High-Strength Concrete Comes of Age

New Technologies Push Strengths to New Heights

By Cary Kopczynski, P.E., S.E., FACI

As recently as 25 to 30 years ago, the steadily increasing availability of concrete with compressive strengths above 6,000 psi had the industry's rapt attention. Back then, in many regions, strengths this high were considered revolutionary. Some people even questioned the need.

Fast forward to 2014, and designers are specifying strengths of 10,000 psi, 12,000 psi and higher. A new 42-story residential tower in downtown Seattle is one of the first in the country to use 15,000 psi concrete in its columns, reflective of the recent advances in concrete materials technology. Used effectively, this "super concrete" allows smaller columns, shorter and thinner shear walls, and reductions in other structural elements. This results in additional interior real estate. And, when this concrete is paired with modern high-production formwork and the advanced pumping technologies now available, the sky is quite literally the limit.

Concrete Advancements

Concrete has been used as a building material for thousands of years and has played a role in the construction of some of the world's most prominent structures. For example, the Pantheon in Rome – its unreinforced cast-in-place concrete dome completed in 126 AD – still stands today. The icon's longevity underscores the superiority of its design and construction. In fact, one wonders if the structure could be improved upon if rebuilt today. Since that time, however, concrete's use has been extended upward into towers of nearly 2,000 feet in height, and it is for these structures that high-strength concrete has found a home.

The 42-story Premiere on Pine residential tower, in downtown Seattle, is one of the first in the country to use 15,000 psi concrete in its columns, reflective of the recent advances in concrete materials technology. It is scheduled for completion in April of 2015. Courtesy of Soundview Aerial Photography.

Concrete strength started trending upward in the last century when high-range water reducers began gaining prominence. Until the 1950s and 1960s, concrete suppliers struggled to create stronger concrete without sacrificing workability. It was well known that concrete's strength could be increased through a reduction in water content, but, without a way of preserving workability, the side effect of excessive water reduction was an extremely low-slump material that was nearly impossible to place. When material scientists began developing more effective chemical water reducers, however, the problems associated with stiff, low slump concrete began to disappear.

"Superplasticizers" such as "Mighty 150" and others hit the market and quickly became popular, gaining mainstream use by the 1980s. These new high-range chemical water reducers allowed the creation of concrete with both higher strength *and* adequate workability. Research and development into superplasticizers saw a steep climb during this time, simultaneous with increased R&D associated with the use of cement replacements such as fly ash, silica fume, and blast furnace slag. The result was the development of the modern high-strength concretes in use today.

As concrete strengths have increased, forming systems and pumping technology have also made significant gains, allowing structural engineers and architects to consider concrete for use in buildings that would previously have been designed using other materials. Concrete forming systems that were formerly "hand set" have largely been replaced by well engineered components that can be assembled and disassembled quickly, allowing higher field productivity and faster construction. Pumping technology has also advanced, eliminating the need for bucketing on even the highest of structures. Concrete for the Burj Khalifa (formerly the Burj Dubai) in the United Arab Emirates, in fact, was pumped to a height of almost 2,000 feet, at which point structural steel continued upward to complete the 163 story, 2,722 foot structure. The Burj Khalifa was completed in January 2010.

Concrete Columns

Today, high-strength concrete has found its niche primarily in the columns of high-rise towers. Just a few decades ago, many designers believed that concrete was inappropriate for tall buildings, since the then lower strength mixes available would require column sizes of prohibitive proportions.

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These two 400-foot, side-by-side residential towers are expected to break ground in Los Angeles by the end of this year, becoming the tallest reinforced concrete buildings ever built in that city. High-strength concrete is expected to be used in these building's columns. Courtesy of Harley Ellis Devereaux.

These excessive column sizes would interfere with floor layouts and monopolize valuable leasable space. Now, with higher strengths more widely available, column sizes can be reduced and often remain constant for a building's full height, with the concrete strength decreasing at higher levels of the structure. With standardized column sizes and fewer changes over a building's height, formwork costs drop and schedule impacts are minimized.

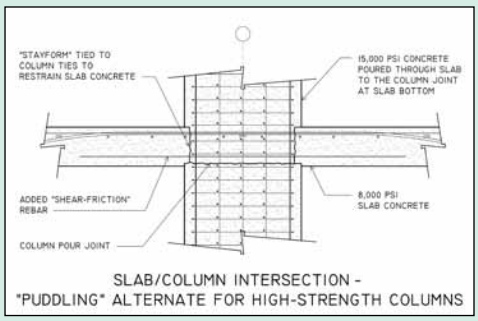
One of the tallest new residential towers in downtown Seattle, Premiere on Pine, is a 42-story concrete structure that uses 15,000 psi column concrete at the base, reducing to 8,000 psi at the upper levels. Structural designers decided to amp up the column strength to take advantage of concrete's efficiencies and maximize the available leasable space. Scheduled for completion in April of 2015, Premiere on Pine took maximum advantage of the high strength concrete available in the Seattle market. Columns sizes of 24 inches x 30 inches and 20 inches x 42 inches are constant nearly to the structure's top, which maximized formwork reuse and helped maintain the rapid construction pace. Column sizes for buildings of this height are commonly 20% to 40% larger. Premiere on Pine's smaller columns increased net rentable square footage when compared to competing towers.

Seattle isn't the only city breaking records for its construction of high-rise concrete buildings. Two 400-foot, side-by-side residential towers are expected to break ground in Los Angeles by the end of this year, becoming the tallest reinforced concrete structures ever built in that city. High-strength concrete is expected to be used in these building's columns as well.

The Challenges of High-Strength Concrete

The use of high-strength column concrete comes with its share of challenges. Since it doesn't make financial sense to pour floor slabs with a similarly high strength mix – 4,000 to 6,000 psi is typically sufficient for slabs and other flexural elements – transferring column loads through lower strength floor plates can be difficult.

If the slab confinement requirements of ACI 318 are met, column concrete strength can exceed the slab concrete by as much as 2.5 times, and a blended strength is used for the column's design. If not, however, there are several ways to retain a high-strength column's integrity as it passes through a floor plate.



By holding back all but several inches of slab concrete from the column perimeter when the slab is poured, an opening is available for the high-strength column concrete to pass through from above. This procedure replaces the "puddling" option, which can sometimes be difficult to execute. Courtesy of Cary Kopczynski & Co.

One is to increase the slab strength at the slab/column intersection by "puddling" high-strength concrete into the column area. The high-strength concrete is poured immediately before the lower-strength floor slab so that the two concretes can be intermixed and the possibility of a cold joint eliminated. While this technique is workable in theory, it can be difficult to execute in the field. It requires precise timing of concrete deliveries and a skilled field crew to ensure that cold joints do not occur.

A less common, but often more effective approach, is to hold back all but several inches of slab concrete from the column perimeter when the slab is poured, leaving an opening for the high-strength column concrete to pass through from above. This eliminates the need to puddle concrete and ensures the integrity of the column. With this approach, shear-friction rebar is typically added through the joint to supplement the strength of the connection.

While high-strength concrete is an obvious choice for columns in tall towers, it also serves a purpose in shearwall and rigid frame construction in these same buildings. Both the strength *and* the stiffness of shearwalls and frames are increased; and, since lateral systems are often drift controlled, the added stiffness is highly beneficial. On the 450-foot tall expansion of Lincoln Square in Bellevue, Washington, for example, designers specified 14,000 psi for strength, but also specified an elastic modulus of 5,700 ksi to control drift, a major challenge in the design of tall buildings.

Different Markets, Different Concrete

The upper strength limit for concrete in a given region is largely aggregate dependent. Some regions have access to better aggregate than others and, as a result, are able to produce higher strength concrete. Chicago and Seattle, for example, have local access to quarries that produce granite aggregate, a relatively non-porous igneous rock that is exceptionally suitable for concrete. Granite is hard and dimensionally stable. It absorbs minimal water, unlike soft limestone or other sedimentary rock found in some other markets, like Los Angeles, Texas and Florida. Such aggregate also tends to be more porous and angular, increasing the required water quantity and making the production of higher strengths more challenging.

Historically, geography has limited the type of concrete used in a given location since transporting aggregate great distances tends to be too costly to make financial sense. The volume of column concrete used on a high-rise project is relatively small, however, compared to the overall project's concrete needs. Thus, some structural engineers are specifying high-strength column concrete even if the necessary aggregate isn't locally available, opting to sacrifice material savings for gains in productivity and additional interior square footage.

While high-strength concrete's use is growing, lower-strength concrete still does the lion's share of the work in concrete construction. The majority of buildings constructed in the U.S. are small enough that high-strength concrete isn't warranted. Further, many structural elements such as floor slabs and foundations don't benefit significantly from the higher-strength material. Nevertheless, as the use of concrete increases and buildings go ever taller, the demand for high-strength concrete is likely to continue growing.▪