Structural Concrete Using Alternative Cements

A supplement to the commentary to ACI 318-19

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Environmental concerns arising from the energy required to produce portland cement have led the industry to develop alternative materials to reduce or eliminate portland cement content in concrete. As these alternative materials are proposed, a new burden is placed on material suppliers, concrete producers, and design professionals. Suppliers must provide detailed information proving their materials will behave in a manner consistent with codified structural design criteria and construction techniques that are based on experience with portland cement concrete. Producers must show they can use these alternative cements to produce consistent concrete that behaves as expected during batching, transportation, and placing. Design professionals must identify concrete properties that are needed to meet performance requirements and ensure that sufficient data are made available to have the confidence that structural design expectations can be successfully met.

The 2019 edition of the ACI 318 Building Code[1] has added provisions allowing the use of alternative cements. This article identifies issues that need to be considered to allow the concrete industry to use these new materials with confidence that code provisions are being met. Much of this information may be time-consuming to generate initially, but once created should have applicability for many projects. Additional documentation may need to be developed to address project-specific needs.

Structural concrete has historically been produced, tested, and placed in structures using portland cement. Over the years, beneficial supplemental cementitious materials such as fly ash, slag cement, and silica fume have been tested extensively so they could be reliably included in the various codes and standards used in design and construction. A similar evaluation and testing regimen is now necessary to implement alternative cements with confidence.

What Are Alternative Cements?

In 2015, Hicks et al.[2] published an overview of alternative cements. Recently, ACI ITG-10 has prepared two documents relating to alternative cements: "Practitioner's Guide for Alternative Cements"[3] and "Report on Alternative Cements."[4] The ITG publications contain the following definition for alternative cement:

alternative cement—an inorganic cement that can be used as a complete replacement for portland or blended hydraulic cements, and that is not covered by applicable specifications for portland or blended hydraulic cements.

Key elements in this definition are that the materials can be used as a complete replacement for portland cement and that the cements are not covered by existing specifications.

Cements that fall within this definition include geopolymers, activated glassy cements, activated fly ash cements, activated slag cements, calcium aluminate cements, calcium sulfoaluminate cements, magnesia cements, and CO_2-cured cement. A complete listing and description of each alternative cement is included in the ITG-10 Report.[4] A material, such as fly ash or slag cement, that is covered by a specification but gains strength through a mechanism other than a hydraulic reaction, is included as an alternative cement. The reference by Hicks et al.[2] states that several of the listed cements are covered by ASTM C1157/C1157M.[5] This assertion is not correct because the cements are not hydraulic.

Background

Cements currently being used are qualified using ASTM C150/C150M,[6] ASTM C595/C595M,[7] ASTM C1157/C1157M, or ASTM C1600/C1600M.[8] ACI 318 has long relied on ASTM standards to define the requirements of cementitious materials, with all of these standards currently recognized with the exception of ASTM C1600/C1600M. The material specifications in ACI 318 apply to hydraulic cement, which is defined as a cement that sets and hardens by chemical reaction with water and is capable of doing so under water. Many alternative cements do not rely on a chemical reaction with water, so these specifications are not applicable.

Materials that do not qualify as hydraulic cement cannot be qualified under the current material specifications.

Additionally, these ASTM materials standards apply to the cementitious material alone or in a mortar. None of the tests are done on a mixture that might be considered structural concrete. Therefore, even if an alternative cement meets the chemical or physical requirements of one of these ASTM standards, it may not automatically be appropriate for use in creating structural concrete. The assumption that a cement qualifying under one of the material specifications will result in structural concrete with the same properties as that produced with portland cement may be erroneous.

Given that alternative cements are defined as not meeting an existing standard, a reasonable course of action is to consider performance expectations. While the need for many attributes of structural concrete will vary from project to project, there are fundamental attributes that will always be required.

Project Implementation Impact

There are two likely scenarios concerning how an alternative cement may be incorporated into a project. The first is where the project team decides in advance to include it. In this case, general information on the required characteristics of the alternative cement could be included in the contract documents, along with identification of appropriate submittals to validate the assumptions of material characteristics. Fundamental material information would be available, and any project-specific issues would be identified and resolved early in the design process.

An equally probable scenario is the proposal of an alternative cement as a substitute for the specified cementitious material during the bidding or construction phase of a project. In this case, the structural design is already complete. Design assumptions have to be validated. The supplier's ability to have data already available to confirm the fundamental structural characteristics becomes critical to avoid delays. A risk remains that some additional data may be needed to address project-specific performance requirements and that delays could occur while developing appropriate data.

In either scenario, much of the same type of information will be needed. It would be beneficial if material suppliers had as much data as possible prepared well in advance. Aggregates used to demonstrate compliance should be similar to those that will be used on the project. Sufficient time must also be allowed for the design team to review the data submitted.

Materials, Design, and Construction Considerations

The following sections list groups of properties that should be established and reviewed in order to use the new materials. Numerous reports and guides in the ACI Collection address these issues, but they are all founded upon historical experience with portland cement-based structural concrete. ACI 225R-16[9] is particularly helpful in assessing the effect of cement on various attributes, especially Chapter 7—Influence of Cement on Concrete Properties. It is beyond the scope of this article to review all aspects of the influence of cement, but the report indicates that cement has a significant influence on thermal cracking; placeability; strength; volume stability; elastic properties; creep; permeability; corrosion of metals; reactions with aggregates; and resistance to freezing and thawing, chemicals, or high temperatures. At least a rudimentary knowledge of the effects of an alternative cement on these characteristics will be required to assess application suitability to a specific project.

Materials characterization

Basic materials properties, similar to those required by existing standards, must be established to ensure uniformity of supply of a given material. According to ASTM C150/C150M, these properties include:

- Chemical composition;
- Loss on ignition;
- Air content of mortar;
- Fineness (or other measure of particle size);
- Autoclave expansion;
- Compressive strength;
- Heat of hydration;
- Sulfate resistance; and
- Other properties dependent on actual material.

Additionally, it is important to know how the material reacts to develop hardened properties. Specifically, is the material hydraulic, or does it harden through another mechanism? If the material is hydraulic, it may fall under ASTM C1157/C1157M. Another consideration is the response of the material to water content. For nonhydraulic materials, the relationships between water-cementitious materials ratio (*w/cm*) and strength and durability may not be the same as for portland cement concrete. This point has implications for design and concrete production as well as specifying durability in accordance with Chapter 19 of ACI 318.

Note that we, the authors of the current article, disagree with Hicks et al.[2] on the assertion that several clearly nonhydraulic materials meet the requirements of ASTM C1157/C1157M and are therefore suitable for use in concrete covered by ACI 318.

Concrete production

Concrete made using the selected alternative cement must be tested to determine how production may have to be modified, if at all. The closer the material is to being "no changes required," the greater the potential for successful production. The following topics warrant consideration:

- Safety;
- Storage of materials;
- Mixture proportioning;
- Compatibility with admixtures and ability to entrain air;
- Mixing time and restrictions on time in the mixer drum;
- Restrictions on retempering; and
- Testing of fresh and hardened concrete properties.

Structural design and performance

The following properties must be addressed:

- Axial, compressive, flexural, shear, and torsional strength;
- Ultimate strain and stress-strain relationship;
- Volume change properties (drying, thermal, creep, and shrinkage);
- Modulus of elasticity;
- Bond of reinforcement; and
- Strain compatibility of concrete and reinforcement.

ACI 318 defines the design requirements for structural concrete to ensure public safety. A brief review of concrete properties that affect each strength consideration is relevant to assessing the applicability of an alternative cement.

Axial strength is directly related to compressive strength, and flexural strength is marginally affected by concrete strength, at least within a reasonable range. The compressive strain at nominal strength is assumed as 0.003. Ideally, the supplier of an alternative cement would have data demonstrating the applicability of the axial and flexural design provisions in ACI 318. Structural reliability must be similar to that for portland cement concrete. Historically, ACI 318 has implied that the risk of failure to meet strength requirements should be less than 1 in 100. Alternative materials must also be able to meet this requirement. A minimum level of pre-project testing specific to the project would be appropriate to confirm that project aggregates do not adversely influence concrete performance. Traditional compression testing in accordance with ASTM C39/C39M[10] plus modulus of elasticity testing in accordance with ASTM C469/C469M[11] would be appropriate to demonstrate compressive strength, compressive failure strain, modulus of elasticity, and strain compatibility with bonded reinforcement.

Shear and torsional strength are a function of the tensile strength of the concrete. Conventional shear and torsion design is based on the assumption that the concrete will resist a certain level of shear or torsion after cracking. Reinforcement is selected based on the demand in excess of the concrete capacity. Ideally, the supplier of an alternative cement would have data demonstrating either the applicability of shear and torsional design provisions in ACI 318 or a documented alternative shear and torsional design approach. A minimum level of pre-project testing specific to the project would be appropriate to confirm that project aggregates do not adversely influence concrete performance. It would be reasonable to require performance of splitting tensile strength tests in accordance with ASTM C496/C496M.[12]

Two other properties significant to structural design are volume change and bond of reinforcement. Establishing properties such as creep and shrinkage plus the many issues related to bond of reinforcement would be a significant challenge to execute on a project-specific basis, so advance testing is necessary. Project-specific testing using project aggregates may be necessary if creep and shrinkage are critical design issues for the project.

Similarly, documentation should be available to demonstrate that bond of reinforcement in accordance with the provisions of ACI 318 can be achieved or that alternative design procedures are required. This documentation may be required to confirm development lengths, splice lengths, hook embedment, or, in the case of bonded prestressed concrete, transfer lengths.

Additional design considerations

In addition, some projects may require consideration of the following attributes:

- Protection of embedded and attached metals;
- Cracking characteristics;
- Serviceability and deflection prediction;
- Fire resistance; and
- Anchoring to concrete.

Serviceability will be a consideration for most projects. The modulus of elasticity used for deflection calculations can be measured directly as described earlier, but cracking characteristics may deserve separate definition if serviceability is critical. Modulus of rupture testing in accordance with ASTM C78/C78M[13] can be used to verify whether ACI 318 provisions concerning determining effective moment of inertia and reinforcement spacing limitations remain applicable to alternative cements.

Fire-resistance performance in the form of heat transmission data and thermal gradient profiles are required to allow for rational fire-resistance calculations. If such data were in reasonable agreement with portland cement concrete data, extrapolation to system fire resistance as described in ACI 216.1-14[14] would be possible. If reasonable agreement is not demonstrated, specific fire testing may be required.

Anchoring to concrete is a very specific consideration, but many projects will have embedments anchored with headed studs or proprietary anchorage components. Most projects require post-installed anchors. Concrete breakout strength in anchoring situations is primarily a function of concrete tensile strength. If splitting tensile testing is required, a reasonably accurate assessment of concrete breakout strength can be established through a comparison to expectations in portland cement concrete. However, adhesive anchors controlled by bond may have usable capacities directly affected by the cementitious material used. Lack of documentation for combinations of adhesives and cements creates a significant implementation barrier for the use of these connectors. Project-specific qualification testing can be done in accordance with ACI 355.4-11,[15] but it may require a large installation to justify the cost.

Durability

ACI 318 addresses durability from the perspective of anticipated exposure categories. Within each category are exposure classes that have varying requirements depending upon severity of exposure. The exposure categories are:

- Exposure to freezing and thawing, including surface scaling and loss of strength in the mortar portion of the concrete;

- Exposure to sulfates in soil or groundwater that results in deterioration due to ettringite formation, which causes expansion and cracking, or gypsum formation, which causes softening and loss of strength;
- In contact with water, which includes provisions for permeability and preventing alkali-silica reactions. Alkali-silica reaction causes cracking as a result of expansion from the formation of reaction by-products; and
- Corrosion protection of reinforcement, which may result in delamination of concrete and strength reduction due to loss of reinforcement area.

Proven solutions are available to prevent deterioration for each of the four durability categories; however, all have been developed for portland cement concrete based upon testing using ASTM standard methods. Concrete produced with alternative cements may react differently, with effects ranging from eliminating concern for a particular condition to rendering historical solutions invalid.

Even for portland cement concrete, solutions are not based on quantitative evaluations of deterioration severity. For example, surface scaling due to freezing and thawing is not measured and then mitigated. Rather, limits are placed on *w/cm*, compressive strength, and air content. Because no scaling acceptance criteria have been established, there is no way to quantitatively evaluate a concrete produced with an alternative cement. While scaling is used as an example here, the same will be true for many of the durability conditions.

As a result, the burden of demonstrating durability will fall to the supplier of the alternative cement. One course of action would be to carry out comparative testing to evaluate similar structural concretes produced with an alternative cement versus portland cement-based mixtures. Parallel tests of resistant portland cement concrete and alternative-cement concrete behaving similarly could demonstrate equivalency. Durability testing by its nature is a long-term undertaking that would be very difficult to do efficiently on a project-specific basis, so gathering this data well in advance is critically important. Additionally, it must be shown that the ASTM test methods are suitable for use with the alternative material (for more on this, refer to the section on "Testing Concrete Properties").

Construction

Current construction procedures were developed and refined based on experience with portland cement concrete. These techniques may need to be evaluated for suitability with alternative-cement concrete. The supplier of the alternative cement should be able to confirm current procedures are viable or, if not, that alternative procedures have been developed. Addressing these issues can be done with test placements or with placements in locations on a project without life-safety concerns. Issues to consider include:
- Placeability;
- Pumping and other concrete conveying;
- Workability and finishing characteristics;
- Control of internal concrete temperature;
- Segregation avoidance and consolidation techniques;
- Slump loss and setting characteristics;
- Wet weather placement;
- Cold and hot weather concrete placement;
- Finishing techniques;
- Bonding for multicourse slabs;
- Initial and final curing;
- Compatibility with curing compounds; and
- Contraction joint spacing.

Testing Concrete Properties

ITG 10.1R points out there may be significant differences in testing concrete mixtures produced using portland cement and an alternative cement. These differences may be more significant for testing materials and durability properties than for testing hardened concrete properties. Following are several examples of testing concerns (for additional examples, refer to Reference 3):
- Compressive strength testing of cubes—ASTM C109/C109M[16] requires a *w/cm* of 0.485 for preparation of cubes for testing. This requirement obviously does not apply for materials that do not depend on water for the development of compressive strength;
- Freezing-and-thawing durability—ASTM C666/C666M[17] requires wet curing of samples prior to testing. Again, this requirement may not be suitable for all materials;
- Curing of specimens before testing—ASTM C31/C31M[18] also requires wet curing of specimens for compressive strength testing. Same concerns regarding curing apply; and
- Compressive strength testing—ASTM C39/C39M is probably directly applicable, curing of specimens aside.

Test reports for alternative cement or concrete made with alternative cement must clearly indicate any modifications made to the standard test method.

ACI 318 and Alternative Cements

The use of alternative cements does not change the basic requirements of ACI 318. In particular, the performance and durability requirements of Chapter 19 are not changed by the use of alternative cements. How these properties are achieved may be substantially different from the assumptions in Chapter 19. Testing for required project-specific concrete properties must be conducted.

As would be expected, ACI Committee 318 has taken a very conservative approach to approving the use of alternative cements in structural concrete. The Code warns the designer that data must be available to show that the proposed concrete mixture incorporating the alternative cement complies with all project requirements. The designer is further warned that the *w/cm* of these materials may not have the same relationship to strength and durability as is expected for portland cement-based concrete mixtures.

First, the Code maintains the same definition as shown from the ITG document.

Second, in the code provisions in Section 26.4, covering materials for use in concrete, the Code and commentary state:

26.4.1.1.1 Compliance requirements [underlined material indicates a change to the Code or commentary]:

(a) Cementitious materials shall conform to the specifications in Table 26.4.1.1.1(a), except as permitted in 26.4.1.1.1(b). [Note that this table lists approved cementitious materials by ASTM standard.]

(b) Alternative cements shall be permitted if approved by the licensed design professional and the building official. Approval shall be based upon test data documenting that the proposed concrete mixture made with the alternative cement meets the performance requirements for the application including structural, fire, and durability.

R26.4.1.1.1(b) Provisions for strength and durability in Chapter 19 and many requirements in Chapter 26 are based on test data and experience using concretes made with cementitious materials meeting the specifications in Table 26.4.1.1.1(a).

Some alternative cements may not be suitable for use in structural concrete covered by this Code. Therefore, requirements are included for evaluating the suitability of alternative cements. Recommendations for concrete properties to be evaluated are discussed in Becker et al. (2019), ITG-10R-18, and ITG-10.1R-xx.

In addition to test data, documentation of prior successful use of the proposed alternative cement in structural concrete for conditions with essentially equivalent performance requirements as those of the project can be helpful to the licensed design professional determining whether to allow use of the material.

Lastly, an additional warning is included in the commentary to the design information provision for concrete mixtures [again, underlined material indicates a change]:

R26.4.2.1(a)(4) In accordance with Table 19.3.2.1, the ***w/cm*** is based on all cementitious and supplementary cementitious materials in the concrete mixture. The ***w/cm*** of concrete made with alternative cements may not reflect the strength and durability characteristics of the concrete made with portland cement and supplementary cementitious materials permitted in Table 26.4.1.1.1(a). As noted in R26.4.1.1.1(b), it is imperative that testing be conducted to determine the performance of concrete made with alternative cements and to develop appropriate project specification.

Summary

The concrete industry's efforts to become more environmentally sustainable have led to the development of alternative cements to replace portland cement in concrete mixtures. ACI 318 now allows use of these materials, but it includes strong warnings to the designer. Current design and construction methodologies, which were developed over many years for portland cement-based mixtures, may not necessarily be appropriate for use with some alternative cements. In order to incorporate these materials properly, all project stakeholders must act in a responsible way to confirm that current design and construction procedures are appropriate for the new materials, and if not, develop new procedures for these materials. Suppliers must conduct appropriate laboratory and field testing, with the end result being a detailed review that concrete producers, design professionals, and contractors can rely upon.

Although this article is primarily focused on the use of alternative cements, the concerns expressed are also applicable for other new materials intended for use in concrete, such as alternative aggregate materials or reinforcement systems.

References

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16. ASTM C109/C109M-16a, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)," ASTM International, West Conshohocken, PA.

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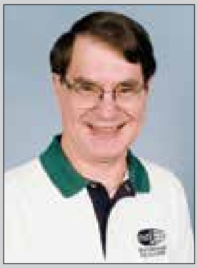

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