Lean, Green and Mean (LGM) Concrete

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ABSTRACT

Sustainability is currently a factor of extreme importance for the concrete industry. Presently, standard practice limits the replacement of cement with fly ash to only about 25 percent. High Volume Fly Ash (HVFA) concrete has recently gained popularity for a resource-efficient concrete application. However, HVFA concrete contains at least 50 percent by mass of the cementitious material content is fly ash. Therefore, many producers have a desire to be more “green” but are constrained from using HVFA due to its tendencies for slower setting times. In this study two types of LGM mixtures, one containing Class F fly ash and one tertiary mix containing Class F fly ash and slag cement, were compared with an East Tennessee commercial mixture. To ensure statewide applicability each mixture was produced with both river sand and manufactured limestone sand as the fine aggregate. The LGM mixtures reached higher long-term compressive strengths, due to the pozzolanic properties of the fly ash and the lower w/cm ratios. In addition, all four LGM mixes produced one-day compressive strengths exceeding 750 psi (5.17 MPa), which is considered the minimum strength for wrecking concrete forms. The compressive strength of the LGM mixtures all exceed 5000 psi (34.47 MPa) at 28-days. Also, the water permeable void contents and absorptions were lower for the LGM mixtures at all ages, indicating that the durability of the LGM is superior to that of the East Tennessee mixtures. Overall, the LGM mixtures exhibit comparable costs, increased compressive strengths, and enhanced durability properties.

INTRODUCTION AND LITERATURE REVIEW

It is becoming increasing popular to replace higher percentages of portland cement with fly ash in concrete. There are three primary reasons that can be attributed to this increased demand of higher fly ash replacement percentages. The first focus is the improved technical advantages. Increasing the amount of fly ash has been proven to increase both overall compressive strength and durability. Secondly, additional fly ash typically improves the economics of the concrete. Fly ash is typically less expensive than portland cement since it is a by-product. Therefore, the cost of concrete will decrease as the replacement percentages of fly ash continue to increase. The last advantage deals with the environmental impact. Fly-ash is an industrial by-product that will fill our nation's landfills if not used in concrete. In 2003, 70 million tons of fly ash was produced in the United States, and only 38 percent was recycled into useful applications.[25] In addition, increasing fly ash proportions sequentially decreases the quantity of portland cement being produced, which in turn reduces the amount of CO_2 emissions being discharged into the atmosphere.

As stated previously, fly ash aids in the production of a better quality mix. It improves both plastic and hardened properties of the concrete. The use of fly ash is known to improve workability and reduce internal temperatures.[5] The improved workability can be attributed to the "ball bearing" action of the spherical fly ash particles. Fly ash improves the grading in the mixture by smoothing out the fine particle size distribution.[6] Also, fly ash has been shown to reduce the amount of water required.[7] Fly ash from modern power plants used in large volumes can reduce the water content by 15 to 20 percent.[1]
The reduction in the water consequently increases overall strength, and produces a more durable concrete. However, research has shown that the properties of concrete are strongly dependent on the characteristics of the cement and fly ash used.[8]

Currently standard practice permits the replacement of cement with fly ash in a range from 0 to 25 by mass of total cementitious material. However, due to the many advantages resulting from the use of fly ash there has recently been an increased popularity in the use of high-volume fly ash (HVFA) concrete. HVFA PCC is considered to be any concrete containing a fly ash content that is greater than 50 percent by mass of the total cementitious materials.[1]

HVFA concretes provide a wide range of benefits. Possibly the most notable property is the enhancement of concrete durability. The improvements in durability are a result of the reduction in calcium hydroxide, which is the most soluble of the hydration products, and from changes in the pore structure.[5] This is can be attributed to the fact that fly ash acts as a water reducer which consecutively decreases mixing water, decreases water to cementitious materials (w/cm) ratio, and also decreases in the total volume of cement paste that is required in HVFA. Also, the decreased heat of hydration at early ages reduces potential for thermal shrinkage and cracking.[1] One indicator of the durability of concrete is the permeability; the more water that can penetrate the concrete, the more potential for freeze/thaw damage. Also, the rate of water absorption by capillary suction has been shown to be a good measure of the potential durability of concrete.[1] Research has shown that the water permeability of HVFA is lower than that of normal PCC.[8,9]

HVFA concrete has been found to be a durable concrete system for many concrete applications. However, there are certain placement and design issues that require particular attention in order to achieve the maximum benefit of HVFA concrete. The two primary factors that need to be addressed to ensure a productive HVFA concrete is a low water to cementitious materials ratio and an extended period of moist curing.[2] This could potentially be the reason that specifications reluctant to permit higher levels of fly ash to be used for general concreting purposes. [2]

While HVFA concretes have a wide range of benefits, they also have a few drawbacks. Generally, the strength development of concretes with high volumes of fly ash is slower than concrete without fly ash.[1] It has been suggested that a compressive strength of 750 psi (5.2 MPa) at one day, which HVFA has been found to obtain, is adequate for formwork removal when no early loads are applied.[10] Also, even though the short term strengths are usually lower than those of normal concrete, the pozzolanic properties of fly ash result in long-term strengths comparable to or better than conventional PCC. The rate of increase in compressive strength is dependent on the level of cement replacement, type of fly ash, and age of the concrete. It has been observed that the rate of early-age strength gain of Class C is higher than that of Class F fly ash. However, the long-term pozzolanic strength contribution for Class F fly ash is greater than Class C, resulting in higher long-term compressive strengths.[3] Overall, higher long term strengths have been observed for HVFA due to the dense microstructure and smaller size of capillary pores, which result from the pozzolanic reactions.[11] Adequate curing is essential to ensure that later-age strength development will occur.[8]

The rate of strength variation is also dependent upon the consistency and presence of different chemical admixtures.[6] Many researchers agree that the use of a superplasticizer or water reducer is necessary in HVFA to ensure workability, especially when low w/cm ratios are used.[1,8] In cases where frost resistance is necessary, the use of an air-entraining admixture is required.[1] However, special caution must be taken when using air-entrainers and large amounts of fly ash. Fly ashes having very high carbon content require much higher dosages of air-entraining admixtures.[8,12] Also, the effectiveness of air-entrainer decreases with an increase in the fly ash to cementitious materials ratio.[6]

As previously stated, the rate of early strength development is slower for HVFA; therefore, the setting time for HVFA concrete is generally longer than conventional concrete using PC alone.[1] The reaction between cement and water is the primary cause of the setting of concrete.[5] Therefore, as the cement content decreases, it makes sense that the time of set would increase. The increased setting time occurs for both fly ash classes and at all levels of fly ash substitution.[7] The delay in setting time can be up to two hours.[1] Initially, it would be expected that Class C fly ash would have less of a reduction in time of set than Class F fly ash, due to the cementitious and pozzolanic properties of C ash. However, Ravina and Mehta found that Class C fly ash has a greater delay in setting time than Class F fly ash, due to its higher sulfate contents.[7] While it is apparent that the setting time is longer for HVFA, results have shown that the amount of retardation is acceptable.[8]

SCOPE

In this study, four different LGM mixtures were studied, two containing Class F fly ash and the other two containing both Class F fly ash and Grade 120 Slag. The LGM mixtures were each compared with an East Tennessee commercial mixture containing the same class of fly ash. To ensure statewide applicability each mixture was produced with both river sand and manufactured limestone sand as fine aggregate. The compressive strength, water absorption, water permeable void content, modulus, and cost were compared. The goal was to produce a concrete mixture that exceeded standard fly ash replacement levels, but were lower than the 50 percent replacement needed for HVFA concrete. The objective was to obtain properties that were comparable to or better than the current East Tennessee Commercial mixes. Table 1 displays the numerical goals for the project that were given to quantify successful mix designs.

Table 1. Numerical Goals

Objective	**Range**
Slump	4" - 7" (10.2 - 17.8 cm)
Air	4.0% - 8.0%
1-day Compressive Strength	≥ 750 psi (5.2 MPa)
28-day Compressive Strength	≥ 4000 psi (2.8 MPa)

MATERIALS

The material proportions for the four LGM mixtures are shown in Table 2 and Table 3. Both Ohio River sand and manufactured limestone were used as fine aggregates for the mixtures to endure statewide applicability. Table 4 displays mixture proportion ratios for the designed mixtures. A #57 limestone obtained from a local quarry was utilized as the coarse aggregate. The #57 limestone and Ohio River sand aggregates both meet the requirements of ASTM C 33.[13] However, according to material finer than No. 200 (75μm) constraint the manufactured sand will only meet ASTM C33 requirements in specified conditions. Type 1 portland cement, in accordance with ASTM C 150, was obtained from a local PCC producer from bulk storage.[14] Local tap water was used for all mixtures. The Class F fly ash was obtained from a regional fly ash producers and met the requirements of ASTM C 618.[15] The Slag cement was obtained from a national supplier and meets the requirements of ASTM C 989.[30]

Table 2. Mixture Proportions with River Sand

Component	40 F RS	20F 20S RS	E. TN Com. RS
Coarse aggregate, lb/yd^3 (kg/m^3)	1899 (1127)	1906 (1131)	1717 (1019)
Fine Aggregate, lb/yd^3 (kg/m^3)	1239 (735)	1244 (738)	1322 (784)
Type 1 PC, lb/yd^3 (kg/m^3)	300 (178)	300 (178)	350 (208)
Class F Fly Ash, lb/yd^3 (kg/m^3)	200 (119)	100 (59)	150 (89)
Grade 120 Slag, lb/yd^3 (kg/m^3)	0	100 (59)	0
Water, lb/yd^3 (kg/m^3)	212.5 (126)	216.5 (128)	255 (151)
w/cm	0.43	0.43	0.51
Air Entrainer, oz/cwt (mL/100kg)	0.7 (46)	0.4 (26)	1 (65)
Type E Admixture, oz/cwt (mL/100kg)	16 (1040)	10 (650)	10 (650)
Type A Admixture, oz/cwt (mL/100kg)	7 (455)	5 (325)	0

Table 3. Mixture Proportions with Manufactured Sand

Component	40F MS	20F 20S MS	E. TN Com. MS
Coarse aggregate, lb/yd^3 (kg/m^3)	1890 (1121)	1897 (1125)	1708 (1013)
Fine Aggregate, lb/yd^3 (kg/m^3)	1274 (756)	1277 (758)	1360 (807)
Type 1 PC, lb/yd^3 (kg/m^3)	300 (178)	300 (178)	350 (208)
Class F Fly Ash, lb/yd^3 (kg/m^3)	200 (119)	100 (59)	150 (89)
Grade 120 Slag, lb/yd^3 (kg/m^3)	0	100 (59)	0
Water, lb/yd^3 (kg/m^3)	217.5 (129)	222.5	260
w/cm	0.44	0.45	0.52
Air Entrainer, oz/cwt (mL/100kg)	0.6 (39)	0.85 (55)	0.6
Type E Admixture, oz/cwt (mL/100kg)	12 (780)	12 (780)	10 (650)
Type A Admixture, oz/cwt (mL/100kg)	6 (390)	6 (390)	0

Table 4. Mixture Proportions Ratio

	LGM	Tertiary LGM	E. TN Com.
Total Cementious, lb/yd^3 (kg/m^3)	500 (297)	500 (297)	500 (297)
Fly ash, % of Total Cementious	40	20	30
Slag, % of Total Cementious	0	20	0

ASTM Type A and E admixtures were used, along with an air-entrainer.[16] Type A admixtures are water reducing admixtures; this was added to the LGM mixture to lower the water to cement (w/cm) ratio, consequently producing stronger more durable concrete while maintaining a workable mix with a slump of four to seven inches. Type E admixtures acts as both a water-reducer and an accelerator. This admixture was added to the LGM mix to reduce the delay in setting time that is frequently associated with high amounts of fly ash. An air-entrainer was inserted into the LGM mixture to ensure an air content of four to eight percent was achieved in the mixture in order to increase the concretes resistance to damage incurred from freezing and thawing of absorbed water.

PROCEDURE

One 2 ft^3 (0.06 m^3) batch was made for each of the six mixtures shown in Table 1 and Table 2. All batches were mixed in a 6 ft^3 (0.17 m^3) nominal capacity electric mixer. After mixing each batch, the temperature of the freshly mixed concrete was determined as per ASTM C 1064, the slump was determined as per ASTM C 143, the unit weight was determined as per ASTM C 138, and the air content was determined using a Type B pressure meter, as per ASTM C 231.[24,17,18,19]

Cylinders were cast in accordance with ASTM C 192 for each mixture. [20] For each batch, 18 4x8-inch (10.2x20.4-cm) and 10 3x6-inch (7.6x15.2-cm) cylinders were cast. The 4x8-inch (10.2x20.4-cm) cylinders were used for compressive strength testing, while the 3x6-inch (7.6x15.2-cm) cylinders were used for density, absorption, and water permeable voids determination. Twenty-four hours after casting, all cylinders except those used for 1 day compressive strength testing were de-molded, labeled, and placed in a lime-water curing tank maintained at 73.5 ± 3.5°F (23.0 ± 2.0°C) as per ASTM C 192.[20] All cylinders remained in the tank until time for testing. Compressive strengths were determined using 4x8 inch (10.2x20.4-cm) cylinders at 1, 2, 3, 7, 14, 28, 56, 91, and 182 days as per ASTM C 39.[21] Fifty durometer neoprene pads were used for all tests preceding 28 days, and 70 durometer neoprene pads were used for all 28 days tests and beyond in accordance with ASTM C 1231.[22] The static modulus of elasticity was determined at 7, 28, 56, 91, and 182 days on 4x8-inch (10.2x20.4-cm) cylinders in accordance with ASTM C 469. [26] The 3x6-inch (7.6x15.2-cm) cylinders were used to determine the density, absorption, and water permeable voids in accordance with ASTM C 642 at 7, 28, 56, 91, and182 days.[23]

RESULTS

The plastic properties for each mixture are shown in Table 3. The results for the 24 hour compressive strengths are shown in Figure 1. The compressive strength development for the river sand and manufactured sand mixtures are displayed in Figures 2 and 3, respectively. The water absorption percentages for all mixtures are revealed in Figure 4. Figures 5 and 6 show the static modulus of elasticity for the river sand and manufactured sands. The individual material costs, as well as the total cost for each of the mixtures, are shown in Table 4.

ANALYSIS OF RESULTS

The LGM mixtures exceeded the desired results in all areas of measure. The LGM mixtures swept the East Tennessee Commercial comparison mixtures in all around performance. The LGM mixtures also exceeded ACI 332's Type 3 severe specifications for use in residential structural concrete.

Plastic Properties

The plastic properties for each mixture are displayed in Table 3. Each mixture was trialed until the preselected plastic property ranges were attained. To ensure adequate workability each mixture provided a slump in the range of four inches (10.2 cm) to seven inches (17.8 cm). In order to provide appropriate durability to freeze thaw resistance the air content remained within four to eight percent. Casting concrete with high temperatures can lead to unrealistically high strengths. Therefore, the concrete temperature for each mix was evaluated to ensure it was below the Portland Cement Association's (PCA) maximum concrete temperature suggestion of 85°F (29°C).[4]

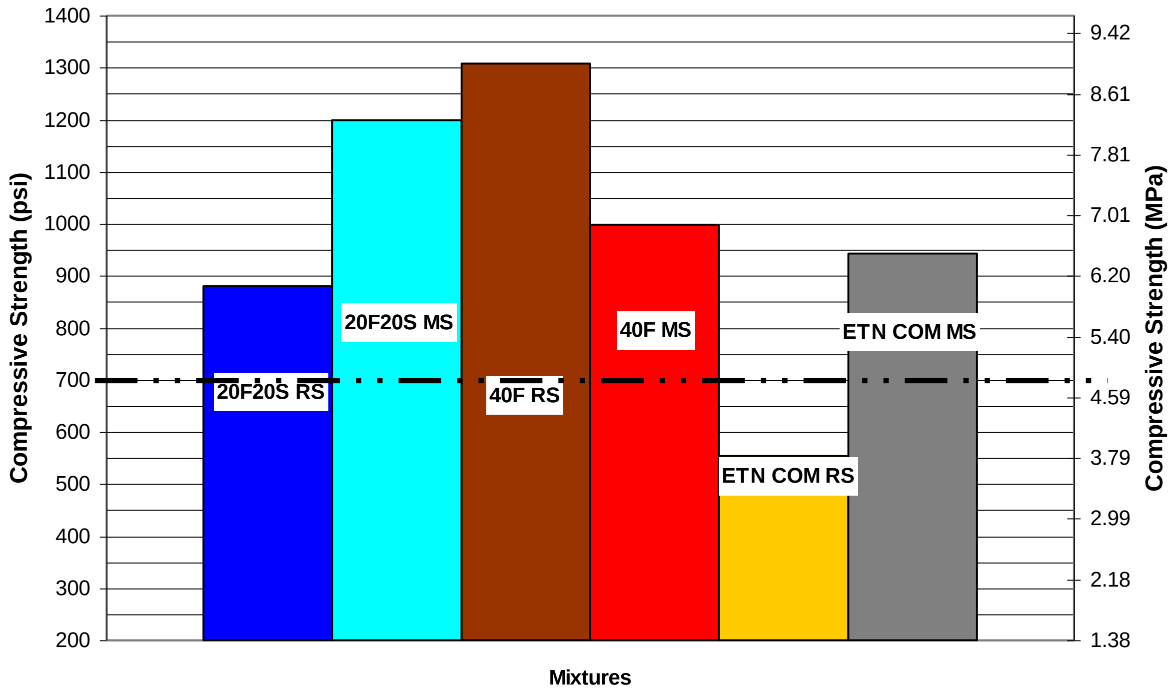
Table 3. Plastic Properties

Component	40 F RS	40 F MS	20F 20S RS	20F 20S MS	E. TN Com. RS	E. TN Com. MS
Slump, in. (cm)	4 (10.2)	4.5 (11.4)	4.25 (10.8)	6 (15.2)	6.75 (17.1)	5.75 (14.6)
Unit Weight, lb/ft^3 (kg/m^3)	147 (2355)	147 (2355)	145 (2323)	142 (2275)	139 (2227)	142 (2275)
Air content, %	4.2	4.5	5.6	5.5	8	6
Temperature, °F (°C)	56 (13)	60 (16)	69 (21)	67 (19)	64 (18)	67 (19)

Early Strength

The recommended minimum concrete compressive strength desired for the removal of framework without damaging the concrete is 750 psi (5.2 MPa). As shown in Figure 1, all four LGM mixtures exceeded the minimum strength by at least 100 psi (0.7 MPa). However, only one of the two East Tennessee Comparison mixtures exceeded the minimum 24 hour strength requirements. Mixture 40F RS displayed the highest 24 hour strength exceeding 1300 psi (9.0 MPa). At first glance, it would appear that the LGM mixtures would produce lower early age strengths. However, the low w/cm ration and increased Type A admixture help aid in overcoming the adverse effect of an increased percentage of fly ash.

Figure 1. 24 Hour Compressive Strength



Compressive Strength

The ultimate strengths of the LGM mixtures were far greater than that of the East Tennessee Commercial mixtures at all ages. Figure 2 shows a display of the compressive strength over time for all the mixes with river sand as the fine aggregate. Whereas, Figure 3 outlines the strength gain of the mixes composed of manufactured sand.

The pozzolanic properties of the Class F fly ash and lower w/cm ratios enabled the LGM mixtures to achieve greater long term strengths than the East Tennessee comparison mixtures. The two tertiary mixes provided similar rate of strength gains. Likewise, the two mixes containing 40 percent Class F fly ash also provided comparable rates of strength gain.

The 28 day compressive strength of all four LGM mixtures exceeded 5000 psi (34.5 MPa). This is 1000 psi (6.9 MPa) greater than the desired minimum compressive strengths. These results exceed the East Tennessee comparison mixtures made with both river sand and manufactured sand, which produced 28-day compressive strengths of 3210 psi (22.1 MPa) and 4160 psi (28.7 MPa) respectively. The lower w/cm ratio of the LGM mixtures partially contributes to this increased strength gain; this can be attributed to the water reducing capabilities that additional fly ash provides to the mixture.

Figure 2. Compressive Strength vs. Time – River Sand Mixtures

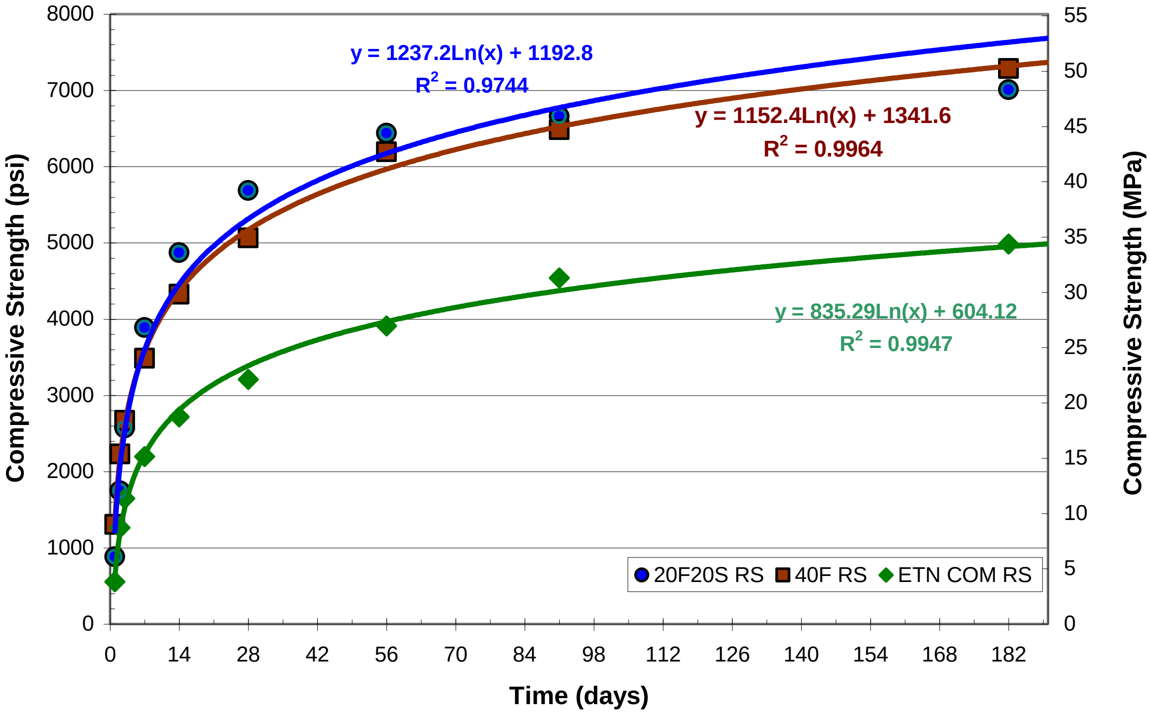
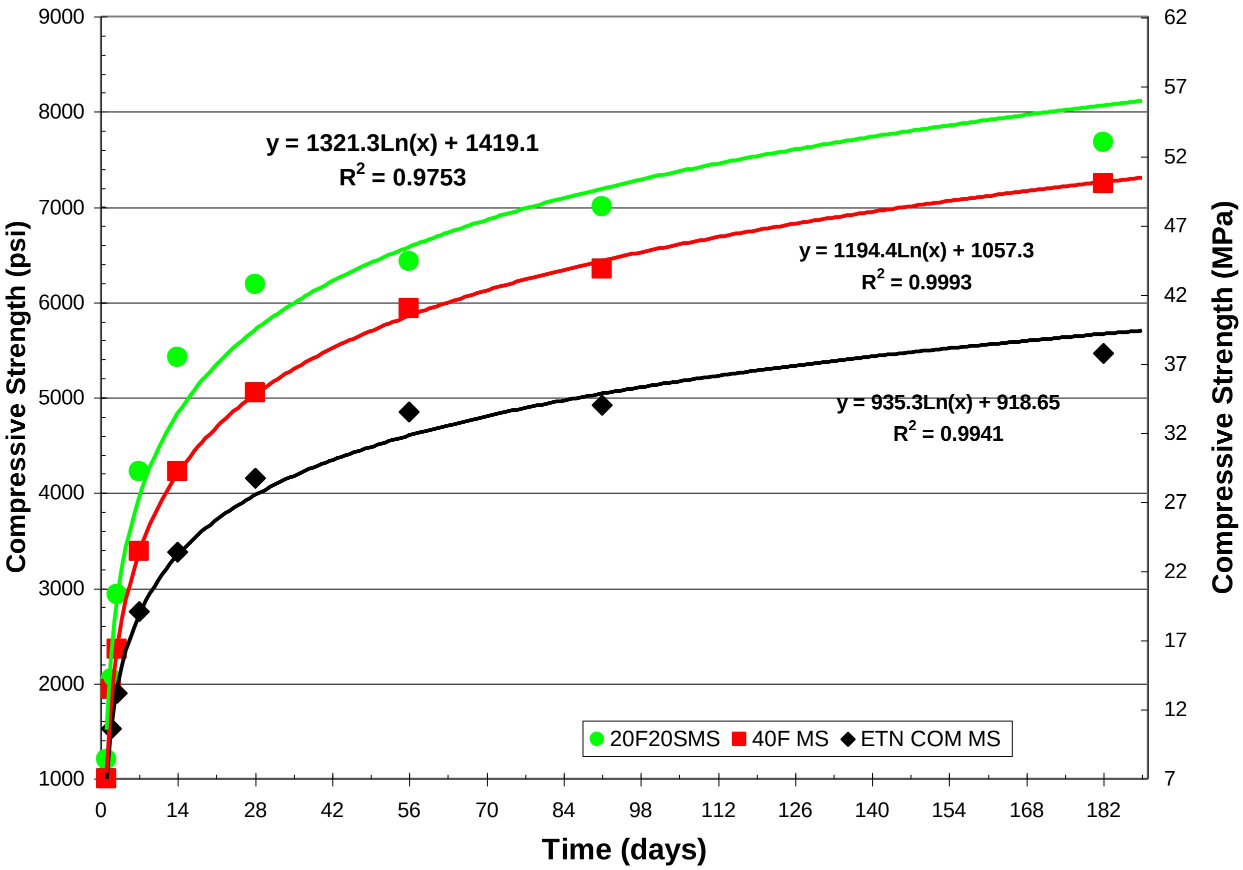


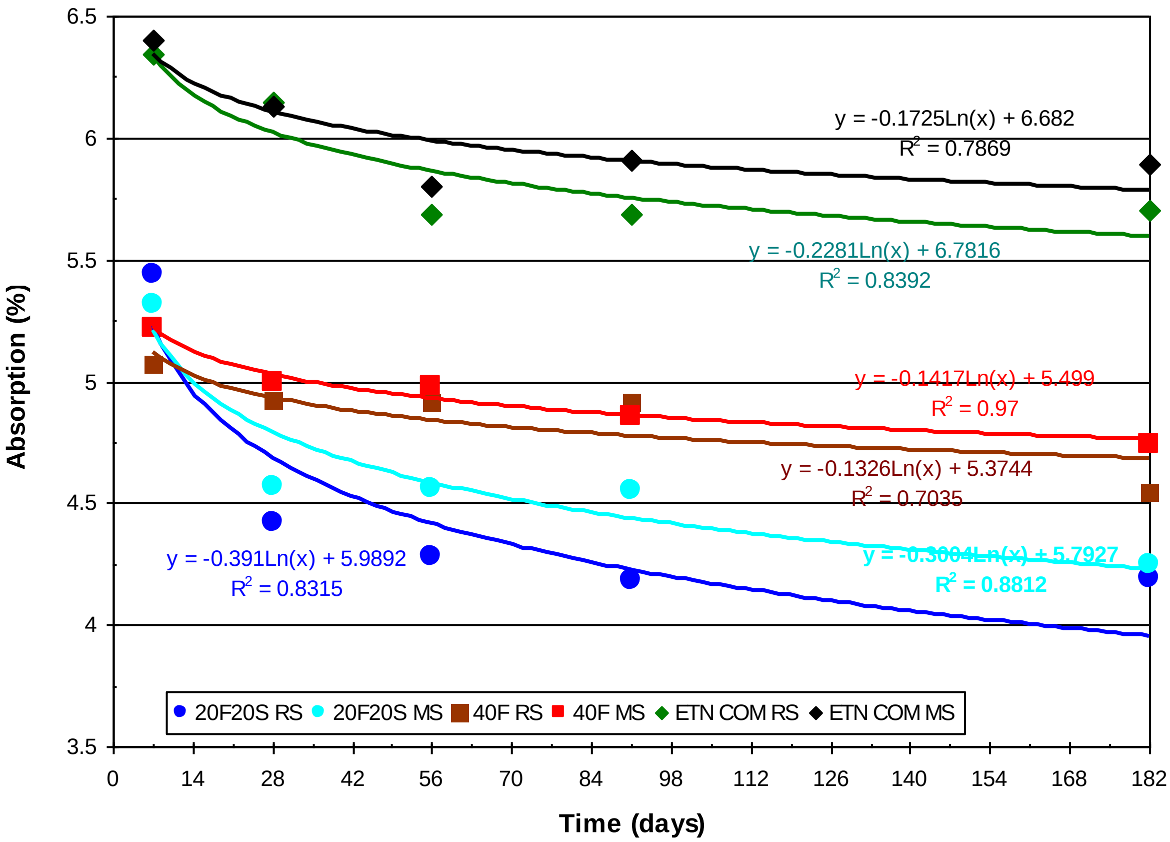
Figure 3. Compressive Strength vs. Time – Manufactured Sand Mixtures



Durability Properties

The water absorption and permeable void contents were determined as per ASTM C 642. High performance concrete level water absorptions were achieved.[4] The water absorption for each of the six mixtures is shown in Figure 4. The LGM mixtures clearly resulted in lower absorption percentages than the comparison mixes. Likewise, the LGM mixtures also provided a lower percentage of water permeable voids than the East TN Commercial mixtures. This indicates that the LGM mixtures will probably exhibit better durability than the East TN Commercial mixtures. This is consistent with the literature, which states that the durability of concrete improves with higher amounts of fly ash. The fly ash provides a denser microstructure that is less permeable, resulting in enhanced durability. The improved durability of the LGM over the East TN Commercial mixtures can also be attributed to a lower w/cm ratio.

Figure 4. Water Absorption vs. Time



Modulus of Elasticity

ACI 318 uses the following equation: $E_c = 33*(w)^{1.5}*(f'_c)^{0.5}$ where w is the density of the concrete to obtain a prediction of the modulus of elasticity .[28] Figures 5 and 6 display the modulus results for each mixture along with their ACI predictions. Table 4 displays the percent difference between the actual and predicted modulus values at 28 days. Each mixture resulted in similar tested and predicted modulus values. Research has shown that the aggregate properties have a large effect on the static modulus of elasticity of normal PCC.[27] However, the same aggregate was used in all mixtures. Therefore, the lower w/cm ratio of the LGM mixtures is believed to be the major contributor to improved modulus over the comparison mixtures.

Table 4. Percent Difference @ 28 Days

Tertiary RS	Tertiary MS	40F RS	40F MS	ETN RS	ETN MS
2.2%	-4.7%	-1.9%	-0.7%	-8.7%	4.8%

Figure 5 Modulus of Elasticity vs. Time—River Sand Mixtures

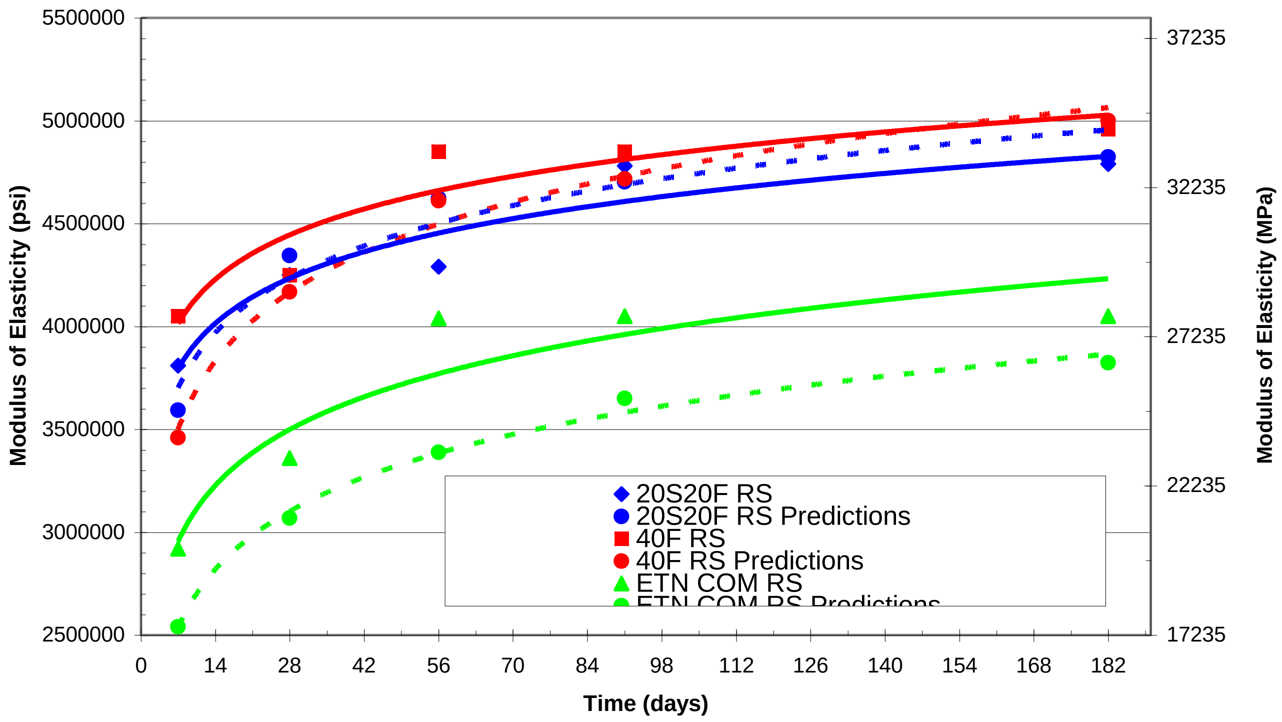
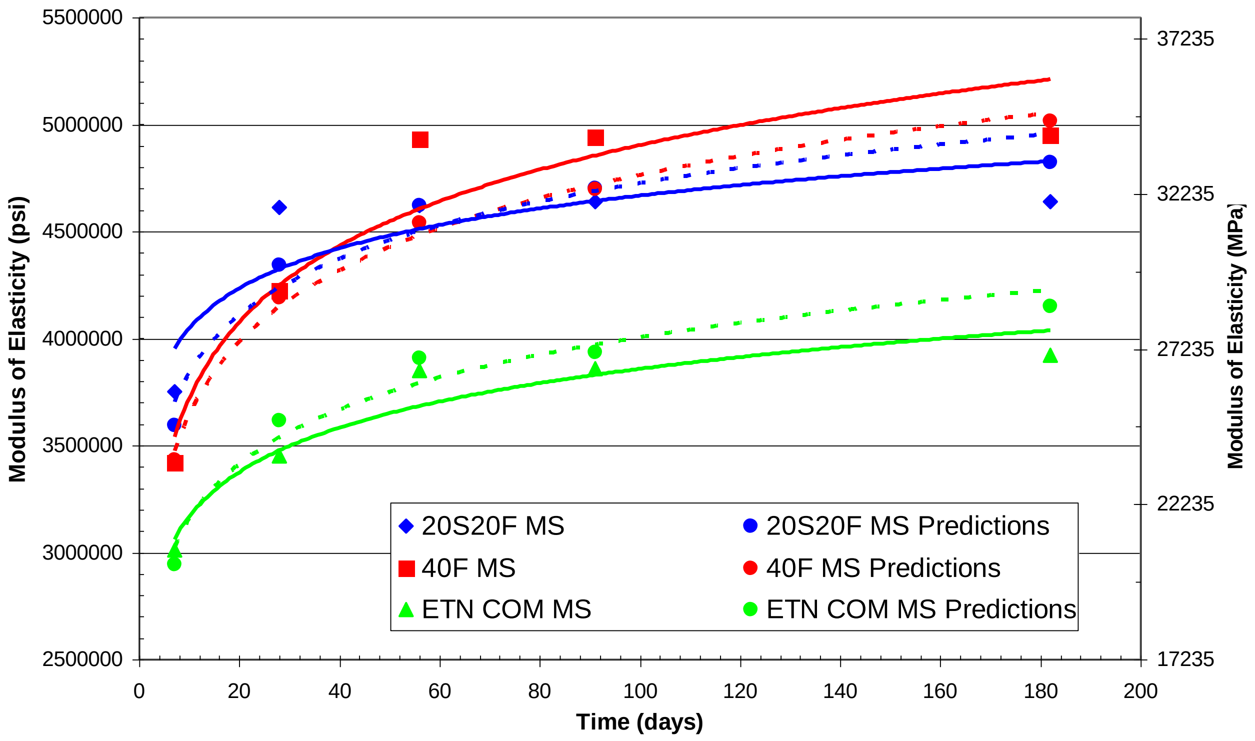


Figure 6 Modulus of Elasticity vs. Time—Manufactured Sand Mixtures



Cost

The cost per cubic yard for each of the four mixtures is given in Table 5. These costs are estimates based on prices obtained from regional suppliers. Water costs were considered negligible. All the LGM mixture compared relatively close is estimated cost to the East TN Commercial mixes. The mixtures composed of manufactured sand were estimated to be slightly higher than those made with river sand.

The costs of each of the LGM mixtures were found to be relatively equal to that of the East TN commercial mixture containing the same fine aggregate. However, upon inspection, it is evident that the increased cost is mainly due to the Type A chemical admixtures. The admixtures in each of the East TN Commercial mixtures accounted for $3.13 of the total cost, while in the LGM the admixture cost range $5.14 to $7.84.

All mixtures in the laboratory were cast at approximately 72^{o}F (22 ^{o}C). When casting in the field at temperatures greater than this, the need for Type E (accelerating) admixtures would be reduced for all mixtures.

Table 5. One Cubic Yard Price Comparison

Materials	**40F RS**	**40F MS**	**20F20S RS**	**20F20S MS**	**ETN COM RS**	**ETN COM MS**
Type I PC (lb/CY)	$18.75	$18.75	$18.75	$18.75	$21.88	$21.88
Class F Fly Ash (lb/CY)	$2.40	$2.40	$1.20	$1.20	$1.80	$1.80
Grade 120 Slag (lb/CY)	$0.00	$0.00	$4.00	$4.00	$0.00	$0.00
No. 57 Limestone (lb/CY)	$5.70	$5.67	$5.72	$5.69	$5.15	$5.12
Manufactured Sand OD (lb/CY)	$0.00	$12.74	$0.00	$12.77	$0.00	$13.60
River Sand (lb/CY)	$9.29	$0.00	$9.33	$0.00	$9.92	$0.00
Water (lb/CY)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Air Entrainer (oz/cwt)	$0.10	$0.09	$0.06	$0.12	$0.15	$0.09
Type E Admixture (oz/cwt)	$5.00	$3.75	$3.13	$3.75	$3.13	$3.13
Type A Admixture (oz/cwt)	$2.73	$2.34	$1.95	$2.34	$0.00	$0.00
TOTAL COST	***$43.98***	***$45.74***	***$44.13***	***$48.63***	***$42.01***	***$45.61***

CONCLUSIONS

Based on the limited data available, the following conclusions may be drawn:

1. The 91-day compressive strengths for all the LGM mixtures exceeded 6000 psi (41.4 MPa).

2. The absorptions and water permeable void contents of the LGM mixtures were lower the East TN Commercial mixtures at all ages. In fact, the absorptions percentages meet the requirements for high performance concrete. This indicates that the LGM mixtures would produce a more durable concrete.

3. The costs of the LGM mixtures were comparable to the East TN Commercial mixtures.

4. All LGM mixtures exceeded the minimum suggested 24 hour strength of 750 psi (5.2 MPa). This ensures that concrete framework can be removed in a timely fashion in order to help keep project construction schedules.

5. The 28 day modules of elasticity for all LGM mixtures surpassed 4000 ksi (27.58 GPa).

6. The LGM mixtures exceed ACI 332 Type 3 server specifications for residential structural concrete.

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