



# TECHNICAL ADVISORY

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## Calcium Aluminate Cement Concrete (Class CAC Concrete) TxDOT Special Specification SS-4491 Tip Sheet by Ryan Barborak, P.E., CST-M&P

### ➔ WHAT IS CALCIUM ALUMINATE CEMENT (CAC) AND HOW DOES IT DIFFER FROM ORDINARY PORTLAND CEMENT (OPC)?

Calcium aluminate cement (CAC) is a unique class of cement that is different than ordinary Portland cement (OPC), particularly due to the chemical make-up. CAC contains a far greater amount of alumina and a far less amount of silica. Table 1 illustrates the major chemical compositions of OPC and CAC.

*uncommon to place this material at temperatures below freezing and with some surface protection, be able to achieve high early strength gains, much quicker than the Class K or HES mix designs TxDOT currently uses.*

Table 2 gives a comparison of the strength development of CAC compared to rapid-hardening Portland cement (RHPC) at low temperatures. The same water to cement (w-c) ratio, specimen size and cement content was used.

Table 1. Chemical Properties of OPC and CAC

(Cement chemistry notation is used C=CaO, S=SiO<sub>2</sub>, A=Al<sub>2</sub>O<sub>3</sub>, and F=Fe<sub>2</sub>O<sub>3</sub>.)

Phase	Ordinary Portland Cement (%)	Calcium Aluminate Cement (%)
<b>C<sub>3</sub>S</b>	50-70	0
<b>C<sub>2</sub>S</b>	15-30	<10
<b>C<sub>3</sub>A</b>	5-10	0
<b>C<sub>4</sub>AF</b>	5-15	10-40
<b>CA</b>	0	40-50

*Silicates* (bracketed next to C<sub>3</sub>S, C<sub>2</sub>S, C<sub>3</sub>A)

*Aluminates* (bracketed next to C<sub>4</sub>AF, CA)

Table 2. Strength Gain of CAC Versus RHPC

Temperature °F (°C)	Cement	Strength, psi (MPa)*			
		6 h	16 h	1 day	2 days
64.4 (18)	CAC	3480 (24)	5655 (39)	5800 (40)	6525 (45)
64.4 (18)	RHPC	0 (0)	580 (4)	1740 (12)	3335 (23)
53.6 (12)	CAC	3045 (21)	5220 (36)	5655 (39)	5945 (41)
53.6 (12)	RHPC	0 (0)	145 (1)	435 (3)	6235 (43)
42.8 (6)	CAC	2755 (19)	5220 (36)	5365 (37)	5655 (39)
42.8 (6)	RHPC	0 (0)	145 (1)	145 (1)	1015 (7)
32 (0)	CAC	725 (5)	4785 (33)	5075 (35)	5655 (39)
32 (0)	RHPC	0 (0)	0 (0)	145 (1)	290 (2)

Sources: Portland Cement Association. Design and Control of Concrete Mixtures. CD 100.1. Based on EB001.14. 2003 Pg 39.

J.N. Clarke, et al. Calcium Aluminate Cements in Construction: A Reassessment. Technical Report No. 46. Concrete Society. 1997.

\* Concrete prisms 2.75 x 2.75 x 11 in (70 x 70 x 280 mm) cement content 590 lb/yd<sup>3</sup> (350 kg/m<sup>3</sup>), w/c = 0.5.)

Source: Scrivener and Capmas (1998)

Generally, CAC has a significantly higher early strength gain (upwards of 6,000 psi at 6 hours of age at 68 °F) and a higher heat of hydration than OPC.<sup>2</sup> **The high early heat and strength gain makes CAC attractive, especially during the winter months and/or when rapid repairs are needed.**

SS-4491 specifies a lower water to cement (w-c) ratio and a higher sack content than that used in Table 2. Hence, a more realistic example of the strength gain of CAC that may be used on a TxDOT project is given in Table 3. The mix design used to obtain the data in Table 3 meets the requirements of SS-4491.

CAC concrete can be placed in very cold weather applications and still achieve high early strength gains. **It is not**

Table 3. CAC Compressive Strength of Mix Design Similar to SS-4491 [Ambient Temperature = 44°F]

Age (hrs.)	Compressive Strength (psi)
2.00	840
2.25	1273
2.50	2314
2.75	2895
3.00	3668
3.25	3875
3.50	4216
3.75	4402
4.00	4629

Source: Tested by S.T.A.T.E. Testing L.L.C. "Compressive Strength Results of GCX/PP-5 Yard Trial." November 24, 2009. Chicago, IL. unpublished.

Literature suggests that in practice, as long as the concrete remains above freezing until the hydration begins (usually about 3 hours), the heat generated by CAC will be sufficient to ensure rapid hardening, even if the aggregates are below the freezing point. Canada has extensively used this material to build foundations in frozen ground.<sup>3</sup> **Consultation with the producer and trial batches at the ambient temperature is recommended for the low temperature (<40°F) applications.**

Frozen aggregates should be avoided when possible as they may introduce frozen water and/or solid dirt into the mixture.

The high early strength of CAC is largely attributed to the accelerator used. Most of the accelerators commonly used are lithium based and the dosage is **not** typically in the range of those used for OPC. The dosage is also dependent on the ambient temperature. In addition, certain high range water reducers tend to extend the working time of CAC concrete more efficiently than others. This is important as the working time of this material is limited. **It is highly recommended that consultation with the producer is sought prior to the trial batches, to ensure that the correct quantity and type of accelerator and high range water reducer is used to ensure the product will meet the specification and provide enough working time to properly place, consolidate and finish the concrete.**

➔ **WHAT IS "CONVERSION" AND HOW DOES IT IMPACT THE STRENGTH OF CAC CONCRETE?**

Although CAC is known for its high early strength gain, which is great when traffic delays need to be minimized, this rapid strength gain is not obtained without a price. **CAC may inevitably undergo a reaction called "conversion" where a strength loss of 50% or more is possible.**

Conversion in a nutshell is the result of the metastable phases of the hydration products converting to more stable hydration products. Once converted, the more stable hydration products form a smaller crystalline structure and take up less space, increasing the porosity of the overall matrix and consequently reducing the strength. The time when this strength loss occurs depends primarily on the temperature the concrete is subject to which includes the hydration temperature and the temperature in service as well as the presence of moisture. This process can range from hours to many years.<sup>2</sup>

➔ **WHAT CAN MINIMIZE THE REDUCTION IN STRENGTH DUE TO CONVERSION?**

Much like OPC, the ultimate strength of CAC is highly dependent on the w-c ratio. Higher w-c ratios cause lower strengths. In addition, the w-c ratio also plays a major role in the conversion process. Typically, strength loss associated with conversion tends to increase as the w-c ratio increases.

**Literature suggests the conversion process can only be reduced, not prevented, by using low w-c ratios and high sack contents.**<sup>3</sup> Using a pure or relatively pure limestone can reduce the strength loss due to the increase in bond strength between the aggregate and the paste. Some limestone aggregates may also reduce the conversion process through "poisoning" where the calcium from the aggregate is believed to help form more stable hydrates. Lower relative humidity can also decrease the conversion rate.<sup>5</sup>

**More recent data has suggested that the conversion process can be significantly reduced or mitigated with using certain blends of supplementary cementing materials (SCMs).** Using SCMs such as fly ash and slag tend to form additional stable hydrates that may offset the effects of conversion.

**To combat the effects of conversion, TxDOT SS-4491 specifies a minimum cementitious content of 675 lb/cu. yd. and a maximum w-c ratio of 0.35.** Crushed coarse aggregates are also required and limestone aggregates should be used when possible.

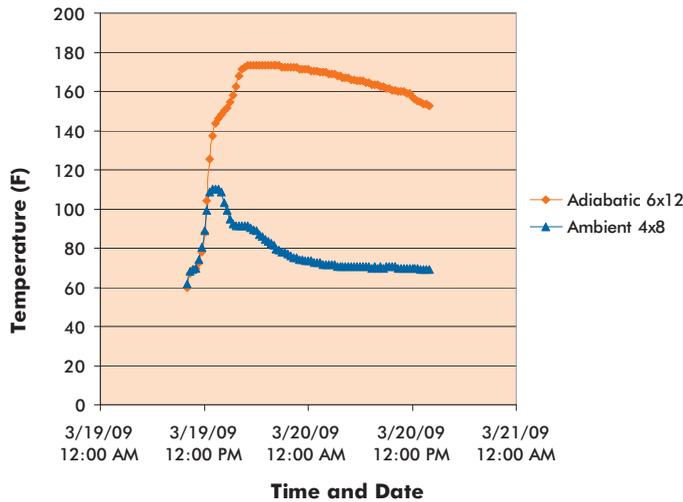
➔ **HOW SHOULD CONVERTED STRENGTH BE ESTIMATED BY TXDOT?**

The temperature during initial hydration plays a major role in determining how fast conversion will take place. Lower hydration temperatures take longer periods of time for conversion to take place (10 years or more). **If the hydration temperature exceeds 140°F (60°C), conversion can take place within 24 hours.**<sup>2</sup>

**TxDOT SS-4491 determines the converted strength by curing 4-6"x12" cylinders in a well insulated**

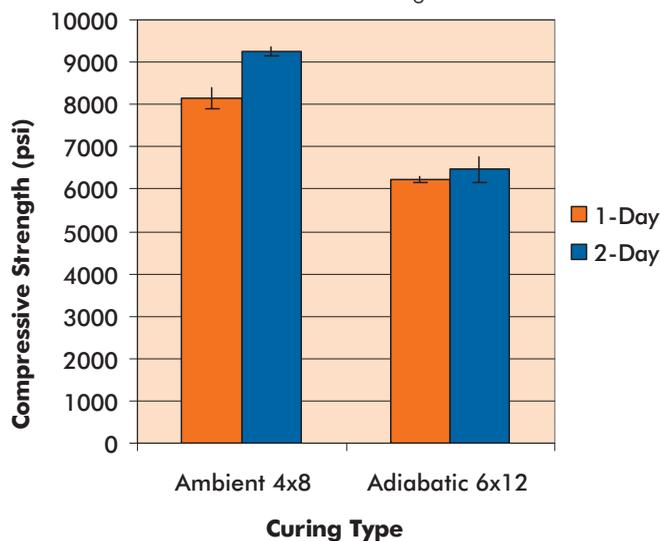
**box.** This type of curing is often referred to as adiabatic curing. The well insulated box allows the cylinders to gain considerable heat as the heat generated by hydration is not easily dissipated. Figure 1 shows a heat-time graph of specimens cured inside (adiabatic) and outside (ambient) of the curing box.

Figure 1. Graph of Heat Generated by CAC



The results in Figure 1 demonstrate how much more heat gain (upwards of 63°F in this particular trial) is achieved by placing a large size specimen in a well insulated environment as opposed to a small specimen placed outside in ambient conditions (~60°F). This high hydration temperature causes the CAC to convert within 24 hours, thereby giving an estimation of the converted strength. Figure 2 shows the corresponding strength results of the same set of specimens subjected to the temperatures given in Figure 1.

Figure 2. Compressive Strength Data of Ambient and Adiabatic Curing



From the results illustrated in Figure 2, the converted strength estimated is approximately 6,000 psi. That is, sometime during the life of the structure, the minimum compressive strength should be approximately 6,000 psi, although it may initially be as high as 9,000 psi or more. Hence the percent reduction in strength is expected to be on the order of 33% and the converted compressive strength of 6,000 psi needs to be used for the design strength.

**It is important to note that the traditional maturity method that is used to quantify the compressive strength of OPC concrete (e.g., Tex-426-A), cannot be utilized for CAC concrete due to the conversion behavior.**

**➔ WHAT ARE THE LIMITATIONS OF ADIABATIC CURING?**

**Adiabatic curing is extremely effective when the initial concrete temperature is above 60°F. When the initial concrete temperature falls below 40°F, the heat generated by the hydration is not enough to exceed the 140°F temperature necessary for conversion to fully take place within the first 24 hours.** This is the reason why the temperature of the specimens must be recorded during the first 24 hours. **If the temperature does not exceed 140°F inside the adiabatic box, it is recommended that the 7-day compressive strength specimens outlined in TxDOT SS-4491 be twice than what the design strength is required.** This will ensure that the converted strength due to conversion will be greater than the design strength. This being the case, it is critical that the 7-day specimens be cured as described in ASTM C 31, paying special attention to the temperature range of 60°F to 80°F, as this will affect the 7-day strength. Keep in mind this is not only important in the winter months but is also equally important in the summer months. If the 7-day specimens are exposed to higher temperature, for instance kept at the job site during the first day at 100°F, the 7-day strength may be reduced since the conversion process may be initiated. Thus, the prediction using 50% of this value will be lowered, too.

**Good record keeping is also recommended for those districts that may use this material frequently.**

Good record keeping will determine the consistency of pours over time which will give an indication of the expected strength reduction due to conversion. This is useful in situations when the temperature of the adiabatic specimens does not exceed the 140°F hydration temperature and we must rely on the 7-day specimens to estimate the converted strength.

It is also important to note that small changes in the w-c ratio will increase the reduction in strength due to conversion, as well as increasing the overall porosity as is typical for OPC.

This sensitivity to w-c ratio coupled with using a volumetric mixer requires a very careful procedure to ensure the expected w-c ratio is achieved, as volumetric trucks may not be as accurate as other mixing and proportioning methods. ***This is why it is important that the concrete supplier should be certified by the Volumetric Mixer Manufacturers Bureau (VMMB) or have an inspection report signed and sealed by a licensed professional engineer demonstrating that the equipment meets the requirements of ASTM C 685 to ensure that the mixer is as accurate as possible. It is also important that a minimum of 2 cubic feet (or until the concrete is well mixed) is discharged and discarded before placing concrete into the forms.***

➔ **MAKING STRENGTH SPECIMENS**

***Typically, ultra rapid strength gaining concrete based on CAC is made using a high amount of superplasticizer to maintain a low w-c ratio and an accelerator to trigger very early hardening. Such mixture is very fluid at the chute of the volumetric mobile mixer but will lose its workability in 10-20 minutes.***

***When making test specimens for strength determination, the most efficient method is to fill the 4"x8" cylinders in two equal lifts, tapping the sides of the cylinder 10-15 times with an open hand during each lift, and then striking the surface level. For 6"x12" cylinders, this is repeated except it is recommended that three equal lifts be used.*** As discussed in the next section, this material can lose its workability very quickly. Rodding the material as described in ASTM C 31 may take too long, which can lead to the formation of voids from the rod as it is penetrated into the stiffening concrete (especially for those specimens that are made last). In addition, it has been observed that some segregation has occurred as a result of the coarse aggregate being forced below the surface of the rodded layer. Since the mixture is so fluid and has the ability to lose its workability quickly, hand tapping should be the only form of vibration needed. ***In addition, when placing the 6"x12" cylinders in the curing box, the temperature recording device can be placed between the specimens in the curing chamber and does not have to be inserted into one of the specimens.***

***The 7-day strength specimens should not be stored in lime water as is typical for OPC. High pH environments may cause dissolution of the aluminate hydrates, which will cause lower strengths. Instead, the specimens should be wrapped with a wet material (e.g., newspaper, towel, etc.) followed by plastic. If being cured in a***

***fog room, the specimens should be left on the shelf and should not be placed in the lime tanks.***

➔ **WHAT ARE SOME CONSTRUCTION CONSIDERATIONS?**

As discussed, CAC tends to lose its workability in a relatively short amount of time. In terms of slump, the material may start at a 9-inch slump and during a period of roughly 15 minutes may decrease to 0 to 1 inch. This loss in workability is "apparent" meaning it is the appearance of the loss of workability. The concrete that appears to be very stiff can actually become very fluid with vibration; however it is not easily finished. This apparent slump loss is primarily the result of the low w-c ratio specified and the amount of accelerator and water reducer added by the concrete supplier.

When pouring CAC concrete, it is important to use the concept of ***"finish as you go."*** Let's assume that the repair area looks similar to the repair area in Figure 3.

In this case, it is important that the concrete pour begins at one side of the repaired area and the pour is continued until that area is full. Do not pour the concrete in lifts or begin at one end and skip around as a cold joint is likely to occur. CAC concrete is very similar to self consolidating concrete (SCC) in its ability to flow while still maintaining its consistency. It is also, to some extent, self leveling and minimal vibration is needed. Figure 4 shows the repaired area being filled with CAC concrete.



Figure 3. SH 45 Section Repaired with CAC



Figure 4. Pouring of CAC Concrete

The CAC concrete should be screeded immediately when the patched area is full. Once flush, in this case with the surrounding pavement, the material needs to be bull-floated as soon as possible as observed in Figure 5.



Figure 5. Finishing of CAC Concrete

The finishing, as illustrated in Figure 5, began before the pour was completed. **Remember, the working time with this material is limited!** Screeding and finishing the CAC concrete as it is poured will help to avoid having to use excessive amounts of finishing water and will avoid unlevel riding surfaces.

Once the CAC concrete is placed and finished, especially during the winter months, a plastic sheet should be placed over the top of the repair area to help trap heat and cure the concrete until it is opened to traffic. Curing blankets may also help to insulate the surface of the concrete. **The strength gain is directly proportional to the heat development, so the more heat (and less heat dissipation), the quicker the strength gain and the earlier the lane can be opened to traffic.** Curing should continue until traffic is allowed on the roadway. Once the 6"x12" cylinders achieve the required strength (cured at

ambient conditions but also protected), the lane can be opened to traffic. **Although the trial batches should have been conducted at the anticipated ambient temperature (temperature during pour) and hence the required strength should be achieved at low temperatures, it is recommended that during the winter months when the temperature is below 40°F, an extra set of 6"x12" cylinders are made for early strength determination to ensure enough specimens are available for latter ages (e.g., greater than 3 hours) to ensure the strength requirement is met prior to opening the lane to traffic.**

### ➔ WHAT FACTORS INFLUENCE THE DURABILITY?

The durability of CAC is largely dependent on whether or not it has converted and the w-c ratio. As previously discussed, the conversion process increases the overall porosity of the matrix. Increased porosity usually is indicative of an increased permeability. Permeability has a major influence of the durability.

CAC concrete was originally developed for applications in high sulfate environments. Research by Crammond (1990) indicated that good performance was observed with CAC concrete in field structures exposed to high sulfate environments even when the CAC concrete was converted. However, laboratory investigations have suggested the opposite, CAC concrete did not perform well in sulfate solutions.<sup>6</sup>

In terms of acid attack, CAC concrete is expected to be more resistant than OPC concrete as the hydration products contain no calcium hydroxide. In the case of conversion, Bayoux, et al. (1990) found that the more stable (converted) phases were more acid-resistant than the unconverted phases.<sup>7</sup>

CAC concrete should not be used in high alkaline environments, especially when it is exposed to solutions with a pH greater than 12 due to the dissolution of the aluminate hydrates. The aluminate hydrates may also decompose by a process called alkali hydrolysis. Although not fully understood, alkali hydrolysis is the result of the alkali decomposing the aluminate hydrate to form alkali aluminate and calcium hydroxide. In the presence of carbon dioxide, the alkali aluminate and calcium hydroxide are converted into hydrated alumina and calcium carbonate. This conversion then frees the alkali which continues the process causing further damage. Being Portland cement is a highly basic material and contains alkalis, there have been some concerns that alkali hydrolysis make take place in the interface of the repair between OPC and CAC concrete. However, there have been no known cases reported and alkali hydrolysis is

believed to be very unlikely in CAC concrete when low w-c ratio mixtures are used.<sup>2</sup>

The freeze-thaw resistance of CAC is expected to be similar to that of OPC concrete. The effect of air on compressive strength with CAC is unknown, but it is expected to be similar to OPC concrete. If air entrainment is used, it is recommended that the testing is conducted on the converted concrete. According to Scrivener, et al. (1998), “good quality CAC concrete with w-c ratios of less than 0.40 is likely to be freeze-thaw resistant even without air entrainment.”<sup>3</sup>

In terms of corrosion, CAC concretes contain fewer alkalis and do not produce calcium hydroxide as a hydration product when compared to OPC concrete. Therefore, at least during the initial hydration, the pH of CAC concrete is less than OPC concrete. This lower pH causes some concern for corrosion as the high pH of OPC concrete is responsible for the passivation of steel. However, Gaztanaga (1993) has shown that within 24 hours of hydration, the pore water of CAC concrete is as high as 12 to 13.<sup>8</sup> Experimental measurements have also suggested the tendency for reinforcing steel to corrode in CAC concrete is unlikely.

In terms of corrosion due to chlorides, there has been little work relating to chloride ingress. Unpublished work has suggested that young, converted concrete with the surface removed may be favorable for a high rate of chloride ingress. On the other hand, the Florida Department of Transportation has shown that unconverted CAC concrete outperformed OPC concrete by more than an order of magnitude when the chloride ingress was measured under an imposed current. Studies performed on field structures exposed to sea water over 60 years indicated that the dense outer layer of CAC concrete significantly inhibited the ingress of chlorides. In terms of carbonation, good quality CAC is comparable to good quality OPC concrete and hence the corrosion due to carbonation is expected to be similar.<sup>3</sup> Dunster (2008) verified that the carbonation rate of CAC concrete was comparable to OPC concrete with the same quality.<sup>9</sup>

To date, no testing has been conducted to determine the susceptibility of CAC concrete to alkali-silica reaction (ASR). Being CAC concrete has a lower pH, the assumption is CAC concrete is less susceptible to ASR than OPC concrete. Further research is needed to confirm this.<sup>5</sup> CAC is not susceptible to delayed ettringite formation (DEF) as is OPC concrete cured at high temperature without any mitigation options.

As previously discussed, the permeability and thus the durability of CAC concrete depends on whether or not it is converted and the w-c ratio. However, we must keep in mind that it is possible for the near-surface regions of the structure to be different than the interior regions of the CAC concrete, as these regions may not have been exposed to the high internal temperatures during the hydration. Therefore, it is

possible that a “shell” of unconverted CAC concrete with low permeability may protect the structure against the intrusion of deleterious materials.<sup>2</sup> In addition, much of the research to date has focused on higher w-c ratios and lower sacks contents than are specified in SS-4491.<sup>2,3</sup> Hence the durability of the CAC concrete listed in SS-4491 is expected to be at least comparable to good quality OPC concrete and more durable than what is published in literature.

For questions on this article or any concrete issues, please contact the Rigid Pavements and Concrete Materials Branch at 512/506-5856.

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