17*). When quicklime is treated with water, calcium hydroxide (hydrated lime) is formed, which is one of the most common forms of lime used in stabilization (*16, 17, 18, 19*). While lime provides several benefits for a material through modification and improvement, it may not be sufficient in providing all the necessary properties of stabilization (*20*). Therefore, an additional stabilizing agent like fly ash can be added with lime to obtain the desired properties (*20*). This combination increases the pozzolanic reactions to improve the physical properties of the soil or aggregate (*12, 15*). As a result, use of lime and fly ash in combination can provide significant improvements to strength gain and has been found to be beneficial for stabilization (*13, 15, 21*).

Substandard Materials

Fly Ash

Use of fly ash in a given application is based on its properties, most commonly carbon content and fineness (*19, 22*). Carbon content contributes to loss-on-ignition (LOI), which has a large influence on the reactivity of the material (*19*). A higher LOI ash is less reactive and often has adverse effects on air entrainment, particularly in concrete (*19*). However, it has been found that LOI is not as detrimental to performance in stabilization applications as it is in concrete applications (*21*). Fineness also influences the reactivity of the fly ash; larger particle sizes tend to react at a slower rate, due to a smaller surface area, and also tend to have an adverse effect on concrete properties (*10, 19*).

Limestone Screenings

Aggregate use is often based on its gradation (*10*). Typically, a high fines content, determined by the amount of material passing the No. 200 (0.075-mm) sieve, makes an aggregate unsuitable for various applications (*23*). Therefore, the aggregate is often stockpiled and underutilized, such as byproduct limestone screenings (*24, 25*). Screenings tend to be of a uniform size with a significant amount of fines and typically have negative effects on aspects like density and stability, particularly in concrete applications (*26, 27*). To some extent, however, it has been found that byproduct aggregate can be used successfully in various highway applications, providing a beneficial use for generally unused materials (*24, 26*).

MATERIALS

TDOT Specification 312 requires hydrated lime, fly ash, and TDOT Grading C limestone for use in ALFASB. The hydrated lime used did not meet ASTM C 977 (but was close) and was obtained from a regional supplier in Luttrell, Tennessee. The properties and ASTM C 977 requirements for hydrated lime are shown in Table 1 (*28*).

Fly ash used in ALFASB is required to meet ASTM C 593, with several exceptions, particularly that the LOI must not exceed 10% (*29*). Therefore, Cumberland City Class F Ash, the most widely used Class F fly ash in Tennessee for use in concrete mixtures, was used as the control fly ash; Cumberland City F Ash has an LOI of 1.6% and conforms to ASTM C 618. For the variable fly ash, TVA was contacted and requested to provide the highest LOI fly ash available. A high LOI fly ash was considered to be underutilized, very economical, and a worst case scenario for the TDOT ALFASB. TVA provided a fly ash from the Colbert Plant in Northwestern Alabama, which is reported to have an LOI that sometimes reaches 12%. The properties of each fly ash and ASTM C 618 requirements, as well as AASHTO M 295 (*30*) requirements, are shown in Table 2.

TABLE 1 Hydrated Lime Properties and Requirements

Parameter	Typical Properties of Bulk Hydrated Lime from the Luttrell Plant	ASTM C 977 Requirements
Calcium Hydroxide (%)	94.4	—[*]
LOI (%)	24.1	—
Available CaO (%)	70.8	—
Calcium Oxide (%)	74.2	90 min.
Magnesium Oxide (%)	0.7	
Silica (%)	1.0	—
Ferric Oxide (%)	0.3	—
Alumina (%)	0.7	—
Moisture (%)	0.6	2.0
Percent Passing No. 200 (%)	94.6	75 min.
Percent Passing No. 325 (%)	84.9	—
Loose Bulk Density, pcf (kg/m^3)	21 (336)	—

[*] *data not applicable*

TABLE 2 Fly Ash Properties and Requirements

Parameter	Control (Cumberland City F Ash)	Colbert Ash	ASTM C 618-08	AASHTO M 295-07
Silicon Dioxide (%)	45.7	47.8	—[*]	—
Aluminum Oxide (%)	18.2	21.5	—	—
Iron Oxide (%)	18.6	8.7	—	—
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	82.5	78.0	70 min.	70 min.
Calcium Oxide (%)	8.3	7.9		—
Magnesium Oxide (%)	1.2	1.7	—	—
Sulfur Trioxide (%)	2.4	0.0	5 max.	5 max.
LOI (%)	1.6	8.0	6 max.	5 max.
Moisture Content (%)	0.1	25.0	3 max.	3 max.
Alkalies as Na_2O (%)	0.7	1.1	—	1.5 max.

[*] *data not applicable*

TDOT Grading C limestone can be produced by blending ASTM C 33 No. 57 limestone with limestone screenings (*31*): 55% (by mass of total aggregate) No. 57 limestone and 45% (by mass of total aggregate) byproduct limestone screenings. The No. 57 limestone was dry sieved over a ¾-in (19-mm) sieve, or "scalped," to comply with requirements for the laboratory compaction procedure for the TDOT ALFASB. Less than 10% of the original aggregate weight was lost during scalping and the "scalped" limestone still met ASTM C 33 No. 57 gradation requirements. The component (No. 57 stone and screenings) and blend gradations, in addition to the TDOT Grading C requirements, are shown in Table 3.

Finally, local tap water was used in each mixture. Tap water was considered more applicable to field use, rather than use of distilled or de-ionized water. The amount added was dependent upon the optimum moisture content (OMC) found for each mixture.

TABLE 3 Aggregate Gradations and Requirements

Sieve Size	Sieve Size, mm	Scalped No. 57 Limestone (% Finer by Mass)	Limestone Screenings (% Finer by Mass)	55/45 Blend (% Finer by Mass)	TDOT Grading C Limestone (% Finer by Mass)
1.5-in	37.5	100	100	100	100
1-in	25	100	100	100	90 - 100
¾-in	19	100	100	100	—[*]
½-in	12.5	40	100	67	—
3/8-in	9.5	20	100	56	45 - 74
No. 4	4.75	4	96	45	30 - 55
No. 8	2.36	2	63	30	—
No. 16	1.18	1	38	18	—
No. 30	0.6	1	25	12	—
No. 50	0.3	1	18	9	—
No. 100	0.15	1	14	7	4 - 15
No. 200	0.075	0.8	11.3	5.5	—

[*] *data not applicable*

PROCEDURE

Optimum Moisture Content Determination

TDOT Specification 312 for ALFASB requires hydrated lime, fly ash, and TDOT Grading C limestone in percentages by dry weight of the total mixture of 3.5, 11, and 85.5, respectively. The OMC of each mixture was determined according to AASHTO T 99 Method C (*32*). At least 10 specimens at various moisture contents were used to determine the OMC for each set of materials; the use of multiple specimens at various moisture contents helped to define the proctor curve and ensure isolation of the OMC point. The OMC and maximum dry density (MDD) for each mixture are shown in Figure 1 and are identified by the type of fly ash and aggregate contained.

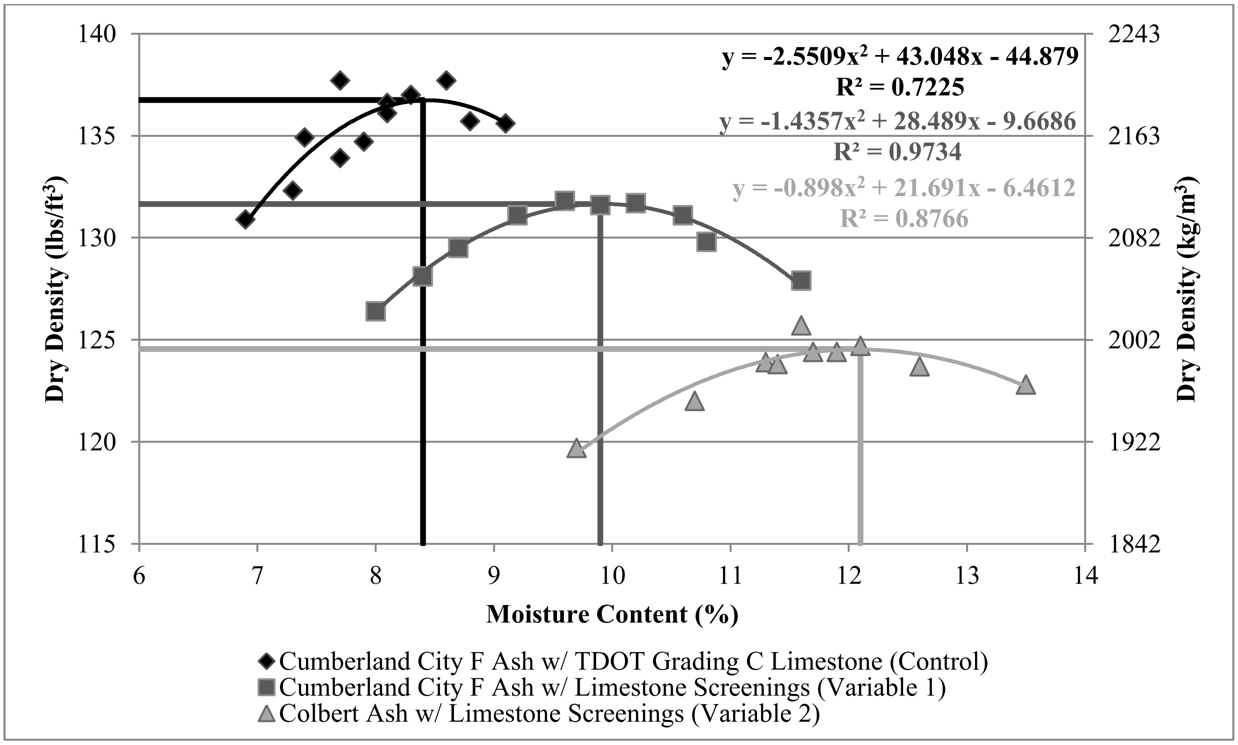

FIGURE 1 Standard Proctor Results.

Proctor Specimen Fabrication and Curing

Twenty-four Standard Proctor compressive strength specimens (eight sets of three each) were compacted to determine TDOT Specification 312 compressive strength compliance for each control and variable sets of materials. Six specimens (two sets of three each) were usually compacted per day. All specimens were compacted in Standard Proctor molds 4-in (101.6-mm) in diameter as in AASHTO T99 Method C. Due to the large number of specimens, moisture contents were not conducted on trimmings from each specimen; rather, a single check specimen was compacted each day. The as-compacted and oven-dried mass of the check specimens were determined to establish that the moisture content and dry density were close to OMC and MDD. The Standard Proctor compressive strength specimens were cured in 1-gal (4-L) cans with double friction lids for 28-days at 100 ± 3°F (38 ± 2°C) in a forced air electric oven according to TDOT Specification 312. The curing time required for these specimens was longer than the 7-days required by ASTM C 593, but the storage method and temperature requirements were the same.

Proctor Specimen Compressive Strength Testing

The specimens were removed from the sealed cans at the conclusion of the curing period, reweighed, and soaked for four hours. After soaking, the specimens were removed from the water and the average diameter of each specimen, used in calculating compressive strength, was measured. The length of each specimen was not measured however, since no length to diameter ratio (l/d) correction factor was used in determining compressive strength, as per ASTM C 593. After measurements were taken, each specimen was capped with a sulfur mortar and allowed to set for two hours, rather than the one hour required by ASTM C 593. Each specimen was then tested according to ASTM C 39 using a 22.3-kip (100-kN) electric compression frame (*33*). Three specimens were considered to complete a test as required by ASTM C 593 and TDOT Specification 312.

Specimens for Estimating Static Modulus of Elasticity

Correlations for modulus of elasticity and compressive strength are the basis for the structural layer coefficient a_2 for stabilized bases in the American Association of State Highway and Transportation Officials (AASHTO) Design Guide for Pavement Structures (*34*). Therefore, an estimate of the elastic modulus was needed to relate to the AASHTO Design Guide information. Due to specimen similarity and equipment availability, estimation was completed following the procedure in ASTM C 469 (*35*). Sixteen specimens (eight sets of two each) were compacted to estimate the static modulus of elasticity for each set of materials. Eight specimens (four sets of two) were typically compacted per day. All specimens were compacted in split steel molds 6-in (152-mm) tall by 3.1-in (79-mm) in diameter to yield a specimen tall enough for an ASTM C 469 compressometer with an l/d close to two. The compactive effort for the modulus specimens was the same as that used for the Standard Proctor compressive strength specimens, but the number of hammer blows per layer was decreased and the number of layers was increased in order to do so. Moisture contents and dry densities were conducted with a single check specimen in the same manner as the Standard Proctor compressive strength specimens. The modulus specimens were cured in sealed 1-gal (4-L) cans with double friction lids for 28-day at 100 ± 3°F (38 ± 2°C) in a forced air electric oven according to TDOT Specification 312.

Testing Modulus Specimens

As with the Standard Proctor compressive strength specimens, the modulus specimens were removed from the sealed cans at the conclusion of the curing period, reweighed, and soaked for four hours. After soaking, the specimens were removed from the water and the average diameter of each specimen, used in calculating compressive strength and estimating modulus of elasticity, was measured. No l/d correction was required for the modulus specimens since the l/d was close to two. After measurements were taken, each specimen was capped with sulfur mortar and allowed to set for two hours, rather than the one hour required by ASTM C 593. For each set, a companion specimen was first tested for compressive strength as per ASTM C 39 using the 22.3-kip (100-kN) electric compression frame. The compressometer was then attached to the second specimen and was tested according to ASTM C 469 using the 22.3-kip (100-kN) electric compression frame. Lastly, the compressometer was removed and the second specimen was tested for compressive strength as per ASTM C 39 using the 22.3-kip (100-kN) electric compression frame. Two specimens were considered to complete a test as required by ASTM C 469.

Specimen Quality

The wet density variability results for the Standard Proctor compressive strength specimens and comparisons to OMC and MDD for the check specimens for each set of materials are shown in Table 4. The wet density variability results for the modulus specimens and comparisons to OMC and MDD for the check specimens of each set of materials are shown in Table 5. The coefficient of variation and percent range values was less than 2.5% for the control mixture and less than 2% for the two variable mixtures. Wet density averages were within 1.5% of target values for the control and within 1% for each variable. The dry density averages of the check specimens varied from target values by less than 1.5% for the control and less than 1% for the variables. The average moisture contents of the check specimens were within 0.5% of OMC for the control mixture and within 0.2% for both variable mixtures. Since the Colbert Ash was provided at a high moisture content of approximately 25% and the screenings consisted of a high fines content, accounting for the excess moisture and probable moisture absorption, respectively, could have resulted in the small deviation from OMC. All specimens were deemed adequate for their intended uses.

TABLE 4 Standard Proctor Compressive Strength Specimen Variability

Parameter	Control Mixture	Variable Mixture 1	Variable Mixture 2
Mean Wet Density of 24 Specimens, pcf	150.6	144.5	140.0
Wet Density Range of 24 Specimens, pcf	3.1	1.9	2.4
Percent Range	2.1	1.3	1.7
Wet Density Standard Deviation, pcf	0.9	0.5	0.7
Wet Density Coefficient of Variation, (%)	0.6	0.4	0.5
Maximum Wet Density, pcf	151.6	145.5	141.1
Percent Standard Proctor Maximum Wet Density	99.3	99.3	99.2
Number of Check Specimens	4	4	4
Check Specimen MDD, pcf	140.7	133.0	126.6
Check Specimen Mean Dry Density, pcf	139.0	132.0	125.8
Check Specimen Percent MDD	98.8	99.2	99.4
OMC, (%)	8.4	9.9	12.1
Check Specimen Mean Moisture Content, (%)	8.1	9.8	12.0
Deviation from OMC, (%)	-0.3	-0.1	-0.1

NOTE: 1-pcf = 16.02-kg/m^3

TABLE 5 Modulus Specimen Variability

Parameter	Control Mixture	Variable Mixture 1	Variable Mixture 2
Mean Wet Density of 16 Specimens, pcf	148.1	143.9	139.0
Wet Density Range of 16 Specimens, pcf	2.9	1.1	0.8
Percent Range	2.0	0.8	0.6
Wet Density Standard Deviation, pcf	0.7	0.3	0.3
Wet Density Coefficient of Variation, (%)	0.5	0.2	0.2
Maximum Wet Density, pcf	149.5	144.5	139.4
Percent Standard Proctor Maximum Wet Density	99.1	99.6	99.7
Number of Check Specimens	2	2	2
Check Specimen MDD, pcf	137.7	131.4	124.5
Check Specimen Mean Dry Density, pcf	137.7	131.2	124.4
Check Specimen Percent MDD	100.0	99.8	99.9
OMC, (%)	8.4	9.9	12.1
Check Specimen Mean Moisture Content, (%)	7.9	9.8	12.1
Deviation from OMC, (%)	-0.5	-0.1	0.0

NOTE: 1-pcf = 16.02-kg/m^3

RESULTS

The compressive strength results for the Standard Proctor compressive strength specimens are shown in Table 6, respective to each control and variable sets of materials. The compressive strength and estimated modulus results for the modulus specimens are shown in Table 7, respective to each control and variable sets of materials. The average compressive strength results are rounded to the nearest 5-psi (0.034-MPa). The estimated modulus is rounded to the nearest 50-ksi (0.34-GPa), as required by ASTM C 469.

TABLE 6 Standard Proctor Specimen Compressive Strength Results

Mixture	Set	Specimen 1, psi	Specimen 2, psi	Specimen 3, psi	Mean, psi
Control Mixture	1	1352	1425	1255	1345
	2	1231	1326	1046	1200
	3	1223	1217	1335	1260
	4	1233	1148	1218	1200
	5	1186	1223	1201	1205
	6	1352	1201	1287	1280
	7	1431	1395	1356	1395
	8	1349	1155	1163	1220
Variable Mixture 1	1	1438	1477	1505	1475
	2	1509	1487	1466	1485
	3	1546	1360	1375	1425
	4	1405	1493	1415	1440
	5	1612	1463	1323	1465
	6	1359	1360	1325	1350
	7	1391	1481	1342	1405
	8	1259	1308	1278	1280
Variable Mixture 2	1	981	990	922	965
	2	936	932	923	930
	3	901	899	950	915
	4	933	956	1005	965
	5	901	1006	1016	975
	6	1036	984	1004	1010
	7	975	1020	994	995
	8	987	954	983	975

NOTE: 1-psi = 0.00689-MPa

TABLE 7 Modulus Specimen Compressive Strength and Estimated Modulus Results

Mixture	Set	Specimen 1 Compressive Strength, psi	Specimen 2 Compressive Strength, psi	Mean Compressive Strength, psi	Estimated Static Modulus of Elasticity, ksi
Control Mixture	1	1922	1858	1890	3250
	2	1955	1885	1920	3250
	3	1999	1741	1870	3000
	4	1969	1825	1895	3100
	5	2004	1573	1790	2600
	6	1799	1649	1725	2800
	7	2091	1856	1975	2850
	8	2055	1758	1905	3150
Variable Mixture 1	1	1632	1716	1675	2650
	2	1761	1829	1795	2700
	3	1874	1849	1860	2900
	4	1972	1639	1805	2550
	5	1826	1905	1865	2650
	6	1707	1618	1665	2550
	7	1855	1772	1815	2750
	8	1791	1664	1730	2450
Variable Mixture 2	1	846	891	870	1450
	2	862	882	870	1300
	3	859	874	865	1400
	4	865	842	855	1350
	5	848	857	855	1500
	6	797	842	805	1400
	7	830	771	800	1200
	8	872	870	870	1600

NOTE: 1-psi = 0.00689-MPa, 1-ksi = 0.00689-GPa

ANALYSIS OF RESULTS

Variability of Results

The average results and parameters pertaining to the variability of the results for the Standard Proctor specimens and modulus specimens are shown in Table 8. The coefficient of variation of compressive strength results was less than 6% for all six sets of results. The variability of the individual specimens within a test was characterized by mean range and mean percent range values. The mean percent ranges of the specimens varied from 3.7 to 11.1%. No guidance is provided by TDOT or ASTM C 593 on acceptability. However, ASTM C 39 states that the acceptable range of individual cylinder strength for three 4-in by 8-in (100-mm by 200-mm) concrete cylinders should not exceed 10.6% of their average. The control specimens varied from this limit slightly, but were close, with both the Standard Proctor and modulus specimens averaging 11.1%. Both variable specimen sets met this limit with results averaging less than 10%. Therefore, the results for the control and both variable Standard Proctor and modulus specimens seemed adequate to characterize material behavior. ASTM C 469 states that the results of duplicate cylinders from different batches should not differ by more than 5% of their average; however, this requirement is for concrete with a higher modulus range. However, the average percent of the average range of sequential modulus results met this limit for the control and both variable specimens. Deviations from this limit were found with non-sequential pairs, but were not common.

TABLE 8 Statistical Parameters for Specimens

Specimen Type	Parameter	Control Mixture	Variable Mixture 1	Variable Mixture 2
Standard Proctor Specimens	Mean Strength, psi	1263	1416	966
	Standard Deviation, psi	73	70	31
	Coefficient of Variation, (%)	5.8	4.9	3.2
	Mean Range of Specimens within a Test, psi	139	112	56
	Mean Percent Range of Specimens within a Test	11.1	7.8	5.8
Modulus Specimens	Mean Compressive Strength, psi	1871	1776	849
	Standard Deviation of Specimen Compressive Strengths, psi	79	78	29
	Coefficient of Variation of Specimen Compressive Strengths, (%)	4.2	4.4	3.4
	Mean Range of Strength Specimens within a Test, psi	206	111	31
	Mean Percent Range of Strength Specimens within a Test	11.1	6.3	3.7
	Mean of the Static Modulus of Elasticity, ksi	3000	2650	1400
	Standard Deviation of the Static Modulus of Elasticity, ksi	233	139	122
	Coefficient of Variation of the Static Modulus of Elasticity, (%)	7.8	5.2	8.8
	Mean Range (Percent of Mean Modulus) of Sequential Modulus Results	1.7	1.7	3.0

NOTE: 1-psi = 0.00689-MPa, 1-ksi = 0.00689-GPa

TDOT Specification 312 Compliance

The individual and average results from Table 6 show that the control and first variable specimens met both the TDOT average and individual compressive strength requirements. The second variable specimens, however, met the individual compressive strength requirements, but failed to meet average compressive strength requirements, meeting only 75% of the time. Still, these specimens maintained an average greater than 900-psi (6.2-MPa). However, by TDOT Specification 312 requirements, the second variable specimens were deemed inadequate.

Comparison of Results

A paired t-test using a 5% level of significance was conducted to determine if a significant difference existed between compressive strengths of the control and first variable mixtures, the control and second variable mixtures, and the first variable and second variable mixtures, respectively, for the Standard Proctor and modulus specimens; these comparisons are shown in Table 9. A significant difference was apparent in the comparisons of the control and first variable Standard Proctor specimens, but was not apparent in the comparisons of the modulus specimens. The average compressive strength results for both the control and first variable mixtures were much higher for the modulus specimens than for the Standard Proctor specimens, differing by 608-psi (4-MPa) and 361-psi (2-MPa), respectively. Theoretically, higher l/d modulus specimens should have a lower compressive strength. The Standard Proctor specimens had a higher average wet density and the check specimens indicated a higher dry density and similar as-compacted moisture content, which would signify a higher compressive strength. Therefore, a plausible explanation for the much higher compressive strength in the modulus specimens is not available. A significant difference was also apparent in the comparisons of the control and second variable mixtures, as well as the comparisons of the first variable and second variable mixtures, for the Standard Proctor and modulus specimens. The average compressive strength results for the second variable mixtures were lower for the modulus specimens than for the Standard Proctor specimens, differing by 118-psi (1-MPa).

A paired t-test using a 5% level of significance was conducted to determine if a significant difference existed in the estimated static modulus of elasticity of the control and first variable mixtures, the control and second variable mixtures, and the first variable and second variable mixtures, respectively, for the modulus specimens. A significant difference was not apparent in the comparisons of the control and first variable mixtures, but was apparent in the comparisons for the control and second variable mixtures and the first variable and second variable mixtures. On average, the first and second variable mixtures only obtained 88.3% and 46.7%, respectively, of the estimated static modulus of elasticity of the control mixture. However, Table 9 shows that both the variable mixture specimens have an average estimated static modulus greater than the 1.1-million-psi (7.60-GPa) required for an AASHTO layer coefficient a_2 of 0.28, which TDOT has assigned to TDOT Specification 312 ALFASB for pavement design calculations.

TABLE 9 Comparison of Results

Comparisons	Parameter	Proctor Specimens	Modulus Specimens
Control vs. Variable 1	Significant Difference in Compressive Strength	Yes	No
	Percent of Control Compressive Strength	112.1	94.9
	Significant Difference in Estimated Modulus	—[*]	No
	Percent of Control Estimated Modulus	—	88.3
Control vs. Variable 2	Significant Difference in Compressive Strength	Yes	Yes
	Percent of Control Compressive Strength	76.5	45.4
	Significant Difference in Estimated Modulus	—	Yes
	Percent of Control Estimated Modulus	—	46.7
Variable 1 vs. Variable 2	Significant Difference in Compressive Strength	Yes	Yes
	Percent of Control Compressive Strength	68.3	47.8
	Significant Difference in Estimated Modulus	—	Yes
	Percent of Control Estimated Modulus	—	52.8

[*] *data not applicable*

CONCLUSIONS

Based on the testing of one substandard fly ash and one substandard aggregate, the following conclusions can be determined:

1. The use of 100% (by mass of total aggregate) byproduct limestone screenings, in combination with hydrated lime and Cumberland City Class F fly ash, produced a mixture that met TDOT Specification 312 compressive strength requirements.

2. The use of substandard fly ash and 100% (by mass of total aggregate) byproduct limestone screenings, in combination with hydrated lime, produced a mixture that met the TDOT Specification 312 individual compressive strength requirement, but not the average compressive strength requirement. However, the produced mixture did maintain an average compressive strength greater than 900-psi (6.2-MPa) despite using both substandard materials.

3. The use of substandard fly ash and 100% (by mass of total aggregate) byproduct limestone screenings, in combination with hydrated lime, produced a mixture with adequate estimated static modulus of elasticity to merit an AASHTO layer coefficient a_2 of 0.28.

ACKNOWLEDGMENTS

The authors greatly appreciate the donation of hydrated lime by Kenneth Cantrell of Pozzolanic Contracting and Supply Co., Inc. of Knoxville, TN, the delivery of the hydrated lime and technical assistance by Barry Wilder of the Portland Cement Association Southeast Region, and the donation of Colbert Fly Ash by the Tennessee Valley Authority. Special thanks to Joe Diedrich of Cemex of Knoxville, TN for analyzing the Colbert Fly Ash composition.

The authors would like to thank Jeff Holmes and Perry Melton of Tennessee Technological University (TTU) for their patience and skill in fabrication, maintenance, and repair of equipment as well as obtaining and storing materials for the project. We would also like to thank Aaron Crowley, Allen Browning, John Hendrix, and Joshua Hogancamp for their help in the laboratory.

The authors appreciate the financial, administrative, and information technology support provided by the TTU Center for Energy Systems Research.

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