Design and performance of precast, prestressed concrete beams made with fly-ash-based alkali-activated concrete

Grant P. Magnuson, Mary U. Christiansen, and Benjamin Z. Dymond

- This paper discusses research into the mixture proportions, fabrication procedures, and mechanical properties of fly-ash-based alkali-activated concrete and the design of precast, prestressed concrete beams using alkali-activated concrete.

- The researchers evaluated mortar and concrete compositions of alkali-activated concrete to determine mixture proportions and mixing procedures that would be safe and cost-effective for beam production at precasting plants.

- Precast, prestressed concrete beams were fabricated using the preferred alkali-activated concrete mixture and then tested to determine flexural and shear capacity.

- The research concluded that precast, prestressed alkali-activated concrete beams can be designed using standard concrete design theory and fabricated using the current technology available at precasting plants, but further testing is needed for commercialization.

Concrete is the second-most-widely used material in the world after water, and global cement production accounts for as much as 8% of human-generated carbon dioxide emissions annually.[1,2] Many countries and corporations are pledging to reduce their carbon footprint in the coming decades, creating demand for greener products; however, many concrete applications are directly related to life safety and require a high level of confidence and reliability. All building codes for reinforced and prestressed concrete are written with a portland cement binder in mind. At this time, there are very few ASTM International standards and specifications written for concrete materials other than portland cement concrete.

Most alternative cements operate similarly to portland cement; a binder is formed through a series of chemical reactions that bind the coarse and fine aggregates, creating a monolithic concrete. Alkali-activated concrete is comparable to portland cement concrete in many ways, but instead of portland cement and water making up the binder, a powdered aluminosilicate precursor and alkaline liquid activator are used. In alkali-activated concrete, the dry precursor can be a variety of materials, including fly ash, slag, or metakaolin; sodium hydroxide and sodium silicate are commonly used as alkaline activators. External heat may need to be applied for some alkali-activated concretes to gain strength, but this requirement depends on the chemical composition of the raw materials. Precast concrete is a logical application for alkali-activated concrete because precasting plants commonly use heated beds, heat chambers, or ovens to accelerate the curing of conventional portland cement concrete.

Limited research has been conducted on full-scale alkali-activated concrete specimens.[3] Most research on alkali-activated materials has predominantly involved the study of the paste and microstructure rather than how it can be commercially produced and how it performs in a structural application. Thus, there remains a need to quantify the mechanical properties of alkali-activated concrete for use in structural applications and test the structural properties of full-scale specimens to verify that alkali-activated concrete can be designed using current design specifications, such as the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)*[4] or the *PCI Design Handbook: Precast and Prestressed Concrete*.[5] While a few studies have tested medium- to large-scale alkali-activated concrete specimens made with low-calcium fly ash, almost no research has been conducted on similar specimens with high-calcium fly ash. The variability of the calcium content within the fly ash precursor can affect the mixture proportions and performance of alkali-activated concrete, so it is necessary to test and develop different mixture proportions compatible with different fly ashes.

Research objectives

There were two main objectives in this research study. The first was to develop an alkali-activated concrete mixture and mixing process suitable for precast concrete production using regionally available materials. This was achieved by optimizing preliminary mortar mixtures considering the performance requirements of a precasting plant while maintaining the necessary properties for structural building materials. After a suitable mortar mixture design was developed, small batches of alkali-activated concrete were made in the laboratory to verify mechanical properties. The second objective of this study was to design, fabricate, and test full-scale precast, prestressed concrete beams made with fly-ash-based alkali-activated concrete. Within the second objective, it was important to evaluate roadblocks that may limit alkali-activated concrete production in the precast concrete industry. Full-scale precast, prestressed alkali-activated concrete and portland cement concrete specimens were successfully fabricated in a plant setting. Furthermore, the alkali-activated concrete mechanical properties and beam structural performance were characterized to verify the suitability of ACI 318-19 for designing structures using alkali-activated concrete.

Background

Alkali-activated concrete is made with a powdered aluminosilicate precursor and alkaline liquid activator. There are three primary steps in alkali activation: dissolution, reorganization, and hardening.[3] Heat helps facilitate the process, whether externally applied or through heat of hydration. Alkali-activated concrete achieves most of its design strength after approximately 24 hours of heat curing at a minimum of 60°C (140°F).[6–8] Portland cement concrete also exhibits higher initial strength from early-age heat curing compared with ambient curing, but portland cement concrete continues gaining strength for several weeks after production. The most common dry precursor used to make alkali-activated concrete is fly ash; however, it is important to note that compositional variations between fly ashes can affect performance.[3,9] Fly ash with higher calcium content is associated with lower workability, shorter set time, and lower compressive strengths,[10,11] though the additional calcium content can also aid in long-term strength development.[12] Sodium hydroxide and sodium silicate are commonly used as alkaline activators in alkali-activated concretes. An increase in sodium hydroxide concentration typically yields higher-strength specimens to a point,[10,13] but in one study, it yielded lower strengths.[7]

Curing times of less than 24 hours are desirable in the precast concrete industry because formwork needs to be reused daily. Depending on the available curing temperature, additional time may be required for alkali-activated concretes to cure properly. Using a curing time of up to 48 hours is attainable in a precasting plant if a specimen is left to sit over a weekend. This additional curing time can produce better mechanical and durability properties for alkali-activated concretes. However, initial heat curing periods longer than 48 hours often provide minimal initial strength gain, and some research results have demonstrated that prolonged initial heat curing can result in decreased strength.[3,10,12,14] An early compressive strength of 24.1 MPa (3500 psi) is often specified as the required initial strength to detension prestressed concrete components.[5] Required curing temperatures for alkali-activated concrete generally range from 40°C to 90°C (104°F to 194°F), with 60°C (140°F) being the most-reported temperature. Temperatures below 60°C are known to be associated with slow compressive strength gain.[15]

Precast, nonprestressed alkali-activated concrete has been studied in multiple applications, including beams, columns, slabs, wall panels, median barriers, box culverts, sewer pipes, and railway sleepers.[3,14,16–21] Many studies concluded that alkali-activated concrete and portland cement concrete showed similar behavior. Ridtirud et al.[14] are the only researchers who have fabricated and tested a fly-ash-based prestressed alkali-activated concrete slab, which was done to quantify deflection. Sodium silicate and 15M sodium hydroxide were used as activators, and the slab curing conditions were not reported. Jeyasehar et al.,[7] Pires et al.,[19] Tempest et al.,[21] and Yost et al.[22] all made conventionally reinforced alkali-activated concrete beams or beam-columns. Jeyasehar et al. and Pires et al. tested 2.1 and 3.0 m (7 and 10 ft) long reinforced alkali-activated concrete beams to characterize full-scale flexural capacity and other small-scale specimens to characterize modulus of elasticity, compressive strength, and splitting tensile strength. Both studies found that alkali-activated concrete behaved similarly to portland cement concrete. Tempest et al. tested reinforced alkali-activated concrete beam-columns with

190 × 184 mm (7.5 × 7.25 in.) cross sections, and Yost et al. tested 3.0 m long reinforced alkali-activated concrete beams. Both studies found that the beams performed similarly to or better than the predicted capacities for portland cement concrete using ACI 318-14 and ACI 318-08, respectively.[23,24]

Research teams have reported that the cost of alkali-activated concrete varies, ranging in cost from the same as portland cement concrete to three times portland cement concrete.[3,24] The high cost is mainly attributed to the sodium hydroxide and sodium silicate activators; however, the cost of fly ash in the alkali-activated concrete is only about 20% of the portland cement cost in portland cement concrete.[3] Tempest et al. stated that the high-grade activators that they used were unnecessary, and Pacheco-Torgal et al. recommended investigating the use of "less-expensive waste feedstocks" with similar required characteristics (for example, a high pH) to reduce cost.[3,25]

Some researchers investigating alkali-activated concrete include environmental analyses in their work.[3,25,26] Fly ash is typically considered carbon-neutral when used in alkali-activated concrete because its embodied carbon is already attributed to the electric power produced during its production. Reduction in emissions associated with alkali-activated concrete compared with portland cement concrete is estimated to be about 40% to 60%;[27] however, the activators used in alkali-activated concrete[27,28] and the energy needed to heat cure alkali-activated concrete for appropriate strength gain[29] can have large carbon footprints due to the amount of electricity required.

Alkali-activated concrete materials, mixing procedure, and precast concrete mixture proportions

Materials

Fly ash was the pozzolan selected for this project because it was readily available at the regional precasting plant. Furthermore, fly ash was used as the precursor in this research because the use of a different pozzolan when switching between alkali-activated concrete and portland cement concrete production was a roadblock to production for the precasting plant. Fly ash used by the precasting plant came from two different power plants, denoted as sources A and B. Both sources produced Class C fly ash. Chemical analysis results of three fly ash samples, labeled FA1, FA2, and FA3 are shown in **Table 1,** along with a chemical analysis of the portland cement used by the precasting plant. FA1 and FA3 came from source B, which was selected for precast concrete production. FA1 was only used near the beginning of the project, and a sample of FA3 was gathered to check consistency between two samples from the same source. Consistency between the FA1 and FA3 samples was important to ensure that the large-scale precast, prestressed alkali-activated concrete specimens fabricated late in the project would display similar characteristics to the alkali-activated concrete produced in the laboratory (work completed early in the project). FA2 came from source A and was used to characterize the variability of the mechanical property results between mixtures containing the two different fly ash sources. The amount of material retained on a no. 325 sieve for each specimen is also shown in Table 1,

Table 1. Chemical analysis results for fly ash and portland cement samples

Chemical analyses and other properties	FA1	FA2	FA3	Portland cement
Fly ash source	B	A	B	n/a
Silicon dioxide, SiO_2	38.3	35.3	38.8	19.5
Aluminum oxide, Al_2O_3	19.5	20.6	19.4	4.8
Iron oxide, Fe_2O_3	6.68	5.63	5.58	2.2
Sum of SiO_2 + Al_2O_3 + Fe_2O_3	64.5	61.5	63.8	26.5
Calcium oxide, CaO	20.9	25.1	21.2	63.4
Magnesium oxide, MgO	6.22	4.46	6.68	3.2
Sodium oxide, Na_2O	2.46	2.63	2.33	0.05
Potassium oxide, K_2O	0.77	0.51	0.80	0.45
Sulfur trioxide, SO_3	1.47	1.78	1.28	3.8
Loss on ignition	0.42	0.26	0.26	2.5
Available alkalis, as Na_2O equivalent	1.05	1.40	1.07	0.35
Amount retained on no. 325 sieve	9.5	14.2	9.2	0.7

Note: All composition values are weight percent oxide. n/a = not applicable; FA1 = fly ash sample 1; FA2 = fly ash sample 2; FA3 = fly ash sample 3.

which indicates that the portland cement had a smaller particle size than the fly ash samples.

In this study, commercially available sodium hydroxide and sodium silicate were used as activators, which aligns with other alkali-activated concrete research studies.[3,7,14,19,21,22] Sodium hydroxide is typically used as a solution in alkali-activated concrete. In this study, sodium hydroxide in solution and solid forms (flakes and pellets) was explored. In the early stages of this research, sodium hydroxide solution with a concentration of 10M was used, though other molarities were investigated. Production difficulties and safety issues associated with large volumes of highly-basic sodium hydroxide solution were anticipated in a plant setting, so the mixing procedure was changed to include solid sodium hydroxide. Sodium hydroxide flakes were added directly to the mixtures along with the equivalent water to reach 10M concentration.

The same coarse and fine aggregates from the precasting plant were used in all concrete mixtures. The coarse aggregate was classified as a 14.3 mm (0.563 in.) crushed carbonate, with a density of 2.66 relative to water and an absorption value of 1.90%. The fine aggregate was classified as natural sand, with a density of 2.67 relative to water and an absorption value of 0.60%.

Mixture performance requirements

For this project, the mixture performance requirements were motivated by the precasting plant production schedule, available materials, and available equipment. In the literature, many alkali-activated concrete research projects described performance requirements that were unrealistic in a production environment. For example, many researchers cured alkali-activated concrete samples at a temperature higher than what is achievable using typical equipment at a precasting plant and cured alkali-activated concrete samples for longer than is feasible during precast concrete production. Thus, an optimal alkali-activated concrete mixture that worked within the requirements of the regional precasting plant was sought. The final performance requirements included the following:

- a minimum 15 minutes of workability after the concrete leaves the mixer, with a total set time of 45 minutes from the start of mixing
- a slump of 76 mm (3 in.)
- a maximum curing temperature of 49°C (120°F)
- a curing time of about 16 hours, which allows the local precasting plant to strip forms, move the specimens to the shipping yard, and prepare to cast the next batch of concrete specimens (The cure time for alkali-activated concrete specimens in this study was approximately 60 hours, which was achieved by casting the concrete specimens on a Friday and allowing them to cure over the weekend.)
- a concrete compressive strength at 16 hours of 24.1 MPa (3500 psi) and a 28-day compressive strength of at least 41.4 MPa (6000 psi)

Mixing procedure

A total of six different mixing procedures, presented as MP1 through MP6 in **Table 2**, were investigated during mortar testing. The procedure that led to mortar with optimal fresh and hardened properties was selected to make concrete. Mixing procedures MP1 through MP4 were based on procedures from the literature, as highlighted in Table 2. Mixing procedure MP1 was defined by adding all of the activator in one step, whereas the activator was added in multiple steps in MP2. Mortar made with MP2 had better workability than mortar made with MP1. Mixing procedure MP3 was defined by mixing all dry ingredients first and adding the activator in the final steps, which led to good workability and a reduction in the water-to-solids ratio *w/s* (which is comparable to the water-cement ratio in portland cement concrete) compared with mortar made with MP1 and MP2. Mortar made with MP4 did not perform well, and this procedure was not pursued beyond one trial batch. MP5 was adapted from MP3 and used to mix concrete batches in the laboratory. Mixing procedure MP6 was the procedure used at the precasting plant and had a shorter mixing time (6 minutes) due to the efficiency of the mixing equipment.

Mixture design process and results

To create an alkali-activated concrete mixture that satisfied all performance requirements from the precasting plant, 26 unique small-batch mortar mixtures were first investigated in the laboratory by Magnuson.[30] The best-performing mortar was scaled to make laboratory alkali-activated concrete mixtures, and the alkali-activated concrete mixture proportions were optimized before use at the precasting plant. The initial mortar mixtures focused primarily on workability and available set time. Mortars with flow values above 75% of the goal were considered to have good workability, and mixtures with at least 45 minutes of workability were considered to have an acceptable set time. The mortar mixtures contained aggregate-to-aluminosilicate and activator-to-aluminosilicate ratios of 2.75 and 0.50 by mass, respectively. The *w/s* was calculated using the total mass of water (including water in the activator) divided by the total mass of solids (including solids in the activator). Different mixtures were made to investigate the effects of varying *w/s*, sodium hydroxide molarity, sodium hydroxide–to–sodium silicate ratio, mixing procedure, and curing conditions.

Fly ash sources A and B both produced Class C fly ash, but source A had a higher calcium content (25% compared with 21%). Alkali-activated concrete made with higher-calcium fly ash has been shown to be associated with lower compressive strength.[11] Two test mortar batches were produced to check consistency between the fly ash sources. The mortars made with fly ash from sources A and B had average compressive strengths

Table 2. Mortar and concrete mixing procedures investigated in this study

Mixing procedure, use	Mixing time, minutes	Step 1	Step 2	Step 3	Step 4
MP1[*] laboratory mortar	13	Add fly ash and start mixer	Add activating solution while mixing over 1 minute; mix for 3 minutes	Add additional required water; mix for 1 minute	Add fine aggregate while mixing for 2 minutes; mix for 6 minutes
MP2[†] laboratory mortar	15	Combine fly ash, sodium hydroxide, and water; mix for 5 minutes	Add fine aggregate; mix for 5 minutes	Add sodium silicate; mix for 5 minutes	n/a
MP3[‡] laboratory mortar	14	Combine half of fly ash and half of fine aggregate; mix for 2 minutes	Add remaining fly ash and fine aggregate; mix for 2 minutes	Add half of activators; mix for 5 minutes	Add remaining activators; mix for 5 minutes
MP4[§] laboratory mortar	4	Combine sodium hydroxide pellets with sodium silicate in a separate container	Combine fly ash and fine aggregate in mixer; mix for 1 minute	Add the activating solution (step 1) and equivalent water for sodium hydroxide solution; mix for 3 minutes	n/a
MP5 laboratory concrete	18	Combine half of coarse and half of fine aggregates; mix for 2 minutes	Add the remaining coarse and fine aggregates; mix for 2 minutes	Add half of fly ash and mix for 2 minutes; repeat for the other half of the fly ash	Add half of the activators and equivalent water; mix for 5 minutes; repeat for the other half of the activators
MP6 precasting plant concrete	6	Combine coarse and fine aggregate; mix for 1 minute	Add fly ash and mix for 1 minute; stop mixer and add sodium hydroxide flakes	Start mixer, add water, and mix for 2 minutes; stop mixer and add sodium silicate	Mix for 2 minutes; add extra water as necessary for workability

Note: n/a = not applicable.

[*] Data from C. A. Schlosser, *Alkali Leaching Properties of Waste Glass-Based Geopolymers*, MS thesis (University of Minnesota of Duluth, 2018), https://conservancy.umn.edu/items/cd29ac94-f183-4b49-aed0-32cd703c0007.

[†] Data from Ridtirud, Lam, and Sapsin (2018).

[‡] Data from Yost, Radlińska, Ernst, and Salera (2013).

[§] Data from S. Akçaözoğu and C. Ulu. 2014. "Recycling of Waste PET Granules as Aggregate in Alkali-Activated Blast Furnace Slag/Metakaolin Blends." *Construction and Building Materials*, no. 58 (2014): pp. 31–37, https://doi.org/10.1016/j.conbuildmat.2014.02.011.

of 24.6 and 27.1 MPa (3570 and 3930 psi), respectively, when cured for 18 hours at 54°C (129°F). The compressive strength differences were larger for curing times of 14 and 48 hours, with differences of 3.4 and 4.2 MPa (490 and 600 psi), respectively. The higher calcium content and the larger particle size of ash from source A (Table 1) may explain the insignificant differences. A larger particle size provides less overall surface area, reducing reactivity, and the activator may have dissolved fewer particles for mixtures made from source A fly ash.

The precast concrete producer requested that the solid sodium hydroxide be added directly to the mixer with the required amount of water, rather than predissolving the flake. This was the easiest and safest method given the existing manufacturing setup at the precasting plant; however, there was concern related to excessive heat generation from the rapid dissolution of solid NaOH when adding sodium hydroxide pellets directly to the mixer; this behavior could cause the alkali-activated concrete to flash set. To address this concern, mortar batches were made to investigate the effects of directly mixing sodium hydroxide pellets with water rather than using a premixed solution. Results indicated that there was a slight reduction in workability and set time when using solid sodium hydroxide mixed into the batches. The additional heat generated from mixing the pellets with water may have shortened the set time. Using solid sodium hydroxide also led to mortar with compressive strength that was consistently lower than the compressive strength of mortar made using sodium hydroxide solution by approximately 4.8 MPa (700 psi), regardless of curing time. Although switching from a sodium hydroxide solution to solid sodium hydroxide had a negative effect on compressive strength and set time, it was decided that using solid sodium hydroxide best fit the constraints of the precasting plant.

To investigate the relationship between curing temperature and early-age compressive strength, mortar samples were oven cured in a closed container at 100% humidity and temperatures between 49°C and 70°C (120°F and 158°F). The compressive strengths of the samples was obtained after curing for 14, 18, and 48 hours. In general, a higher curing temperature yielded a more rapid strength gain, but the compressive strength from samples cured at each temperature ended up being nearly identical after 48 hours of curing. After 14 hours of curing, the compressive strength increased 42% when the curing temperature was increased from 54°C to 70°C (129°F to 158°F). After 18 hours of curing, the compressive strength only increased 16% when the curing temperature was increased from 54°C to 70°C. After 48 hours of curing, an increase in curing temperature from 54°C to 70°C resulted in a compressive strength decrease of 3%. The data showed that higher curing temperatures were associated with increased compressive strength at cure times less than 48 hours. This finding aligned with the performance requirements of the precasting plant, where formwork is reused daily and a cure time between 14 and 18 hours is required.

Ultimately, a mortar mixture was identified as having properties that could be scaled to alkali-activated concrete for use in precast concrete production. This mixture had an NaOH to SS ratio of 2 to 1 by mass, an NaOH concentration of 10M, and a *w*/*s* of 0.40. In the laboratory, alkali-activated concrete batches were designed based on a conventional portland cement concrete mixture currently used at the regional precasting plant. The original conventional portland cement concrete mixture had a design slump of 76 mm (3 in.), 16-hour compressive strength of 24.1 MPa (3500 psi), and 28-day compressive strength of 41.4 MPa (6000 psi). Alkali-activated concrete cylinders were made from three laboratory batches and were cured at 49°C (120°F) for 18, 48, and 72 hours. The only difference between the three laboratory alkali-activated concrete batches was the water content, which was varied slightly to determine the best *w*/*s* to allow the alkali-activated concrete to meet fresh- and hardened-property requirements. The recorded slump of the mixtures ranged from 63 to 114 mm (2.5 to 4.5 in.). All

Table 3. Mixture proportions used for production of the precast, prestressed alkali-activated concrete and portland cement concrete beams, per 0.76 m^3

Material	Alkali-activated concrete		Portland cement concrete	
	Weight, kg	Weight, %	Weight, kg	Weight, %
Type III cement	0	0	291	12.4
Fly ash	315	13.3	154	6.6
Solid NaOH	30	1.3	0	0
Water for 10M NaOH	75	3.2	0	0
Sodium silicate	52	2.2	0	0
High-range water-reducing admixture	0	0	31	1.3
Accelerator	0	0	21	0.9
Air-entraining admixture	0	0	5	0.2
Fine aggregate (coarse sand)	809	34.1	773	33.0
Pea gravel	0	0	225	9.6
Coarse aggregate (14.3 mm)	1062	44.7	688	29.3
Water	29	1.2	157	6.7
Total binder weight	501	21.2	602	25.7
Total admixture weight	0	0	57	2.4
Total aggregate weight	1872	78.8	1686	71.9
Total weight	2372	100	2345	100
Target water-to-solids ratio	0.41		0.35	

Note: 1 mm = 0.0394 in.; 1 m^3 = 1.308 yd^3; 1 kg = 2.205 lb.

three batches had similar fresh concrete temperatures that ranged from 29°C to 32°C (84°F to 90°F). Short-term results indicated that the alkali-activated concrete compressive strength increased with increased curing time. Batches 1, 2, and 3 were cured for 18, 48, and 72 hours, respectively. When cured for 48 and 72 hours, the alkali-activated concrete had compressive strengths of 25.2 and 29.3 MPa (3650 and 4250 psi), respectively, compared with 17.4 MPa (2520 psi) when it was cured for 18 hours. The data gathered from the laboratory alkali-activated concrete batches highlighted the need for a weekend cure of approximately 60 hours at the precasting plant, which allowed for an acceptable compressive strength at transfer (that is, greater than 24.1 MPa). The alkali-activated concrete cylinders had a 28-day compressive strength from 27.9 to 32.3 MPa (4050 to 4680 psi), which meant that the long-term compressive strength of this mixture would not likely reach the 41.4 MPa requirement of the precasting plant; however, this mixture design provided an adequate compressive strength at transfer, so it was selected to make the precast, prestressed alkali-activated concrete beams.

Precast alkali-activated concrete mixture proportions

Table 3 shows the final alkali-activated concrete mixture proportions used in this research, along with the conventional self-consolidating portland cement concrete mixture proportions typically used at the precasting plant. The aggregates were assumed to be in a saturated surface dry (SSD) condition. The row titled "Water for 10M NaOH" in Table 3 indicates the amount of water needed with the specified amount of solid sodium hydroxide to make an equivalent 10M sodium hydroxide solution. The alkali-activated concrete mixture proportions were based on the laboratory concrete batches with a target *w/s* of 0.41 and a slump of 76 mm (3 in.).

Full-scale beam design and fabrication

Beam design details

Four full-scale precast, prestressed alkali-activated concrete rectangular beams were fabricated and tested to better understand the requirements of producing alkali-activated concrete in a precasting plant setting and investigate both the flexural and shear capacity compared with predictions made using ACI 318.[4] Two additional portland cement concrete beams were fabricated first and served as trial specimens for the heat-curing ability of the precasting plant. The portland cement concrete beams were not tested as a part of this study, but mechanical property specimens from the portland cement concrete batch were tested and compared with the alkali-activated concrete mechanical property test specimens. The compressive strength of the alkali-activated concrete beams were specified to have 3-day and 28-day compressive strengths of 24.1 and 41.4 MPa (3500 and 6000 psi), respectively. All beams were 254 mm wide × 610

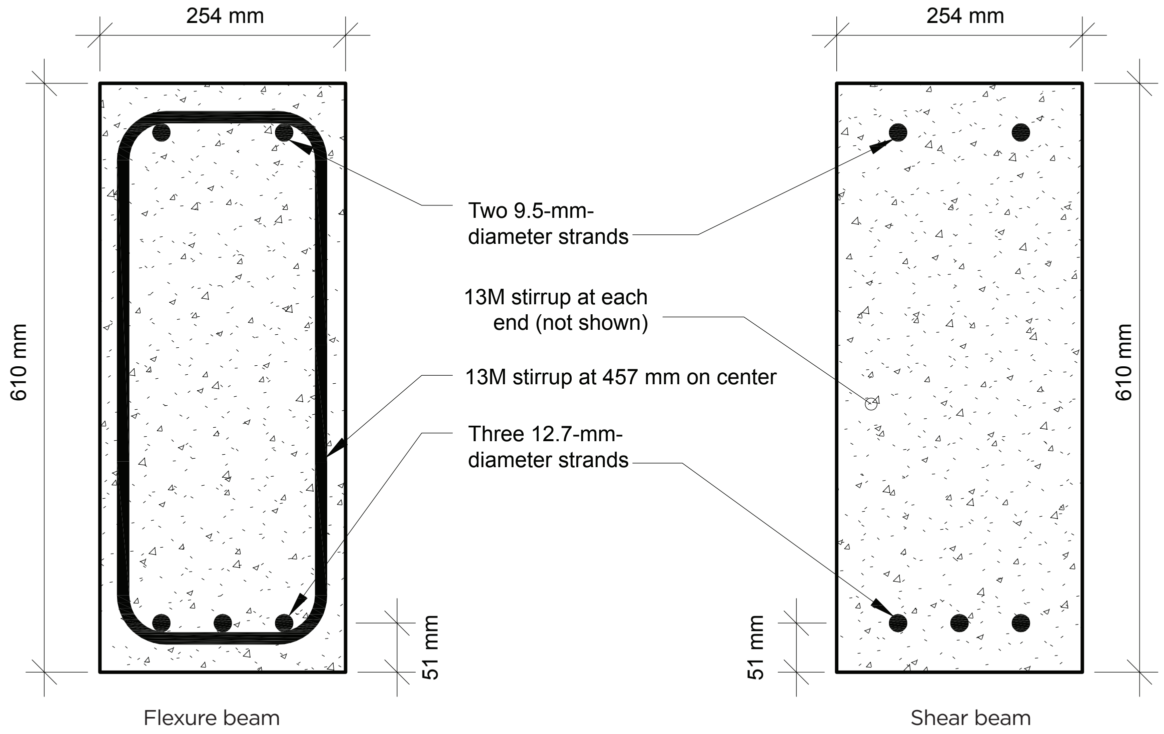

Figure 1. Cross-sectional view of the rectangular precast, prestressed concrete flexure and shear beams at midlength showing the dimensions, longitudinal prestressing reinforcement, and transverse shear reinforcement. Note: 13M = no. 4; 1 mm = 0.0394 in.

mm tall × 5.64 m long (10 in. × 24 in. × 18.5 ft) (**Fig. 1**). Five low-relaxation strands were placed in each beam and tensioned to 70% of the guaranteed ultimate tensile strength. Three 12.7 mm (0.5 in.) diameter, 1860 MPa (Grade 270) strands were placed 51 mm (2.0 in.) from the bottom of each beam, which resulted in a depth of 559 mm (22.0 in.) from the top of the beam to the centroid of the strands. Two 9.5 mm (0.375 in.) diameter, 1724 MPa (Grade 250) strands were placed 51 mm from the top of each beam for constructibility. The beams that were designed to fail in flexure and not shear had 13M (no. 4), 414 MPa (Grade 60) transverse (stirrup) reinforcement spaced at 457 mm (18.0 in.) on center. The beams that were designed to fail in shear and not flexure did not have stirrups, except for one at each end to control cracking when the prestress was transferred. The beam design methodology did not use any strength-reduction factors or load factors. The overall strand eccentricity likely caused a minor amount of camber, but the initial camber and changes in camber over time were not monitored in this project.

Beam fabrication and curing

The full-scale beams were cast in two stages. First, the portland cement concrete beams were cast to gather preliminary data on the heat-curing ability of the precasting plant. The beams were cast with the 610 mm (24 in.) side against the heated bottom bed so that the heat only had to travel vertically through the 254 mm (10 in.) dimension. The portland cement concrete was a flowable mixture that resembled self-consolidating concrete. Workers screeded the surface of the concrete to obtain a consistent beam cross section, and no further finishing was required. After the concrete was placed and finished, a plastic sheet was placed over the beams to maintain moisture. Insulated blankets were draped over

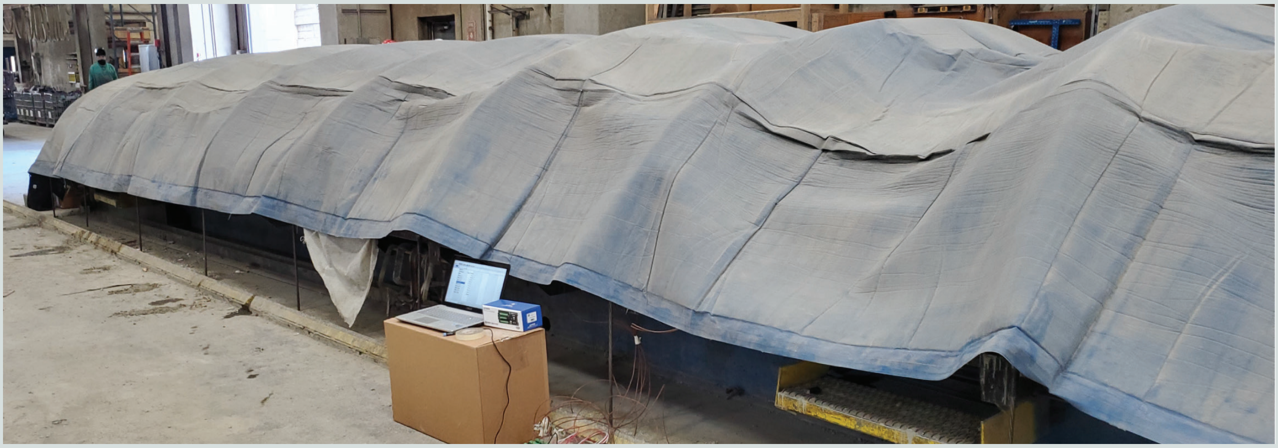

Figure 2. Beam curing setup with a heated bed and insulated blanket covering the specimens.

Figure 3. One supplemental forced-air heater, shown here, was placed at each end of the casting bed during portland cement concrete beam curing.

steel rods above the bed in a tent shape, creating an oven-like atmosphere for the specimens (**Fig. 2**). The portland cement concrete beams were cured over the weekend for 80 hours.

Two methods of applying heat during the curing process were investigated on separate portland cement concrete placements before fabricating the alkali-activated concrete beams. In the first method, a supplemental forced-air heater (**Fig. 3**) was placed at each end of the curing setup and the heated bed was not used. Temperatures recorded by seven thermocouples placed along the length of the beam and inside the concrete cross section indicated that most locations within the beam reached a temperature of 49°C (120°F) for 10 hours or longer (**Fig. 4**). The forced-air heaters ran for less than a day, so there was not much external heat applied to the beams. In the second method, only the heated bed was used, and no forced-air heaters were used. The bed was completely covered with an insulated blanket, and a curing system at the precasting plant was used to monitor internal concrete temperature. The temperature was 1°C to 2°C (2°F to 4°F) below 60°C (140°F) for several hours and was above 49°C for 52 hours while simulating a weekend cure. It was determined that only using the heated bed and covering the beams with an insulated blanket was sufficient, so alkali-activated concrete beam fabrication would not rely on external, supplementary heating sources.

The alkali-activated concrete beams were made from two batches, amounting to a total of 5.0 m^3 (6.5 yd^3). Both batches used more than the specified water content from the mixture proportions to achieve the desired workability. The actual *w*/*s* were 0.48 and 0.50 for batch 1 and batch 2, respectively, compared with the initial target of 0.41. Miscommunication between the researchers and batching operator about achieving workability with the addition of water resulted in too much water being added. Both mixtures could have maintained the desired workability with much less water, and less water would have resulted in higher concrete strengths. Mixing procedure 6 (Table 2) was used during alkali-activated concrete beam fabrication. The 6-minute mixing time was closer to the typical 4-minute mixing time for portland cement concrete specimens. While mixing the alkali-activated concrete at the precasting plant, the mixer had to be stopped twice to open an access door and manually add the activators. The sodium hydroxide flake was packaged in 25 kg (55 lb) bags, which were emptied directly into the mixer. The sodium silicate came in a 208 L (55 gal.) barrel that was pumped into buckets and weighed according to the batch proportions before mixing. Beyond this manual step of adding the activators, a plant operator completed the rest of the batching and mixing.

In this research, the precasting plant mixer was cleaned before and after batching the alkali-activated concrete by running an empty load of coarse aggregate and water through the machinery. Tempest et al.[3] noted that mixing equipment must be cleaned thoroughly when switching between portland cement concrete and alkali-activated concrete production. This is because of the difference between calcium-rich portland cement and fly ash. The alkali-activated concrete could set faster if enough portland cement were accidentally introduced to the mixture. The alkali-activated concrete beams were cured over the weekend for 67 hours, like the portland cement concrete beams. Temperatures recorded by seven thermocouples placed along the length of the alkali-activated concrete beams and inside the concrete cross section indicated that the beams maintained an internal temperature above 49°C (120°F) for a minimum of 54 hours (**Fig. 5**); however, the alkali-activated concrete took 14 hours to reach a temperature of 49°C, which was much longer than the 8.5 hours it took the portland cement concrete specimens to achieve the same temperature in the same environment.

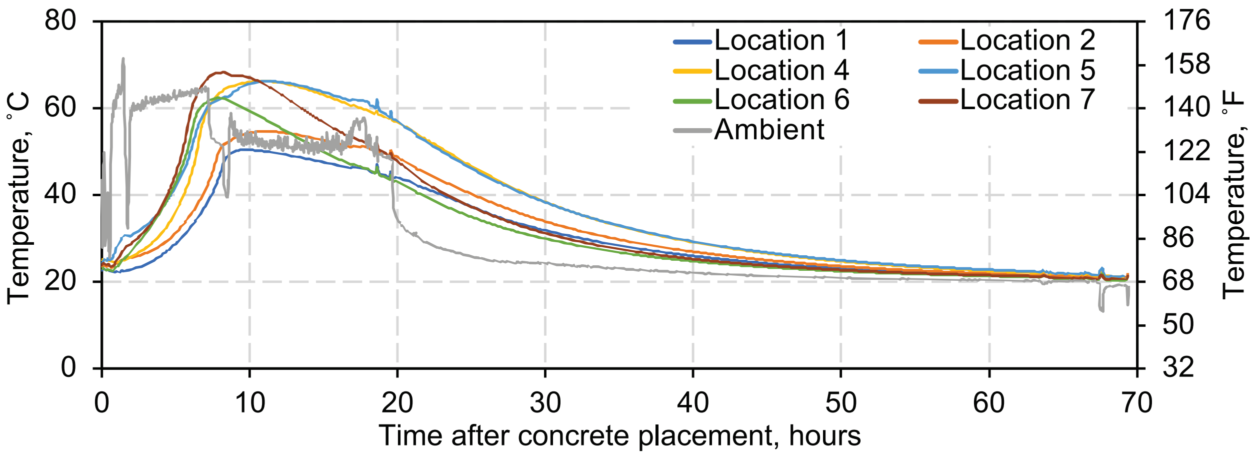

Figure 4. Temperature change over time recorded by thermocouples during portland cement concrete beam curing that only used supplemental forced-air heaters.

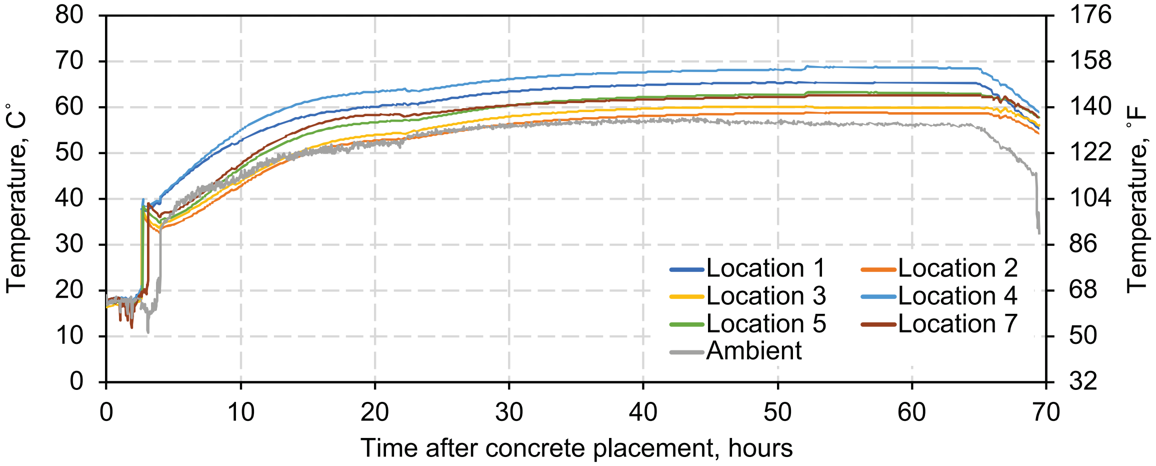

Figure 5. Temperature change over time recorded by thermocouples during alkali-activated concrete beam curing that only used the heated bed and insulated blankets.


Batch 1

Batch 2

Figure 6. Alkali-activated concrete from batches 1 and 2 before and after consolidation.

During concrete placement, it was observed that the alkali-activated concrete had less workability compared with the portland cement concrete (**Fig. 6**), but it was easily consolidated using vibrating equipment. The alkali-activated concrete beams were vibrated with handheld concrete vibrators and finished with screeds and trowels. Workers had difficulty finishing the surface of both alkali-activated concrete batches due to an insufficient set time (that is, less than the required 45 minutes), which resulted in a rough finished surface compared with the smooth finished surface of the portland cement concrete (**Fig. 7**). The alkali-activated concrete set time should be increased to allow for adequate workability, which could be accomplished with set-retarding admixtures like those used in other research.[8,27,31,32] During the detensioning process, prestressing force was transferred to the concrete by simultaneously cutting one strand at a time with torches, with one torch at each end of the beam.

Mechanical property specimens that were used to determine the compressive strength, modulus of elasticity, modulus of rupture, and split-cylinder tensile strength of the alkali-activated concrete and portland cement concrete were fabricated at the same time as the full-scale beams. The cylinders were 102 mm diameter × 203 mm tall (4 in. × 8 in.), and the modulus of rupture beams were 152 mm wide × 152 mm tall × 533 mm long (6 in. × 6 in. × 21 in.). The accompanying cylinders and modulus of rupture beams were cured within the same tent-shaped setup as the precast concrete beams.

Laboratory testing and results

Test setup and procedure

All alkali-activated concrete beams were tested between the ages of 62 and 67 days, and the accompanying mechanical

Alkali-activated concrete

Portland cement concrete

Figure 7. Rough finished surface of the alkali-activated concrete compared with the smooth finished surface of the portland cement concrete.

Flexure beams

Shear beams

Figure 8. Example test setup and observed failure mode for the flexure beams and shear beams.

specimens were tested at an age of 66 days. During testing, the beams were simply supported and had a span length of 5.49 m (18 ft). Each end of a beam rested on neoprene pads that were 127 mm (5 in.) long and 254 mm (10 in.) wide (the same as the beam width). Load was applied to the beams using a 489 kN (110 kip) actuator in displacement-controlled mode. A 445 kN (100 kip) load cell and an internal linear variable displacement transducer were used to measure applied load and displacement, respectively.

During flexural testing, a spreader beam split the applied load into two point loads equidistant from the center of the beam (**Fig. 8**). The distance between the applied loads was 1.16 m (3.8 ft). One load application point was treated as a pin, and the other was treated as a roller. Flexural failure was characterized by visually observing vertical cracks at the bottom of the beam and compression failure on the top surface of the beam. Shear testing was conducted with a single applied point load located 1.46 m (4.79 ft) from the nearest support (Fig. 8), which created a shear span–to–depth ratio of 2.5. Shear failure was characterized by visually observing a diagonal crack extending from the point load toward the nearest support.

Mechanical properties

The compressive strength of alkali-activated concrete and portland cement concrete was determined at 3 (transfer), 7, 28, 56, and 90 days. Typically, the average compressive strength was determined from three cylinders, though some data points only included data averaged from two cylinders. Additional cylinders were tested to determine the compressive strength at two additional times: on or near the beam test dates and at varying times throughout the weekend curing time for alkali-activated concrete cylinders, to monitor the strength gain. Data in **Table 4** indicate that the alkali-activated concrete cylinders did not reach the specified transfer strength of 24.1 MPa (3500 psi) but that the portland cement concrete cylinders did; however, the strands did not slip in any specimens during detensioning, which indicated that full transfer of the prestressing force to the alkali-activated concrete beams was achieved. Furthermore, no cracking near the ends of the beams was observed after transfer. Results in the literature suggested that curing alkali-activated concrete more than 48 hours only provides minimal additional compressive strength,[3,12] but the alkali-activated concrete in this research gained 21% more compressive strength between 48

Table 4. Compressive strength of alkali-activated concrete cylinders at varying times during curing compared with the portland cement concrete compressive strength at transfer

Property	Alkali-activated concrete						Portland cement concrete
Time cured, hours	18	24	30	43	48	67 (transfer)	80 (transfer)
Compressive strength, MPa	5.3	8.0	11.1	15.8	16.6	20.1	50.7

Note: 1 MPa = 0.145 ksi.

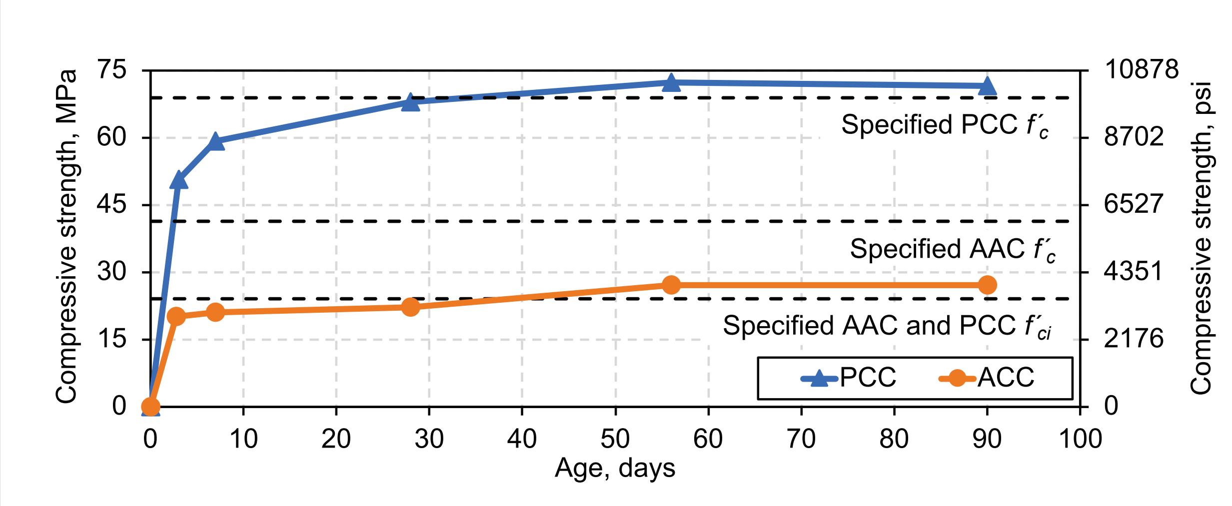

Figure 9. Compressive strength of precast portland cement concrete and alkali-activated concrete at varying ages. Note: AAC = alkali-activated concrete; f'_c = concrete compressive strength; f'_{ci} = initial concrete compressive strength at transfer; PCC = portland cement concrete.

and 67 hours. This may be because the lower curing temperature (49°C [120°F] at the plant compared with 60°C [140°F] reported as the minimum required temperature in the literature[15]) created a slower alkali activation reaction, which resulted in slower compressive strength gain.

Results in **Fig. 9** show that the alkali-activated concrete and portland cement concrete both exhibited compressive strength gain after initial heat curing, even though alkali-activated concrete does not typically gain much strength after heat curing stops. The compressive strength of portland cement concrete increased 41%, from 50.7 to 71.6 MPa (7350 to 10,380 psi), between 3 (transfer) and 90 days, and the compressive strength of alkali-activated concrete increased 35%, from 20.1 to 27.2 MPa (2910 to 3940 psi), between transfer and 94 days. However, the alkali-activated concrete ultimately did not reach the specified 28-day compressive strength of 41.4 MPa (6000 psi), which was likely due to the extra water added to the alkali-activated concrete batches for workability. Additional compressive strength could have likely been realized by having a better understanding of the *w/s* of the batches and better control of the heat curing system. Use of the supplemental forced-air heaters to rapidly increase the initial curing temperature likely would have helped the alkali-activated concrete achieve the specified strength at transfer and at 28 days.

To this end, data from two mortar batches demonstrated the effect of different w/s. The batches were made with a *w/s* of 0.48 and 0.40, respectively. After 18 hours of curing at 54°C (129°F), the compressive strengths of the mixtures were 23.3 and 34.6 MPa (3380 and 5020 psi), respectively. The alkali-activated concrete specimens cured at the local precasting plant were above 49°C (120°F) for 54 hours, so it is reasonable to assume that the 3-day compressive strength of the alkali-activated concrete could have been near or above 24.1 to 31.0 MPa (3500 to 4500 psi) if the *w/s* had been better controlled while making the batches. The lab alkali-activated concrete cylinder batches that were cured at 49°C for 48 and 72 hours reached initial (transfer) compressive strengths of 25.2 and 31.1 MPa (3650 and 4510 psi).

Tests to characterize modulus of elasticity, splitting tensile strength, and modulus of rupture were conducted within a few days of the full-scale beam test dates, and the results are reported in **Table 5**. The measured mechanical property results were compared with predictions made using ACI 318 equations for portland cement concrete;[4,23] the modulus of elasticity and modulus of rupture predictions were made with ACI 318-19, and the splitting tensile strength predictions were made with ACI 318-14 (due to changes in the code commentary). The measured mechanical properties were typically recorded as an average of three tests conducted on any given specimen type. Alkali-activated concrete had a lower modulus of elasticity than portland cement concrete in this research, which corroborated results from Yost et al.[6] and Hardjito et al.,[33] who compared results to ACI 318-08[24] and Australian standard AS1012.17,[34] respectively. Splitting tensile results indicated that both the alkali-activated concrete and portland cement concrete had approximately the same tensile strength as predicted. Modulus-of-rupture results for the alkali-activated concrete were less than predicted, and the portland cement concrete results were higher than predicted. Table 5 also contains ratios of the measured values to the square root of the measured compressive strength, which is a common form of the

Table 5. Measured results compared with results predicted with ACI 318 for modulus of elasticity, splitting tensile strength, and modulus of rupture of normalweight alkali-activated concrete and portland cement concrete

Property	Alkali-activated concrete			Portland cement concrete		
	Measured	ACI 318	Measured/ACI 318	Measured	ACI 318	Measured/ACI 318
Compressive strength f'_c, MPa	27.0	n/a	n/a	70.9	n/a	n/a
Modulus of elasticity E_c, GPa $E_c = 4.7\sqrt{f'_c}$ (ACI 318-19)	22.0	24.6	0.89	35.1	39.9	0.88
$\frac{E_c}{\sqrt{f'_c}}$	4.23	4.7	n/a	4.17	4.7	n/a
Splitting tensile strength f_{ct}, MPa $f_{ct} = 0.56\sqrt{f'_c}$ (ACI 318-14)	2.79	2.89	0.97	4.70	4.69	1.00
$\frac{f_{ct}}{\sqrt{f'_c}}$	0.54	0.56	n/a	0.56	0.56	n/a
Modulus of rupture f_r, MPa $f_r = 0.62\sqrt{f'_c}$ (ACI 318-19)	2.36	3.24	0.73	5.67	5.25	1.08
$\frac{f_r}{\sqrt{f'_c}}$	0.45	0.62	n/a	0.67	0.62	n/a

Note: ACI 318 = ACI Committee 318 (2014) and ACI Committee 318 (2019). n/a = not applicable. 1 MPa = 0.145 ksi.

Table 6. Predicted and measured flexure and shear capacities for four alkali-activated concrete beams

Alkali-activated concrete beam	Failure mode	Flexure, kN-m			Shear, kN		
		ACI 318-19	Measured	Measured/ ACI 318-19	ACI 318-19	Measured	Measured/ ACI 318-19
1	Flexure	279	306	1.10	n/a	n/a	n/a
2	Shear	n/a	n/a	n/a	129	127	0.98
3	Shear	n/a	n/a	n/a	129	124	0.96
4	Shear	n/a	n/a	n/a	129	185	1.43

Note: ACI 318-19 = ACI Committee 318 (2019); n/a = not applicable.

equations for modulus of elasticity and modulus of rupture in ACI 318-19[4] and splitting tensile strength in ACI 318-14.[23]

Beam flexure and shear capacity

Four alkali-activated concrete beams were tested to characterize the capacity in flexure (one beam) and shear (three beams). **Table 6** lists the measured capacities that were compared with values predicted using ACI 318-19.[4] The predicted flexural capacity was determined using measured mechanical properties and conventional flexural assumptions for prestressed concrete beams as outlined in ACI 318-19 sections 22.2 and 22.3. The predicted shear capacity was determined using measured mechanical properties and the lesser of the flexure-shear and web-shear strengths, as outlined in ACI 318-19 sections 22.5 and 22.5.6.3. The flexural capacity of the alkali-activated concrete beam was approximately 10% more than the value predicted using ACI 318-19. Two of the three alkali-activated concrete beams had similar shear capacity, and the shear capacity of the third beam was 47% higher. The higher-capacity beam was made from a combination of alkali-activated concrete from batches 1 and 2, whereas the lower-capacity beams were made from alkali-activated concrete batch 2. Batch 1 had a lower *w/s* than batch 2, which was the most likely cause of the higher shear capacity of the third beam. Furthermore, the splitting tensile strength of the alkali-activated concrete was lower than the ACI 318-14 prediction by approximately 3%, which correlates with the lower shear capacity (by 2% to 4%) of the two beams. Ultimately, flexural capacity predicted with ACI 318-19 was conservative for one beam, and shear capacity predicted with ACI 318-19 was not conservative for two of the three alkali-activated concrete beams.

Conclusion

Mixture proportions for an alkali-activated concrete suitable for precast concrete production were developed. Mortar and concrete mixture proportions were optimized for use during production in a precasting plant while maintaining the necessary properties for structural building materials. Precast, prestressed concrete beams were designed, fabricated, and tested in the laboratory to verify the suitability of ACI 318-19 code provisions for designing structures using alkali-activated concrete. The results of this research highlighted that alkali-activated concrete could be designed for flexure using ACI 318-19 code equations formulated for portland cement concrete, but the data were limited; alkali-activated concrete shear capacity test results were not conservative when compared with current code equations for portland cement concrete. Furthermore, some challenges and roadblocks associated with designing and developing alkali-activated concrete for use in precast concrete components were encountered. Additional research is needed to realize the full potential of alkali-activated concrete by making improvements to the design and fabrication procedures. Some observations of note and recommendations for future work are described as follows:

- Due to the reduced availability of fly ash, other aluminosilicate precursors, including metakaolin or other natural pozzolans, should be explored. Binary or ternary blends of precursors should also be investigated. Many of the methods used in this research can be applied to other alkali-activated concrete mixtures using different precursors. Combinations of portland cement and alkali-activated binders should also be considered, which could help achieve high early strength.

- The laboratory mixing procedure that led to an acceptable workability and set time required mixing the aggregates and fly ash before adding the liquids and activators. Laboratory testing showed that using a sodium hydroxide solution instead of solids could increase the initial compressive strength of alkali-activated concrete by 4.83 MPa (700 psi) regardless of curing time. In the precasting plant, the unplanned use of extra water to achieve adequate workability was not worth the decrease in strength (up to a 33% reduction), even though the alkali-activated concrete had good workability. The use of a retarding admixture in alkali-activated concrete could be useful to extend the set time and allow for finishing of the concrete products. Mixture proportions using lower concentrations of sodium hydroxide should be investigated for safety and environmental reasons. Automating the batching of the caustic activators would minimize human handling, but it would require the precasting plant to store sodium hydroxide solution in large quantities.

- The structural performance of the full-scale precast, prestressed alkali-activated concrete beams was predicted using ACI 318-19[4] methods for flexural behavior (conservatively) and shear behavior (slightly unconservative). This research confirmed that it is possible to make alkali-activated concrete using current technology that is available at precasting plants, but further testing is needed for commercialization.

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Notation

E_c = modulus of elasticity of concrete

f'_c = concrete compressive strength

f'_{ci} = initial concrete compressive strength at transfer

f_{ct} = splitting tensile strength of concrete

f_r = modulus of rupture

w/s = water-to-solids ratio

About the authors

Grant P. Magnuson is a consulting engineer for Simpson Gumpertz & Heger in Chicago, Ill. His experience includes assessing and designing repairs for deteriorated concrete, steel, wood, and masonry structures, and designing new structures. He is a former undergraduate and graduate student in the Civil Engineering Department at the University of Minnesota Duluth.

Mary U. Christiansen, PhD, LEED AP, is an associate professor in the Civil Engineering Department at the University of Minnesota Duluth. Her research interests include alternative supplementary cementitious materials in portland cement concrete, the design and characterization of alkali-activated cements, and development of nonproprietary ultra-high-performance concrete.

Benjamin Z. Dymond, PhD, is an associate professor in the Department of Civil Engineering, Construction Management, and Environmental Engineering at Northern Arizona University. His research interests include design and analysis of concrete structural systems and their components, destructive experimental investigations, short-term field monitoring experiments, and engineering education.

Abstract

Alkali-activated concrete is an environmentally friendly alternative to portland cement concrete that contains no portland cement and typically includes recycled waste materials in the binder. The precast concrete industry is a logical application for this innovative material because external heat is typically required during the initial cure for alkali-activated concrete to gain strength; however, limited data are available on the structural performance of full-scale precast concrete members fabricated with alkali-activated concrete. This research developed and implemented a fly-ash-based alkali-activated concrete mixture suitable for making precast, prestressed concrete beams at a precasting plant. More than 40 mortar mixtures were investigated, and the most suitable mixture design was scaled to make alkali-activated concrete beams and mechanical property specimens. Similar portland cement concrete mechanical property specimens were produced for comparison. Results indicated that the full-scale alkali-activated concrete beam performance varied compared with code-based predictions. Additional research is needed to realize the full potential of alkali-activated concrete by making improvements to the design and fabrication procedures. Results and lessons learned from this project related to adapting an alkali-activated concrete mixture design to fit within production constraints for precast, prestressed concrete were informative.

Keywords

Alkali-activated concrete, concrete mixture design, flexural capacity, mixing procedure, mixture proportions, portland cement concrete, shear capacity.

Review policy

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