Building Code Compliance of Structural Concrete with Lightweight Synthetic Particles

By Mahmut Ekenel, Ph.D., P.E.

Manufacturers are constantly trying to develop new construction materials that may enable them to produce structural systems that are less labor-intensive, more environmentally friendly, or easier to construct. One of these innovations is an alternative material used to produce reduced-density concrete. In recent years, strength-to-weight ratio of concrete has been of interest to manufacturers, since dead weight represents a very large portion of the design load in concrete construction. Higher strength-to-weight ratio of concrete used in the construction may result in structural efficiency, reduced dead load of the structure, reduced project costs, and easier transportation and handling of the concrete. Higher strength-to-weight ratio may even cause a reduction in the number and size of the steel reinforcements, by reducing the design load.

Conventionally, reduced-density concrete can be produced by replacing normal-weight aggregate with lightweight particles in partial increments or as full replacement, or by introducing air bubbles into concrete mixtures as in the cases of aerated concrete or air-entrained concrete. Since most of these techniques require special manufacturing processes or equipment, new techniques have been under investigation. One way of producing simple and relatively inexpensive reduced-density concrete that does not require special equipment is to use proprietary lightweight synthetic particles (polymer spheres) as a partial replacement for fine or coarse aggregate in the concrete mixture, as the density of polymer spheres is nearly negligible when compared to that of conventional aggregate. Polymer spheres are rigid, closed-cell plastic materials manufactured by suspension polymerization in water. In many cases, the polymer spheres utilize expanded polystyrene as the base polymer and are specially formulated and produced to be used in concrete mixtures. The advantages of using polymer spheres are that they are lightweight, have negligible absorption of water, improve insulating properties, and are inert with alkalis.

Because there are no design provisions in ACI 318, which is referenced by the *International Building Code* (IBC), for concrete mixtures with lightweight synthetic particles as aggregate replacement, an acceptance criteria has been developed to address building code compliance. The purpose of this acceptance criteria is to demonstrate that lightweight synthetic particles can be added to concrete as a partial replacement for conventional fine or coarse aggregate, to create a structural concrete while maintaining mechanical, durability and fire characteristics of concrete as defined by the building codes.

Literature Research

The first step in developing the acceptance criteria was to conduct a literature review to find out what has been done in regard to reduced-weight concrete with lightweight synthetic particles. Some of the research work can be summarized as follows:

In research conducted by Zaher Kuhail (2001), concrete with compressive strengths up to 3000 psi was achieved using polystyrene beads as aggregate replacement at dosages up to 1 lb/ft^3. Babu and Babu (2003) produced lightweight concrete by using expanded polystyrene beads as lightweight aggregate and silica fume as supplementary cementitious material. They reported that the chloride permeability and corrosion resistance of these concretes, even at a minimal silica fume content level, was observed to be significantly improved. Yamasaki et al. (1994) produced concrete using polystyrene beads with a diameter of less than 1⁄16 of an inch as an aggregate having no water absorbability. When produced with low water-to-binder ratio, this concrete showed excellent durability and thermal insulation properties. Miled et al. (2007) conducted research on particle size effects on expanded polystyrene (EPS) beads used in lightweight concrete and reported that the compressive strength of EPS lightweight concrete increases significantly with a decrease in EPS bead size for the same concrete porosity.

Chen and Liu (2004) showed that EPS concrete with a density range of 50-115 lb/ft^3 and a compressive strength range of 1500-3600 psi can be achieved by partially replacing coarse and fine aggregate with EPS beads. Babu and Babu (2004) studied the use of EPS beads as lightweight aggregate in both concrete and mortar containing fly ash replacement of 50 percent in the cementitious material. Their study indicated that the EPS mixtures produced with fly ash showed lower absorption values compared to control mixtures, and found to have a better chemical resistance. Bouvard et al. (2007) characterized the microstructural, mechanical and thermal features of EPS concretes with various densities. They concluded that EPS bead is a practical material for the building industry as lightening component of a supportive structure.

Alternative Materials Under the Building Code

In the United States, where the power to regulate construction is vested in local authorities, a system of model building codes is used. The purpose of the model building codes is to establish the minimum requirements to safeguard the public health and safety through structural strength. The IBC is the predominate model building code in the United States. The IBC has been adopted in all 50 states, the District of Columbia, Puerto Rico and the U.S. Virgin Islands, and by the Departments of Defense, State, and Commerce. The IBC permits manufacturers to demonstrate the code compliance of products not specifically described in the code itself. Section 104.11 of the IBC allows alternative materials, designs, methods of construction and equipment, provided that any such alternative has been approved by the code official. One common method of verifying the code compliance of materials that are alternatives to the materials specified in the code is through product testing in accordance with an acceptance criteria. An acceptance criteria outlines specific product sampling, testing and quality requirements to be fulfilled in order to obtain code-compliance verification (an evaluation report). An evaluation in accordance with an acceptance criteria is used to develop an evaluation report that offers code officials an independent resource for demonstrating code compliance, and structural design engineers a resource for preparing a design. An evaluation report provides a description of the material, information regarding its uses, guidelines for the designer (including seismic limitations), installation requirements, assembly conditions and curing guidelines for the contractor, and special inspection requirements for code officials. Tests required by the acceptance criteria are to be done by accredited laboratories selected by the manufacturer. Test laboratories that submit test results for evaluation must be accredited by an accreditation body in accordance with ISO 17025, and be accredited for the specific test standards, under consideration. The accreditation body must also determine that the laboratory has a robust quality system, to assure accuracy of reported results.

Acceptance Criteria (AC408) Requirements

The IBC references ACI 318 for design and production of structural concrete. Because there are no provisions in ACI 318 for design and production of concrete mixtures with lightweight synthetic particles as aggregate replacement, an acceptance criteria has been developed as a means to verify building code compliance (AC408: *Acceptance Criteria for Structural Concrete with Lightweight Synthetic Particles*). The purpose of AC408 is to demonstrate that lightweight synthetic particles (polymer spheres) can be added to concrete as a partial replacement for conventional fine or coarse aggregate, to create a structural concrete that maintains mechanical, durability and fire characteristics of concrete as defined by the building codes.

Material Properties

AC408 gives consideration to maximum replacement volume, and maximum size and density of synthetic particles that will be recognized in the evaluation report. AC408 requires synthetic particle properties, including maximum diameter and gradation, bulk density, and water absorption to be tested in accordance with ASTM C 136, ASTM C 29 and ASTM C 128, respectively. A series of tests is also required by AC408 to determine density and compressive strength of concrete that is to be evaluated under AC408. Concrete compressive strength measurement is to be in accordance with ASTM C 39. ASTM C 567 and ASTM C 138 are used to measure the equilibrium concrete density and unit weight, respectively. These properties are measured and reported to be used for flexural strength, splitting tensile strength and modulus of elasticity calculations.

Mechanical Properties

As required by AC408, concrete flexural strength is to be determined using ASTM C 78, and average test results are to be equal to or higher than the value obtained from $7.5\sqrt{f_c}$, where f_c is the measured compressive strength of the concrete in accordance with ASTM C 39. The reason measured compressive strength (f_c) is used in the comparison, as opposed to specified compressive strength (f'_c) as required for design by ACI 318, is to take a conservative approach. Also, for evaluation of concrete splitting tensile strength in accordance with ASTM C 496, AC408 requires the average results to be equal to or higher than the value obtained from $6.7\sqrt{f_c}$, where f_c is the measured compressive strength. Again, using measured compressive strength, as compared to specified compressive strength, is considered a conservative approach. In order to evaluate whether the addition of lightweight synthetic particles adversely affects the concrete modulus of elasticity, tests are required to be conducted in accordance with ASTM C 469, with the results to be equal to or higher than the values obtained from the ACI 318 formula: $w_c^{1.5} 33\sqrt{f_c}$, where f_c is the measured compressive strength and w_c is the measured unit weight in accordance with ASTM C 138.

Durability and Compatibility Requirements

Comparative tests in compliance with ASTM C 1581 are required by AC408 to be conducted to show that concrete with lightweight synthetic particles can maintain the same crack resistance as concrete without lightweight synthetic particles. The acceptance requirement is that the average age of cracking of specimens with lightweight synthetic particles must be at least equal to that for control specimens.

ASTM C 666 tests are used to determine the freeze-thaw resistance of concrete with lightweight synthetic particles, and an 80 percent durability factor is required after 300 cycles. A durability factor of 80 percent is usually expected from high-performance concrete samples; therefore, expecting an 80 percent durability factor from lightweight synthetic particle utilized concrete is considered conservative.

In order to determine whether the addition of lightweight synthetic particles to concrete has an adverse effect on bond strength of reinforcement, ASTM C 234 tests are required to be performed. Comparison tests are done with concrete specimens having equivalent compressive strengths. After the tests, equivalent or better bond strength is required from specimens with lightweight synthetic particles, as compared to control specimens without lightweight synthetic particles.

Fire-resistance and Combustibility

AC408 also contains two optional tests: noncombustible building material evaluation by testing in accordance with ASTM E 136 to show that concrete with lightweight synthetic particles can be classified as noncombustible material; and fire-resistance-rated construction tests conducted in accordance with ASTM E 119 to determine the fire-resistance ratings of assemblies with concrete containing the lightweight synthetic particles in the concrete mixture.

Acceptance Criteria Statements

If a product demonstrates through tests that it satisfies all requirements of AC408, an evaluation report is issued verifying that the product can be used as an alternative to building code-specified materials. However, evaluation with AC408 of concrete produced using polymer spheres, to show building code compliance, also leads to the following in the evaluation report:

1) Evaluation reports must state the maximum replacement amount of the lightweight synthetic particles that was utilized during the qualification tests, along with particle density and maximum water absorption values.
2) To maintain product consistency, AC408 requires third-party follow-up inspections by an approved inspection agency for the manufacture of the lightweight synthetic particles. This is required so that the manufacturer will continue to produce the same product used during the qualification tests.
3) Concrete quality must comply with Section 1905 of the IBC.
4) Plain or reinforced concrete systems must be designed in accordance with the provisions of Chapter 16 and 19 of the IBC, and ACI 318. However, for structural design purposes, concrete containing lightweight synthetic particles must be considered as structural lightweight concrete. This requires use of ACI 318 parameters and design coefficients specified for structural lightweight concrete. Because the density of concrete produced using lightweight synthetic particles as aggregate replacement may vary, implementing lightweight concrete coefficients and parameters is considered to be a conservative approach for design of reduced-weight concrete with synthetic lightweight particles.
5) In addition to the items noted in Section 16.1 of ASTM C 94, the delivery ticket from the ready-mix plant must include the type and amount of lightweight synthetic particles added to the concrete mixture.
6) Because of the presence of compressible EPS beads in the concrete mixture, the creep of the concrete was of concern. Therefore, for applications where computed deflections contain long-term deflections due to sustained loads, creep effects based on creep test results must be considered in design, which must be submitted to the code official for approval.
7) Chloride content of EPS beads was of concern for corrosion of reinforcement. Therefore, the evaluation report holder must disclose to the registered design professional the amount of water-soluble chloride in the synthetic particles for each project, which must be checked for maximum allowable amount permitted by the codes.
8) When supported by the results of an investigation, the evaluation report must state the need for special or modified tests to measure the properties of fresh concrete. This is required in the criteria because of the lightweight nature of synthetic particles.▪

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