CALCIUM SULFOALUMINATE CEMENT CONCRETE FOR PRECAST, PRESTRESSED BRIDGE GIRDERS

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ABSTRACT

Calcium sulfoaluminate cement is a very fast setting, hydraulic cement that produces concrete with high early strength and excellent durability. The exceptionally fast strength gain has the potential to substantially improve the speed of production of precast prestressed bridge girders and other precast products. The increased water requirement for hydration over conventional portland cement also results in almost no drying shrinkage, and thus has the potential to reduce prestress losses and durability issues resulting from shrinkage cracking. The compressive strength typically required for prestress release at an age of 18-24 hours can be reached in just a few hours, without the need for heat curing. With proper management, use of this cement could significantly decrease member turnaround time, and by doing so significantly increase production of a particular product. The study presented in this paper examined the fresh properties, strength gain, and elastic modulus of concrete mixtures meeting the required specifications for prestressed bridge girders in Oklahoma. It was determined that concrete with adequate fresh concrete properties and compressive strength gain could be produced using calcium sulfoaluminate cement and the modulus of elasticity was very similar to that of conventional concrete.

Keywords: Concrete, Research, Calcium Sulfoaluminate, High Early Strength, Strength Gain,

INTRODUCTION

Calcium sulfoaluminate (CSA) cement is a very fast setting, hydraulic cement that produces concrete with high early strength and excellent durability. The exceptionally fast strength gain of CSA cement concrete has the potential to substantially improve the speed of production of precast prestressed bridge girders and other precast products. The compressive strength typically required for prestress release at 18-24 hours can be reached much more quickly, without the need for heat curing.[1] With proper management, use of this material could potentially lead to a substantial increase in production. Other critical limitations of labor and material placement must be overcome to make an increase in production possible. This potential increase in production could be very beneficial for precast producers attempting to meet the demand created as a push is made to repair and improve structurally and functionally deficient bridges across the country. This study investigated the possibility of meeting the fresh and hardened concrete properties required for prestressed bridge girder concrete in the state of Oklahoma along with specifications for typical precast double-tee production.

BACKGROUND

Concrete used for pretensioned prestressed concrete members must gain strength quickly enough to withstand the stresses caused by prestress release at an early age. Type III portland cement, heat curing, or a combination of the two are typically used to produce the required compressive strength. Rapid setting CSA cement can achieve the compressive strength required for prestressed concrete construction in less than one-third the time required for conventional concrete mixtures and thus has the potential to increase production efficiency. It also presents a number of other benefits related to the durability and sustainability of members made with this material. Production of portland cement is an energy intensive process that also produces a significant amount of carbon dioxide emissions and accounts for as much as 3% of annual global energy use and 5% of manmade carbon dioxide emissions.[2,3] Calcium sulfoaluminate cement clinker is fired at a temperature approximately 100° to 200° C less than portland cement, produces less than half the carbon dioxide during production, and is easier to grind.[1-5] The lower firing temperature can increase clinker production by more than 20% and reduce the consumption of coal by 15%.[4] Others report energy savings of up to 25%.[6] While CSA cements are not widely used in the United States and Europe, they have been used in China for many years in a wide variety of applications.[2,4-6] These have included some precast applications[1,5] and self-stressed concrete pipes.[7]

Conventional portland cement is primarily composed of tricalcium silicate (alite, C_3S) and dicalcium silicate (belite, C_2S) which react with water to form calcium silicate hydrate (C-S-H), the main strength producing compound in hardened portland cement concrete. A relatively smaller amount of tricalcium aluminate (C_3A), ferrite (C_4AF), and other compounds are also present within a typical portland cement,.[8] The C_3A reacts almost immediately with water and addition of gypsum is required to control the setting time. The rate of hydration of C_3S is substantially higher than that of C_2S but produces a weaker reaction product. The C_3S content for cements is therfore often limited, even in high early strength Type III cement. The high early strength obtained using Type III cement is achieved through grinding the cement much finer than for Type I cement.[8]

Calcium sulfoaluminate cement clinker is made from limestone similarly to conventional portland cement, but also bauxite, which increases material costs. CSA cement is composed primarily of tetracalcium trialuminate sulfate, or ye'elimite ($C_4A_3\mathit{S}$) and C_2S.[2-5,9] Calcium sulfoaluminate cements can also contain significant amounts of ferrialuminate (C_4AF) depending on the clinker used.[2] Different levels of calcium sulfate (gypsum) are ground with the clinker to produce the different types of CSA cements including rapid-hardening and expansive cements. The amount of calcium sulfate significantly affects the hydration and expansion properties of the cement.[1,2,4,9] The $C_4A_3\mathit{S}$ in the cement reacts quickly to form monosulfate and ettringite in a series of reactions depending on the combination of the interground materials.[2,4,6] The $C_4A_3\mathit{S}$ is usually consumed within the first 7 days of hydration.[5] Ettringite is the main product of the cement reaction and produces a strong crystal structure and resulting high compressive strength at early ages as the reactions occur much faster than in traditional cements.[1,7,10] The setting time depends on the specific composition, but typically varies between 30 min and 4 hours. The C_2S in the cement is then available to react and produce calcium silicate hydrate, which contributes to strength at later ages.[2,4,5]

The reaction of $C_4A_3\mathit{S}$ requires significantly more water for hydration than typical portland cement.[5] A *w/c* of between 0.40 and 0.60 is required to completely hydrate calcium sulfoaluminate cement as opposed to the 0.20 to 0.25 required for portland cement.[2,3,11] Within these bounds a lower *w/c* exhibits higher compressive strengths for CSA cement mortars.[9] Using a lower *w/c* than required for complete hydration can result in a large number of unhydrated cement grains that have the potential to react and cause expansion if the material is exposed to water at later ages.[5] The increase in chemically required water allows for a *w/c* high enough to produce excellent workability yet the majority of water is consumed quickly, reducing the water available to contribute to concrete porosity and shrinkage. Even with the increased available water from the high *w/c*, CSA cement concretes tend to lose workability rapidly if a retarder is not added.[4] Superplasticizers have been shown to be effective in reducing the viscosity of CSA mixtures, therefore improving the workability when necessary.[9] The reduction of porosity and shrinkage are additional benefits of this material in a prestressed concrete application above and beyond early age compressive strength. The combination of reaction products formed in CSA cement produce a dense microstructure and low porosity.[3] Concretes made with CSA cement have a high resistance to freezing and thawing and sulfate attack, but more research is needed on long term behavior.[1,2,4] Prestressed concrete bridge girders are placed in a potentially harsh environment and corrosion of reinforcement can lead to loss of prestress and other serious damage to the girders, both resulting in a loss of capacity. The excellent durability of CSA cement concrete could improve the performance of girders in this environment and even lead to an elimination of the need for air entrainment.

Performance in other areas has been shown to be equal to or better than portland cement as well.[1,3] Research has shown that shrinkage of CSA cement concrete not proportioned for expansion is negligible.[4] A smaller value of total shrinkage has the potential to reduce prestress losses and therefore potentially allow for a smaller required number of prestressing strands in a given application. The ettringite produced in the hydration of CSA cement may be prone to carbonation, which could lead to deterioration of the concrete.[4]

The compressive strength gain, high durability, and low shrinkage of CSA cement concrete make it a very appealing material for use in pretensioned prestressed concrete applications. A substantial quantity of research has been conducted concerning the composition and hydration of CSA cement. However, little published research was found focusing on material properties of CSA cement concrete. The structural and functional performance of the material should be proven before it can be safely used in a particular application and the added cost of the material must be weighed against the potential benefits.

EXPERIMENTAL PROGRAM

Typical requirements for bridge girder concrete were investigated in order to determine whether the strength gain of concrete made using CSA cement was adequate for use in prestressed bridge girders. A thorough search of the Oklahoma Department of Transportation (ODOT) bridge design standards[12] was conducted and required strengths for standard bridge girder sections and spans were collected. Inquiries were made to the two major precast girder manufacturing facilities in Oklahoma concerning the typical concrete compressive strengths used at those plants. Fresh concrete properties and basic concrete mixture composition requirements were taken from discussions with the precast producer and the ODOT Standard Specifications[13] for class P concrete used in prestressed bridge girders. The ODOT specifications for class P concrete are shown in Table 1. Compressive strengths were examined for standard Oklahoma girder types and standard spans ranging from 30 ft to 130 ft (9.1 m to 39.6 m). Strength combinations of 4500 psi at release and 6000 psi at 28 days and 6000 psi at release and 8000 psi at 28 days (31.0/41.4 MPa and 41.4/55.2 MPa) were chosen for testing in this project.

Table 1. ODOT Requirements for Class P Concrete

Entity	Cement, lb/yd^3	Air Content, %	*w/cm*	Slump, in.
ODOT	564 (min.)	5 ± 1.5	0.25 – 0.44	3 ± 1

Note: 1 lb = 0.4536 kg, 1 ft = 0.3048 m, and 1 in. = 25.4 mm

Material testing was conducted to ensure that the CSA cement mix designs could meet the properties required by ODOT for prestressed bridge girder concrete and by the precast producer for double-tees. Materials used for each mixture included CSA cement, ¾ in. crushed limestone with a specific gravity of 2.68, washed river sand with a specific gravity of 2.63, a polycarboxylate high range water reducer, and an air entraining admixture. The mix design provided by the precast producer and the cement manufacturer was tested with several variations to examine the effects of citric acid set retarder and to meet the slump and air content limits given in the ODOT material requirements.[13] This mix was used as a "low strength" value and had a targeted compressive strength of 4500 psi (31.0 MPa) at 6 hours and 6000 psi (41.4 MPa) at 28 days. Additional testing was performed to develop a mix design considered a "high strength" value with a compressive strength of 6000 psi (41.4 MPa) at 6 hours and 8000 psi (55.2 MPa) at 28 days. This was accomplished by decreasing the *w/c* of the mixture from 0.48 to 0.40. At least three batches were made using each basic mix design, with the variation of parameters spread among these batches. Slump flow or slump was measured for each batch, depending on the expected properties, in accordance with ASTM C 1611[14] and ASTM C 143.[15] Air content was measured using the pressure method in accordance with ASTM C231[16] for batches incorporating air entrainment. Concrete temperature was measured using the procedures of ASTM C1064.[17] Compressive strength was measured using 4 in. by 8 in. (100 mm by 200 mm) cylinders tested at 2, 3, 6, 12, and 24 hours and at 28 days in accordance with ASTM C 39.[18] In some instances the 12 hour measurements were taken at 14 hours due to scheduling issues. Modulus of elasticity was measured using the methods of ASTM C 469[19] at 6, 12, and 24 hours and 28 days for a replicate of the standard mix provided by the cement manufacturer and the concrete producer and the high strength mix developed by the researchers.

RESULTS AND DISCUSSION

A total of 18 batches of concrete were mixed to examine the possibility of producing an effective concrete mixture that would meet the strength and workability requirements of both ODOT and the precast producer. The effects of high range water reducer dosage, citric acid set retarder, air entrainment, and adjusting *w/c* were investigated during this process. These trial batches can be broken into four basic mix designs presented in Table 2.

1. The basic mix design provided by the cement manufacturer and the precast producer (LSC).
2. The basic mix design modified to meet ODOT slump and air content specifications (LSO).
3. Two adjusted mix designs intended to have higher compressive strengths (HSA and HSB).

The LSC mix design was provided by the cement manufacturer after approval by the precast producer. The *w/c* used for the mixture was close to the approximate theoretical minimum value required for complete hydration of the cement.[2,3] The LSO mix designs included simple modifications to the admixture dosages to achieve the properties required by the ODOT standard specifications.[13] The HSA and HSB mix designs utilized very similar proportions to those of the LSC mix design, but had a *w/c* ratio of either 0.40 or 0.44, both less than the theoretical minimum of 0.45 required for complete hydration of CSA cement, as specified by the cement manufacturer.

The admixture dosages used for the LSC mix design and the resulting concrete properties are presented in Table 3. The HRWR dosage rate was adjusted in order to achieve a slump flow near the range of 24 in. to 28 in. (610 mm to 710 mm) desired by the precast producer. High dosage rates were required for this material, but it was noted that a smaller dose could be

Table 2. Calcium Sulfoaluminate Cement Mix Designs

Material	LSC	LSO	HSA	HSB
Cement, lb/yd^3	658	658	658	648
Rock, lb/yd^3	1782	1782	1782	1560
Sand, lb/yd^3	1188	1188	1321	1313
Water, lb/yd^3	316	316	263	285
w/c	0.48	0.48	0.40	0.44
HRWR, fl oz/cwt	10.0-24.0	2.0-7.0	4.5-18.0	6.0
AEA, fl oz/cwt	0.0	0.5-1.1	0.0-0.5	0.5
Citric acid, lb/yd^3	0.0-0.3	0.0-0.3	0.0-0.3	0.0-0.3

Note: 1 lb = 0.4536 kg, 1 ft = 0.3048 m, 1 psi = 0.006895 MPa, 1 fl oz = 29.57 mL, and cwt indicates hundred pounds of cement

used when citric acid was also included in the mixture. Batch LSC2 was highly segregated due to the large dose of HRWR and cylinders were only cast for testing at 3 hr, 24 hr, and 28 days. Each mixture exceeded the desired compressive strength of 4500 psi (31.0 MPa) at 6 hours and the mixtures without citric acid exceeded this value at 3 hours. As shown in Figure 1, the incorporation of citric acid had a marked effect on the compressive strength gain of the concrete at ages up 24 hours. The compressive strength for both LSC batches without citric acid was higher than that of the mixtures incorporating citric acid at all ages, even when those without citric acid required a larger dose of superplasticizer. It is interesting to note that the highest compressive strengths were measured for batch LSC1, which was cast on the day with the lowest ambient temperature and a fresh concrete temperature of approximately 40° F (4.4° C).

Batch LSC5 was used to test modulus of elasticity at 6, 12, and 24 hours and 28 days of age. The measured values from these tests are shown in Table 4 along with the ACI Code[20]

Table 3. Admixture Dosage and Properties of LSC Mixes

Batch	LSC1	LSC2	LSC3	LSC4	LSC5
HRWR, fl oz/cwt	20.0	24.0	20.0	10.0	18.0
Citric acid, lb/yd^3	0.0	0.3	0.3	0.3	0.0
Slump Flow, in.	19.0	33.0	26.5	28.5	21.5
2 hr, psi	5030	--	--	2970	--
3 hr, psi	5930	3690	4010	3750	5590
6 hr, psi	6760	--	5000	4900	6380
12 hr, psi	--	--	5750	5560	7020
24 hr, psi	8490	6420	6380	--	7760
28 day, psi	10900	8920	7820	8470	10070

Note: 1 lb = 0.4536 kg, 1 ft = 0.3048 m, 1 psi = 0.006895 MPa, 1 fl oz = 29.57 mL, and cwt indicates hundred pounds of cement

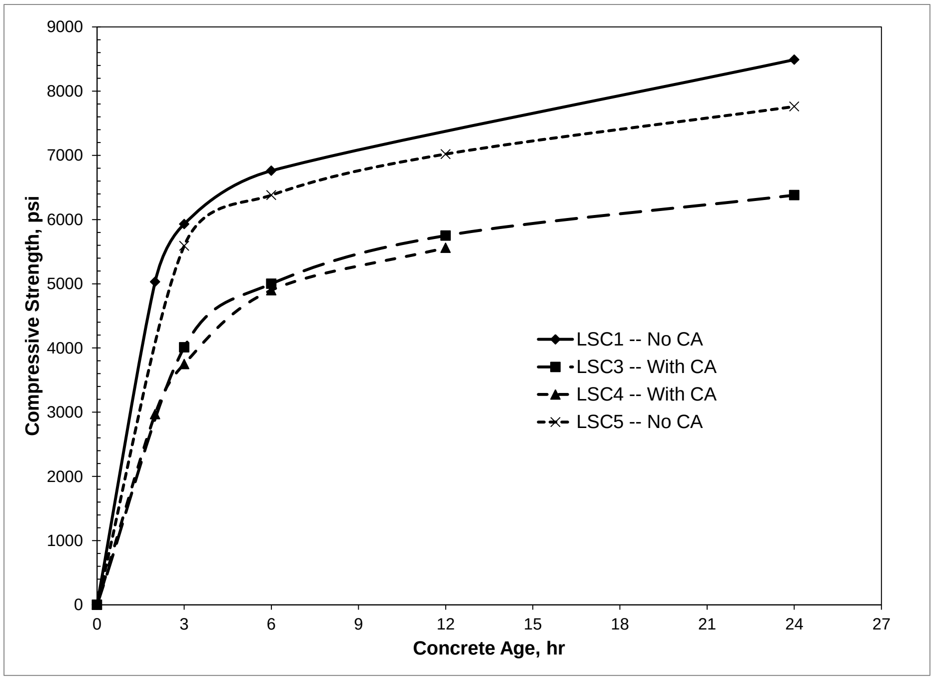

Figure 1. 24 Hour Strength Gain of LSC Mixtures

Table 4. Measured Modulus of Elasticity for LSC Mix (Batch LSC5)

Age	f_c, psi	E_c, ksi	ACI E_c, ksi	Meas./ACI
6 hr	6380	5380	4550	1.18
12 hr	7020	5350	4780	1.12
24 hr	7760	5520	5020	1.10
28 days	10070	6200	5720	1.08

Note: 1 psi = 0.006895 MPa

predictions for the given compressive strength. The measured values exceeded the predictions by more than 10% at all tested ages up to 24 hours and by 8% at 28 days. The difference between measured and predicted values also exhibited a decrease over time.

The admixture dosages used for the LSO mix design and the resulting concrete properties are presented in Table 5. The HRWR dosage was adjusted in order to keep the concrete slump near the desired ODOT range of 2 in. to 4 in. (50 mm to 100 mm).[13] Only batch LSO4 reached the desired compressive strength of 4500 psi (31.0 MPa) at 6 hours. This mixture also had the smallest measured air content. The low strengths of the other mixes can be attributed to the increased air content over that of the LSC mixtures. The strength gain for these mixtures over the first 24 hours is shown in Figure 2. The compressive strength gain of all batches except LSO3 was very similar at 3 hours of age. The reduced strength of batch LSO3 due to the incorporation of citric acid retarder is clearly visible, as is the maximum compressive strength gain achieved by batch LSO4.

The required admixture dosages for the HS batches and resulting concrete properties are presented in Table 6. Due to the low *w/c* for these mixtures, a fairly large dosage of HRWR

Table 5. Admixture Dosage and Properties of LSO Mixes

Batch	**LSO1**	**LSO2**	**LSO3**	**LSO4**	**LSO5**
HRWR, fl oz/cwt	2.0	5.0	2.0	7.0	2.3
AEA, fl oz/cwt	1.0	0.5	1.0	0.5	1.1
Citric acid, lb/yd^3	0.0	0.0	0.3	0.0	0.0
Temp, °F	--	--	65	70	69
Slump, in.	2.25	--	4.5	3.75	5
Slump Flow, in.	--	17	--	--	--
Air content, %	6.00	7.40	6.00	4.30	6.80
2 hr, psi	2270	2840	1800	3450	2830
3 hr, psi	3220	3380	2400	3950	3480
6 hr, psi	3740	4380	3200	4530	3760
12 hr, psi	4700	4820	3770	4850*	4080
24 hr, psi	4680	5080	3610	5670	4260
28 day, psi	6220	6640	4930	7530	5550

Note: 1 lb = 0.4536 kg, 1 ft = 0.3048 m, 1 psi = 0.006895 MPa, 1 fl oz = 29.57 mL, and cwt indicates hundred pounds of cement, °F = 1.8(°C) + 32, *indicates compressive strength at 14 hours due to scheduling error

was required to maintain workability, and the flow requirement mentioned previously was targeted instead of the slump. Citric acid was used to delay setting of the concrete for all mixtures after batch HS1A as well. Even with this addition, one batch became excessively stiff and unworkable resulting in very poorly consolidated specimens. Citric acid was mistakenly not added to another batch and reached initial set before all test specimens could

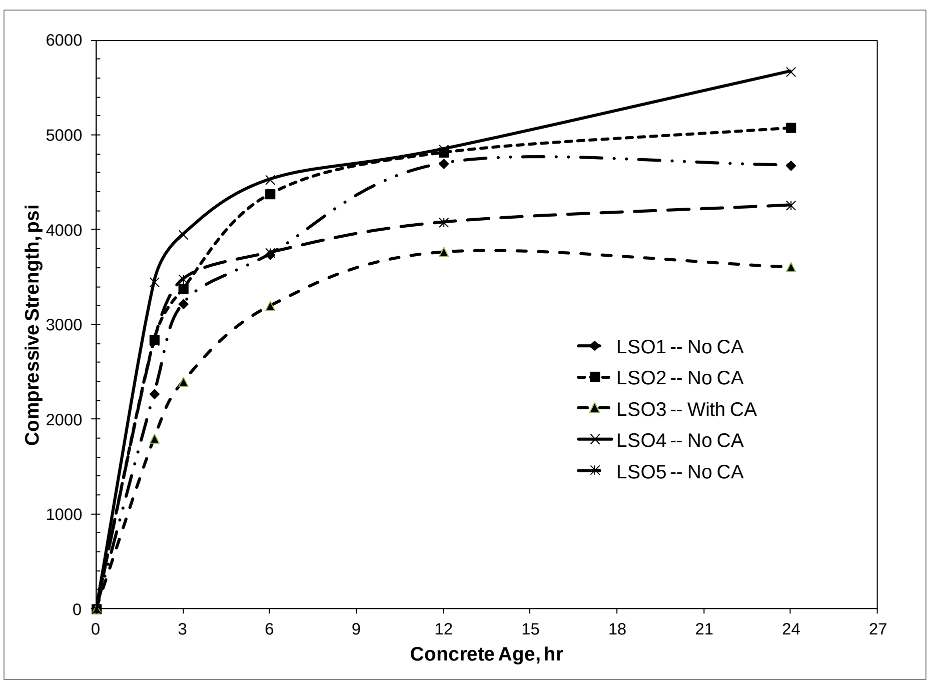

Figure 2. 24 Hour Strength Gain of LSO Mixtures

Table 6. Admixture Dosage and Properties of HS Mixes

Batch	**HS1A**	**HS2A**	**HS3A**	**HS4A**	**HS5A**	**HS6B**
HRWR, fl oz/cwt	14.0	18.0	8.0	5.0	15	6.0
AEA, fl oz/cwt	0.0	0.0	0.0	0.5	0.0	0.5
Citric acid, lb/yd^3	0.0	0.3	0.3	0.3	0.3	0.3
Temp, °F	65	63	65	76	--	62
Slump, in.	--	--	--	2.5	--	--
Slump Flow, in.	14	28	14.5	--	21.5	17
Air content, %	--	0.35	2.55	0.20	2.40	6.60
2 hr, psi	4880	4950	3810	4350	3780	3160
3 hr, psi	5420	5880	4260	4780	4350	4290
6 hr, psi	6570	7140	4990	4810	5280	5090
12 hr, psi	6920	8370*	5410	6470	5780	5600
24 hr, psi	7500	8900	6110	6620	6230	5980
28 day, psi	9980	11410	8510	8490	8300	8370

Note: 1 lb = 0.4536 kg, 1 ft = 0.3048 m, 1 psi = 0.006895 MPa, 1 fl oz = 29.57 mL, °F = 1.8(°C) + 32, and cwt indicates hundred pounds of cement, *indicates compressive strength at 14 hours due to scheduling error

be made. These results were not included in the data shown in Table 6. Only batches HS1A and HS2A reached the desired 6000 psi (41.4 MPa) at 6 hours, neither of which included entrained air. The large strength gain of these mixtures can be seen in Figure 3. Batch HS6B was the only HSB batch done, and it did not show a marked improvement in any desired concrete property over the HSA or LSC mixtures. It exhibited a very low strength gain compared to the other batches, as shown in Figure 3. Batch HS4A was the only HSA batch including air entrainment, and while it did have a compressive strength less than that of batches HS1A and HS2A, the strength wasgreater than that of batch HS3A which had a higher measured air content than batch HS4A. However, the measured air content for batch HS4A is questionable due to an air meter malfunction. If such is the case, air content was again the controlling factor in reducing the available strength. Citric acid did not greatly affect the compressive strength as the only HS mixture without citric acid, HS1A, had a smaller compressive strength than batch HS2A with citric acid and had a similar compressive strength to the other batches. The 28-day strength for all batches exceeded the desired 8000 psi (55.2 MPa). The high strengths in conjunction with a *w/c* which may be less than the theoretical minimum required for complete hydration may indicate that the minimum *w/*c for complete hydration may be smaller than 0.45 or that less cement can be used and a high strength still be obtained.

Batch HS5A was used to measure modulus of elasticity. The values obtained from these tests are shown in Table 7 along with the ACI Code[20] predictions for the given compressive strength. The measured values exceeded the predictions by more than 7% at all tested ages. The difference between measured and predicted values exhibited a slight decrease over time similarly to the LSC modulus.

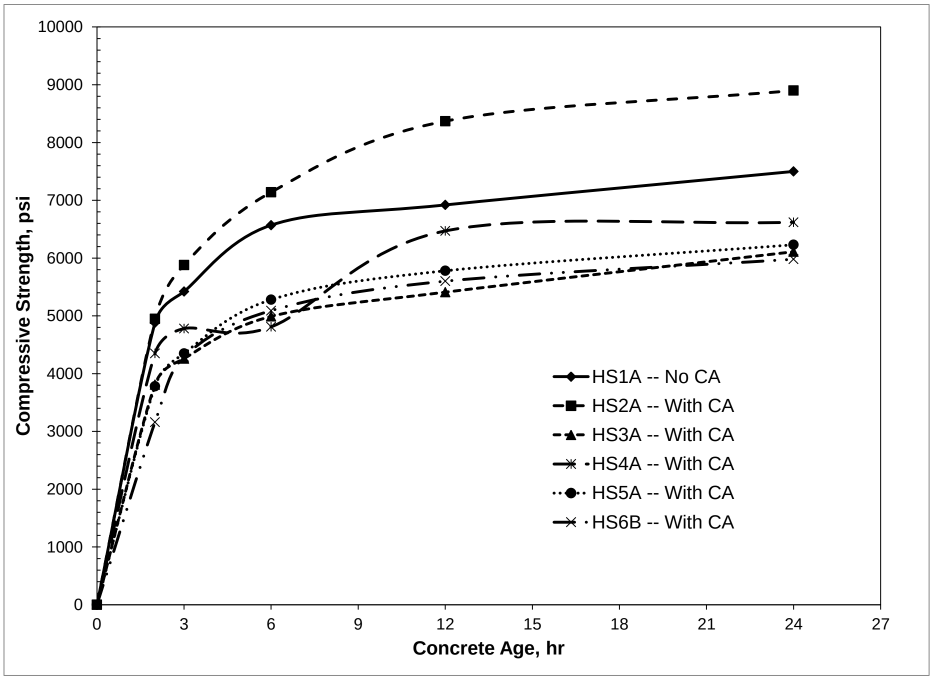

Figure 3. 24 Hour Strength Gain of HS Mixtures

Table 7. Measured Modulus of Elasticity for HSA Mix (Batch HS5A)

Age	f_c, psi	E_c, ksi	ACI E_c, ksi	Meas./ACI
6 hr	5280	4460	4140	1.08
12 hr	5780	4690	4330	1.08
24 hr	6230	4890	4500	1.09
28 days	8300	5530	5190	1.07

Note: 1 psi = 0.006895 MPa

A number of benefits and challenges associated with the use of CSA cement in precast applications were noted from both the background literature survey and material testing. A partial list of these advantages and disadvantages is presented in Table 8. While several benefits make the use of CSA cement very appealing, the material cost and lack of knowledge of the material properties are significant obstacles to using the material. The major issues encountered while testing these materials were the speed at which the concrete lost workability and strength reductions with the specified air content. Adequate compressive strength to meet the two strength levels was achieved by an age of 6 hours for at least one batch in all mixture categories. Increased experience would lead to better reproduction of these results. Mixtures containing entrained air were tested due to the ODOT requirements for Class P concrete listed in Table 1. While these mixtures were more difficult to produce, it was possible to develop mix designs with adequate strength also containing entrained air. If the requirement for entrained air could be waived due to the known excellent durability of concrete made with CSA cement accompanied by proof testing, mixtures could easily be designed to meet the strength and workability requirements for typical prestressed concrete bridge girders.

Table 8. Advantages and Disadvantages of Using CSA Cement

Advantage	**Disadvantage**
Reduced CO_2 emissions	High cost
High early-age strength	Fast set
Dimensional stability	Lack of experience using the material
Low permeability	Lack of knowledge of material behavior
High early-age stiffness	
Reduction in heat curing	
Higher *w*/*c* for same strength	

The modulus of elasticity of the typical LSC mixture exceeded the prediction produced by the ACI Code equation[20] by between 8% and 18% and the HSA mixture modulus exceeded the prediction by between 7% and 9% depending on the concrete age. This prediction is specifically based on the 28-day strength of the concrete and not necessarily that at early ages. However, both mixes exceeded the ACI prediction and by approximately the same amount at 28 days. The crystal structure of the ettringite formed during hydration of CSA cement differs from that of C-S-H formed during hydration of typical portland cement. This difference in structure may be responsible for the increased modulus of elasticity at early ages, even if the modulus of elasticity is most affected by the coarse aggregate. The modulus of elasticity of the concrete at early ages has an especially large impact on elastic shorting losses and prestress transfer. It is important that this property be similar to that of conventional concrete in order to achieve similar performance.

CONCLUSIONS

This project consisted of a preliminary investigation of the feasibility of producing CSA cement concrete mixtures meeting the required specifications for prestressed bridge girder concrete. Material testing indicated that mixtures could be produced using CSA cement for use in prestressed concrete bridge girders. These mixtures can achieve the required compressive strengths at an age of 6 hours or less as opposed to the typical 18 to 24 hours, without the need for heat curing. Use of these mixtures and implementation of an improved production plan would require substantial logistical planning in order to mitigate critical issues other than curing time, but could significantly increase production speed when necessary.

The following conclusions relate specifically to the material testing performed in this project:

- A viable concrete mixture can be designed and produced using CSA cement to meet the workability and strength requirements for prestressed bridge girder concrete at a much earlier age than conventional mixtures using Type III cement.
- Use of citric acid retarder improved the working time of the CSA cement concrete mixtures, but was detrimental to the strength gain at early ages.

- High compressive strengths were achieved using a *w/c* less than the reported theoretical minimum required for hydration of this particular CSA cement. Further research is needed to investigate the implications of this result.
- Stiffness of both the LSC and HSA concrete mixes, in the form of modulus of elasticity, was very similar to ACI Code prediction[21] and indicated that the concrete would have very similar performance to conventional concrete in terms of elastic shortening losses.

The use of CSA cement for prestressed concrete members has significant potential benefits for use when a large number of girders are required in a short period of time, but the economic costs and benefits must be carefully weighed. The excellent durability and potential sustainable impact of using this material in the form of reduced embodied energy and carbon footprint are also very appealing. Reduced carbon dioxide emissions from CSA cement production and energy savings from a reduction of heat curing could be very beneficial to improving the sustainability of the precast concrete industry. Possible elimination of required air entrainment could also simplify production. Therefore, this material could be a viable alternative for increasing production when demand for girders is very high and additional investigation of material properties and implementation should be conducted. Research concerning the long-term performance of CSA cement concrete in prestressed concrete applications is needed before it can be used effectively.

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