# Building Blocks

updates and information on structural materials

# The Promising Future of Middleweight Concrete

By Kenneth B. Bondy, S.E.

For several years in the early 2000s, as a senior member of ACI Committee 318, I chaired a 3-person Task Group whose mission was to improve and unify the provisions governing lightweight concrete in the *ACI Building Code*. Our recommendations were incorporated into the 2005 edition of the Code. I was not selected for the job because I had any particular expertise in the chemistry, properties, or production of lightweight concrete. I was primarily a taskmaster, nagging and prodding, making sure our work was responsive to the mission and completed on time. The heavy technical lifting was done by the other Task Group members, Calvin McCall and Tom Holm, who do know a lot about lightweight concrete. Nonetheless, because of my participation in this Task Group, and the generally favorable reviews our recommendations received from users of the code, I developed a mostly undeserved reputation for knowing a lot about lightweight concrete.

That may explain why, in 2006, I was approached by a major chemical company and asked to review a new product they were developing. The product was a portland cement concrete made by supplementing a portion of normalweight coarse and fine aggregates with lightweight synthetic particles (LSP), resulting in a concrete with a substantially reduced unit weight (110-120 pcf). The chemical company, at that time, considered this product to be "lightweight concrete", thus retaining me for this work seemed reasonable. My assignment was to determine if and how the product conformed to the ACI Building Code (ACI 318-05 at the time), and to make recommendations for additional testing and research, which would assist in gaining general approval of the product

*CU beads in concrete. Courtesy of Syntheon.*

*Elemix in a hand. Courtesy of Syntheon.*

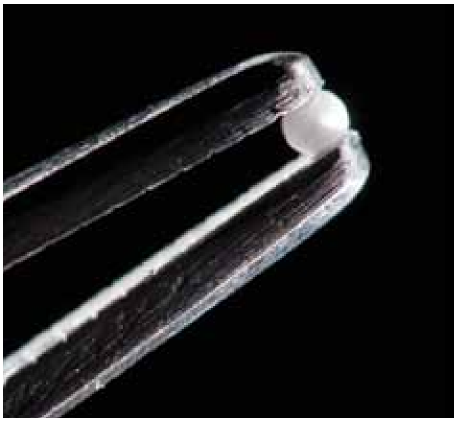
within the engineering and construction communities. The work sounded interesting and, because of my recent lightweight concrete code experience, I felt I could help them. I enthusiastically accepted the assignment and completed it with a final report in early 2007.

My first conclusion was that the product was not, in fact, lightweight concrete. Since the product contains no lightweight aggregate, it could not be considered lightweight concrete in accordance with ACI 318 definitions. Thus, it must be considered normalweight concrete, albeit with a very low unit weight. The term "middleweight concrete" was coined to describe this novel material. Further, LSP would not qualify as an aggregate, even though it replaced aggregate. Under 318 definitions, it would, however, qualify as an admixture.

Test results already completed at the time of my review showed that compressive and tensile strengths of middleweight concrete were similar to strengths developed with conventional normalweight concrete without LSP and with the same *w/cm*. However, I pointed out to my client that a normalweight concrete with a unit weight of 120 pcf would raise performance questions from engineers and building officials. Accordingly, I recommended additional testing in the areas of 1) bond and anchorage, and 2) shear. Finally, I recommended that the client obtain an ICC Evaluation Report from the ICC Evaluation Services for this product, which would demonstrate *de facto* conformance to ACI 318 and the International Building Code (IBC).

*continued on next page*

*Ken Bondy, S.E. is a consulting structural engineer specializing in the design, construction, and retrofit of concrete buildings. He is a senior member of the ACI Standard Building Code Committee (ACI 318), first joining the committee in 1973.*



*Tweezers holding a bead. Courtesy of Syntheon.*

*Elemix Canada Olympic Park elevated deck. Courtesy of Plasti-Fab Ltd.*

## Shear and Bond Behavior

Three years later, the client had accomplished everything I had recommended and more. Notably, they completed an extremely comprehensive testing program at North Carolina State University supervised by Dr. Paul Zia, a renowned researcher and an ACI colleague of mine. The NCSU work included testing to failure of 27 large-scale specimens addressing shear, bond, and anchorage of middleweight concrete members. They also obtained, from ICC Evaluation Services, an Acceptance Criteria report (AC408, *Acceptance Criteria for Structural Concrete with Lightweight Synthetic Particles*) and an ICC approval (*ICC-ES Evaluation Report ESR 2574, September 1, 2009*) available at **www.icc-es.org**.

The results of the NCSU testing are particularly impressive. The testing focused on bond and shear behavior of concrete beams and slabs with LSP and normalweight coarse and fine aggregate at target unit weights of 120 and 130 pcf. The results of bond testing "*…confirmed that the bond strength of beams containing [LSP] met the bond requirements specified by ACI 318-08.*" A similar conclusion was reached based on shear testing: "*In all cases the measured shear strength exceeded the predicted values using the equations of ACI 318-08….*" A closer examination of the shear test results shows that $V_c$, the measured shear strength of the concrete (no contribution from web reinforcement) *substantially* exceeded ACI predicted values. For the 120 pcf mix design, the measured shear contribution of the concrete $V_c$ exceeded the predicted value by 58% (measured/predicted=1.58). This is strikingly good behavior. One could argue that this can be explained by conservatism in the ACI shear equations; however, many other beam shear tests (on specimens without LSP) have shown measured/predicted $V_c$ results with much smaller ratios, closer to 1.0. That strongly suggests that the LSP enhanced the concrete shear capacity to some significant degree in these tests. Another notable conclusion of the NCSU testing was that the ACI 318 "λ" modifier for lightweight concrete need not apply to middleweight concrete with LSP.

## Middleweight with Heavyweight Savings

Based on what I have learned in my involvement with this material, I believe that middleweight concrete could have a major impact on concrete construction. A concrete with mechanical properties equal to or better than conventional normalweight concrete, but weighing 20% less is a big deal. Its use results in significant savings in reinforcing steel in all structural elements of a concrete building: the floor system, columns, walls and foundations. Secondary benefits of middleweight concrete include, among others:

- Reduced structural beam depth, resulting in a greener, more sustainable building with:
  - Less volume to heat and cool
  - Less vertical height
  - Less raw materials used in the structure including structural materials, envelope, skin, plumbing, electrical, anything related to building height
  - Less impact on the community at construction (fewer raw material deliveries), during the life cycle (lower HVAC cost), and at demolition (less debris)
  - All the related cost and time savings
- Improved fire resistance and freeze/thaw durability.
- Improved constructability including pumpability, placing, finishing, and reduced formwork loading.

Based on current estimates for the cost of LSP, it appears that its use in the floor systems of cast-in-place concrete buildings can result in a *net* savings in the total cost of the

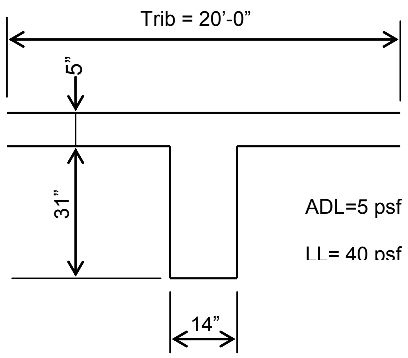
*Concrete with ELEMIX being poured. Courtesy of Syntheon.*

*A ride on trowel levels ELEMIX at the River City Casino in St. Louis, MO. Courtesy of Syntheon.*

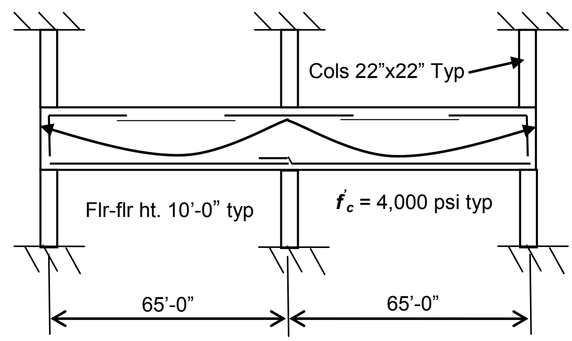
structural frame of 2-4% with no downside, and some significant improvements in performance.

Elaborating further on the economics of middleweight concrete, it has been my experience that the installed cost of reinforcement (prestressed and nonprestressed) represents about one-third of the total cost of a cast-in-place structural concrete frame. Forming and concrete contribute the remaining two thirds. If middleweight concrete (120 pcf) replaces normalweight concrete in a structural frame, and superimposed dead load is negligible, the frame dead load is reduced by 20%. The frame reinforcement designed to resist seismic loads (shearwalls, SMRF, seismic foundation elements) will be reduced by the full 20%, since it is directly proportional to dead load. However, the reinforcement which is designed to resist gravity loads, will be reduced by a smaller percentage.

For example, if a normalweight frame supports a factored dead load of 120 psf and factored live load of 80 psf, gravity load reinforcement is designed to resist 200 psf. If the dead load is reduced by 20% with the use of middleweight concrete, gravity reinforcement would be designed for 0.8x120+80=176 psf, and the net reduction in reinforcement would be (1-176/200)x100=12%. If we assume that the average reduction in reinforcement in typical frames in seismic areas is 15%, the total savings in the cost of the entire concrete frame, with the use of middleweight concrete, should be 0.15x0.33x100=5%, less the premium cost of concrete incorporating the LSP. For buildings designed for gravity and wind loads only (no seismic) the total savings in the cost of the frame should be 0.12x0.33x100=4%. In California, the midrange cost of a complete, well-designed structural frame in a multistory concrete building is about $25/




Section




Elevation

sf; therefore, the resultant savings in reinforcing steel attributable to middleweight concrete is estimated to be $1.00 to $1.25/sf. This, of course, must be reduced by the premium for middleweight concrete with LSP, which, depending on geography and other factors such as required dosage, ranges between $20 and $28/cy for a 120 pcf mix. For buildings with an average floor system concrete thickness of 8 inches (0.025 cy/sf), the cost of LSP will range between $0.50 and $0.70/sf – substantially less than the savings in reinforcement and resulting in a significant net savings in the cost of the frame.

## Post-Tensioned Parking Structure Example

To further investigate the advantages of middleweight concrete in post-tensioned concrete buildings, something I do know about, I designed a representative bay of a commonly proportioned California parking structure with geometry, loading, and material properties shown in the *Figure* above. I designed the beam and slab first with normalweight concrete (150 pcf) and then with middleweight concrete (120 pcf). As might be expected, there was a significant reduction in material quantities between the two unit weights. I did a careful takeoff of the reinforcement in the beams and slabs, and based on extensive experience with parking structures, I estimated the reinforcing steel quantities in the columns, walls and foundations.

Using current California unit prices for tendons and nonprestressed reinforcement, the resulting savings ranges between $0.23 and $0.40/sf, depending on the premium cost of the middleweight concrete with LSP. This is about 2% of the total estimated cost of the frame. In this type of framing, minimum requirements control most of the nonprestressed reinforcing steel in the beams and slabs; therefore, the weight savings is of no benefit there. However, the use of middleweight concrete offered substantial savings in the post-tensioning tendons and in the reinforcing steel in the columns, walls and foundations.

The estimated quantities and unit prices I used for this analysis are shown in the *Table*. The cost savings in reinforcement, resulting from the use of middleweight concrete, is estimated to be $0.82/sf. Since the average concrete thickness of this typical bay is 6.8 inches (0.021 cy/sf), the premium cost for middleweight concrete with LSP would range between $0.42/sf and $0.59/sf, and the net savings in the cost of the structural frame would be between $0.23/sf and $0.40/sf. This is reasonably consistent with the savings projected in the more general analysis above.

For a 200,000 square foot parking structure (about 600 cars), depending on the premium cost of middleweight concrete with LSP ($20-$28/cy), the net savings would range between $46,000 and $80,000. With no structural downside, I don't think anyone would turn that down. It should also be noted that the use of middleweight concrete with this geometry and loading would offer the possibility of reducing the beam depth to 30 inches, a 6-inch reduction in floor-to-floor height with no change in headroom. The savings in tendons would not be as great; however, that might be offset by the savings in total vertical building height and long-term sustainability advantages.

In summary, middleweight concrete made with lightweight synthetic particles has strength, serviceability, and durability properties equivalent to or better than conventional normalweight concrete and, based upon current unit prices for reinforcement and LSP, its use results in a significant reduction in the cost of structural concrete frames.▪

NCSU Testing Results, as mentioned in this article, are: *Use of Lightweight Synthetic Particles to Produce Concrete with Reduced Unit Weight*, Technical Report No. RD-09-05, Constructed Facilities Laboratory, Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, NC.

*Savings in Reinforcement with Middleweight Concrete.*

| | **Concrete Unit Weight (pcf)** | | **Material Savings (psf)** | **Installed price ($/lb)** | **Cost Savings ($/sf)** |
|---|---|---|---|---|---|
| **Item (psf)** | 150 (Normalweight) | 120 (Middleweight) | | | |
| Beam PT | 0.31 | 0.21 | 0.10 | $2.25 | $0.23 |
| Slab PT | 0.28 | 0.23 | 0.05 | $2.25 | $0.11 |
| Beam rebar | 1.20 | 1.20 | 0.00 | $0.80 | $0.00 |
| Slab rebar | 1.10 | 1.10 | 0.00 | $0.80 | $0.00 |
| Non-seismic columns & foundations | 1.70 | 1.44 | 0.26 | $0.80 | $0.21 |
| Seismic walls and foundations | 1.70 | 1.36 | 0.34 | $0.80 | $0.27 |
| | | | | **Total** | $0.82 |