CONCRETE STRENGTH RECORD JUMPS 36%

A Seattle building now going up has 19,000 psi concrete, the strongest ever used in conventional structures.

K.A. GODFREY JR.

Casting of the 19,000 psi concrete columns on Seattle's Two Union Square building began last month. Dramatically stronger than the prior record of 14,000 psi, the concrete is nearly four times as strong as conventional concrete. It is essentially a new material.

Its cost is $140 a cu yd at the ready-mix plant. This is three times as high as ordinary concrete, too high for any use except in the relatively few cases where extremely high strength is needed or where it is cost-effective.

Also novel is the Seattle building's structural system. Its concrete columns possess no conventional reinforcing, but instead have a permanent steel shell lined on the inside with shear studs. The structural engineer says the frame's cost is 30% lower than conventional designs, and the column design and high strength concrete are key reasons why.

Pre-construction test pours have shown that 19,000 psi strengths are indeed being obtained at the design age of 56 days. The strength is obtained by making at least six changes from usual concrete practice: use of what may be a record low water:cementitious ratio of 0.22 (this is the biggest single factor in increasing strength and reducing shrinkage and creep); use of the strongest of available cements; a superplasticizer which rather than water provides the necessary workability; a very high cement content; a very strong, small (⅜ in.), round glacial aggregate available locally; silica fume (increasing concrete strength about 25%); use of a design strength that obtained at 56 days rather than the usual 28; and an extraordinarily thorough quality-assurance program.

The design strength specified for the two Seattle structures was "only" 14,000. That is extremely high, but these strengths have been specified elsewhere: almost the same mix is being used on the First Pacific Center building.

Indirectly, the 19,000 psi was specified, too. It is a byproduct of the design requirement for an extremely high modulus of elasticity of 7.2 x 10^{6} psi. This is about twice the modulus or stiffness of conventional, hardened concrete. The stiffness was desired in order to meet the occupant-comfort criterion for the completed building.

Several years ago the *Wall Street Journal* reported that a few buildings constructed in recent years were structurally safe, but so relatively flexible that in extremely high winds they swayed in a manner that was perceptible to some occupants. In at least one building, workers on upper floors reportedly had to be sent home on windy days due to "seasickness."

Tony Tschanz, of the structural firm that designed the two Seattle buildings, Skilling Ward Magnuson Barkshire, believes his firm has one of the toughest in-house guidelines for occupant comfort: that only one occupant in 100 will feel or see the sway in 10 years.

To achieve this, Tschanz says, there are several options. One is to use the tuned mass dampers that, for example, were placed atop New York's Citicorp Center. Another is to use viscoelastic dampers, such as those in the World Trade Center.

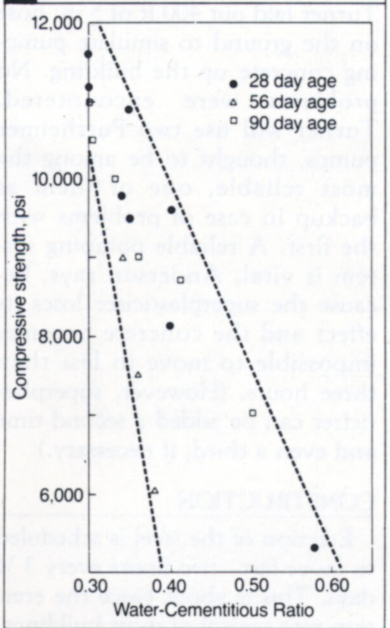
At the new Seattle building, Tschanz says, the least-cost solution proved to be the record-stiffness concrete and visco-elastic dampers. The building frame has four 10 ft diameter core columns. Its 14 perimeter columns range in diameter from 3 ft to 4 ft at grade, and all are 16 in. diameter at the top, 759 ft above the ground. All concrete in all 18 columns, including that at the top, will be the 19,000 psi material.

NO REINFORCING

The record strength, water:cement ratio and modulus may be the most newsworthy, but they are not the project's only novel aspects. Its cylindrical columns have no reinforcing bars. Instead, they have reinforcing in the form of the permanent, ⅝ in. thick steel shells surrounding their perimeters. Tying the steel skin to the columns' concrete are shear studs on 1 ft centers. Fireproofing will be placed over the shells. The steel shells are now being prefabricated at the Hyundai steel structures plant in Ulsan, South Korea, and will be barged to Seattle.

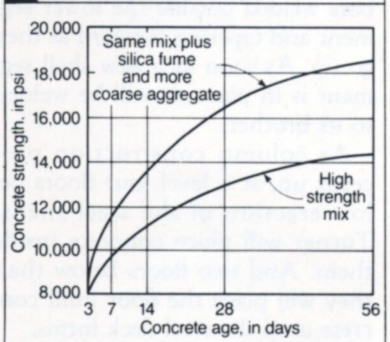
Why the steel shells? At least in

FIGURE 1
WATER/CEMENT RATIO



Seattle concrete's 0.22 ratio and 19,000 psi place it off this curve. (From ACI's High Strength Concrete Committee report, 1984.)

FIGURE 2
SILICA FUME



Effect of adding silica fume and more large aggregate to basically the same concrete mix. 14,000 psi concrete was once typical. Courtesy Skilling Ward Magnusson Barkshire.

tractor were to place the specified mix under field conditions, and through cylinder testing and other means prove that they were meeting the spec. This has been done in the past year, and has led, after two mockup field pours, to changes in the manner of making and testing the concrete.

Most changes involved the testing lab, Cascade Testing. First, says the firm's Ken Foot, it was found that the 500,000 lb concrete compression-testing machines could not satisfactorily break the 6x12 in. test cylinders. Testing the cylinders up to 20,000 psi meant stressing the machine above its 500,000 lb capacity. So smaller, 4 in. diameter x 8 in. length cylinders are now being used and have roughly halved the loads on the machine.

Studies show that higher compressive strengths and higher elastic modulus result by using the smaller test cylinders rather than the large. Typically, the small-cylinder modulus numbers are 10% higher than in the large, Simons reports, and the small-cylinder compressive strength numbers 10-15% higher. He says the higher the percentage differences, the stronger the concrete will be.

Even when the smaller cylinders were used, they did not fail or break in the desirable manner—a conical failure plane. This meant the cylinder's full strength was not being measured. So the capping compound of sulfur or other material, usually added to both ends of a cylinder for testing purposes, was replaced by a grinding procedure that Cascade developed.

Third, Foot says, was replacing the usual fog-room curing of the cylinders with lime-water immersion curing. This improved the uniformity of curing temperature, reducing the spread in strengths of the cylinders at failure.

All three changes were necessary in order to meet the job's quality-assurance spec. Among the most demanding requirements was that no cylinder vary in compressive strength from any other in its three-cylinder group by more than 400 psi. As a percentage of break strength, this requirement is far more stringent than required for conventional concrete.

Foot proudly reports that on one recent representative cluster of three cylinders, broken at 28 days, strengths recorded were remarkably close—17,290 psi, 17,230 and 17,130. Keeping the strength differences due to testing error very small meant that any large ones were likely caused by inconsistencies in concrete strength. Says Foot, "Whenever a cylinder breaks at a strength more than 400 psi off, we look for the cause, and almost always find a void in the concrete or a particle of weak aggregate."

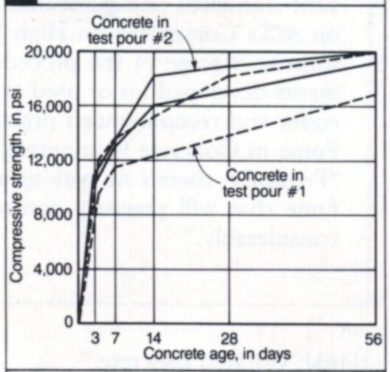
Finally, Foot and Cascade vice president George Lamb report, six times the usual number of test cylinders per 100 cu yd of concrete cast—18 rather than the usual 3—must be made and broken. With conventional concrete, only one 3-cylinder cluster is normally required and broken at the 28 day design age. Here, cylinders will be broken at ages 7 days, 28, 56, 91, 182 and 365.

The ready-mix concrete supplier has had to tune up its operation for this space-age concrete, too. To assure precise batching of ingredients, ready-mix supplier Lone Star's Mark Leatham reports his firm has acquired different computerized batching equipment. And additive supplier W.R. Grace will have equipment on site for storage and batching of its silica fume slurry.

The procedures have been documented in the report "Quality Assurance for Two Union Square," which was submitted to the city. Anderson predicts it will become a model.

Fortunately, Anderson says, the test placement uncovered no problems with concrete placement. One question was, will the concrete be adequately compacted and void-free even with no vibration? After two of the 10 ft diameter, 10 ft high mockup core columns had been cast and cured, they were broken apart. "Despite there being no vibration of the concrete, it had no more and no larger air pockets and voids than in conven-

FIGURE 3
QUALITY ASSURANCE



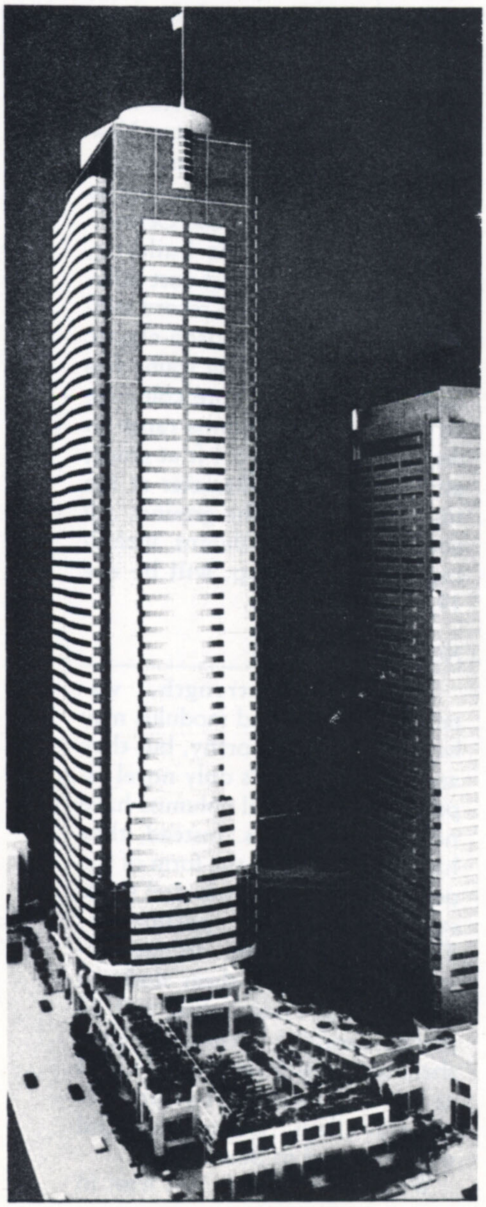
Concrete strength variability was reduced in test pour by changes in test procedures. Strengths in later test averaged higher in part because of smaller test cylinders. Results from test conducted by Turner under the advice of Weston Hester.

part to minimize cost, says project manager John Savo of the architect firm NBBJ Group. "With the steel shells there are no forms to strip, and no reinforcing to place except for shop-placed shear studs."

The structural frame is unusual but not unique. The Skilling firm has used variations of it on three or four other buildings. And three other Skilling buildings now in design, all to be built in Seattle, will use the very stiff concrete and/or the steel-shell columns.

"We use these innovative ideas not for the sake of innovation, but because they result in the least-cost building," Tschanz explains. He says the novel frame cut about 30% from the roughly $30 million cost of the structure.

Frank Anderson of general contractor Turner Construction says the biggest saving comes from using concrete columns rather than steel. The floors consist of I-beams, metal decking and infill concrete, which Anderson says give the building "an impressively low steel weight of 12 ½ psf, about half that for an all-steel framed building." Tschanz says it costs seven times as much to carry a given load with a steel column as with a high-strength concrete one.



Model of Two Union Square, 62 stories and 759 ft high.

CONCRETE MIX

The heart of the job is its record-strength concrete mix. Each of the six innovative factors is important in obtaining the strength. For instance, the cement chosen reportedly can affect the concrete's strength by up to 20%.

Anderson says Seattle is lucky to have extremely strong glacial aggregate, "which, contrary to convention for getting great strength, is round and not angular. We know how fortunate we are. In a Chicago project, they reportedly had trouble getting 12,000 psi, and I think their aggregate is one reason. If we had to import aggregate it would raise the concrete's cost about 25%."

Development of the Seattle concrete mix is explained by materials consultant Bryce Simons, of the city's suburban Champion. "A few years ago John Skilling asked me, 'How high can you go with concrete strength?' I guessed 15,000-17,000 psi. After much study and many trial mixes, my reply was, 'upward of 20,000 psi'."

Knowing that reducing the water:cement ratio dramatically increases the concrete's strength and modulus, Simons prepared trial mixes with the extraordinarily low ratios of 0.25, 0.22 and 0.20. "We ended up with 0.22."

There have been problems bringing this radical mix from the lab to the field, he admits. "We use less than 30 gal per cu yd of water, so the cement tends to ball up and remain incompletely mixed. The ready-mix people said, 'You've got to add more water.' We have not done it."

Getting the lowest practical water:cement ratio was helped greatly by availability of water-reducing and high range water-reducing (superplasticizer) additives. When these are used, water is needed only to hydrate the cement, and the necessary workability of the wet concrete mix is provided entirely by the water reducers.

Another key is the powdered additive silica fume. Early on, Simons ran tests with 2 in. cubes of cement, sand and water, and found that replacing 10% of the cement by weight with silica fume increased the cube's compressive strength 32%.

Tschanz says the silica fume added about 25% to the Two Union Square concrete's strength. It does this in two ways. In conventional concrete, about 25% of the cement paste is calcium hydroxide (lime), which does not contribute to concrete strength. Adding silica fume converts nearly all the calcium hydroxide to calcium silicate hydrate, which is the strength ingredient in cement paste. Second, microphotographs show that the silica fume partially fills the tiny voids between cement grains, and it apparently adds strength in this way.

QUALITY ASSURANCE

The Seattle concrete is nearly four times the strength of that which the writers of the national concrete codes of standard practice had in mind. The design-construct-testing team for Two Union Square knew they would be breaking new ground. If any of the new concrete did not come up to spec, it would mean big trouble because the columns' steel shells would make it very hard to remove and replace it. Superior quality control and quality assurance would be mandatory.

Turner brought in concrete specialist Weston Hester of the University of California-Berkeley. And with Simons' help, Skilling issued a spec with an unusual requirement: before construction began, the ready-mix supplier and con-

METRIC
1 in= 25mm; 1 ft= 0.3m; 1 cu yd= 0.8 m³; 1 lb (mass)= 0.5 kg; 1 lb (force)= 4.5 N; 1 psf= 48 Pa; 1 psi= 6.9 kPa

tional, vibrated concrete."

At least two factors account for this: the specs permit Turner to add superplasticizer at the job site to bring slump up to a high 10 in., and the concrete will be pumped into the steel column shell from the bottom up. That is, each pour will raise the height of the concrete in columns by two floors or 24 ft. The concrete will be pumped through a portal in each column's steel shell, near the bottom of that pour. Thus the concrete will literally be pumped up vertically and forced to mix thoroughly, causing complete and void-free filling of the shell.

During the two mockup pours, Turner laid out 400 ft of 5 in. hose on the ground to simulate pumping concrete up the building. No problems were encountered. Turner will use two Putzheimer pumps, thought to be among the most reliable, one of them as backup in case of problems with the first. A reliable pumping system is vital, Anderson says, because the superplasticizer loses its effect and the concrete becomes impossible to move in less than three hours. (However, superplasticizer can be added a second time and even a third, if necessary.)

CONSTRUCTION

Erection of the steel is scheduled to move fast—two floors every 3 ½ days. This is about twice the erection rate typical of most buildings.

During construction, as a new column-shell segment is lowered into place atop the one below, it will be held in proper alignment by a circular steel band projecting above the top edge of the lower segment and inside it, plus guide bars welded outside the lower segment and tapering outward as they go up. As soon as a new shell segment is in place, it will be welded to its brother.

As column construction proceeds up, at a level four floors below erection of the steel shells, Turner will place concrete inside them. And two floors below that, they will place the floor infill concrete atop the steel deck forms.

Where the floor beams and building perimeter spandrels are to be fastened to the steel column-shell, Hyundai is shop-welding stiffening steel gusset plates to the shells. Thus field welding done later at the Seattle, Wash., building site will not touch the column shells. Where a spandrel or beam in effect continues across the column, the internal gusset plate continues all the way across the inside of the column.

There are a few concerns, but the Two Union Square design-build-testing team also evidences a great deal of pride and excitement, especially Turner's Frank Anderson. "For 42 years I've been constructing buildings. This project is by all odds the most challenging and fascinating."

HOW HIGH STRENGTH?

While Two Union Square is setting new records in structural concrete strength and modulus, those responsible have benefitted from the experience gained in earlier high-strength projects.

During the 1970s Chicago concrete people were the champs. Perhaps their most notable accomplishment was Water Tower Place, constructed in 1975 and at 859 ft then by far the world's tallest concrete frame building. The project's concrete spec called for 9,000 psi concrete, which at the time this was a near-record high.

Seattle's 19,000 psi concrete is twice that, but not the first of its strength. 20,000 psi concrete was used in bank vaults built in the past few years, reports John Wolsiefer, of silica-fume supplier Norcem, Long Island City, N.Y. Turner Construction's Frank Anderson recalls that missile silos with 15,000 psi concrete were built several years ago.

Apparently 19,000 psi is not the ceiling. Henry Russell says his organization, Construction Technology Labs, has made 26,000 psi concrete experimentally, thanks in part to confining steel wrapped around the specimen. Tony Tschanz says confined tests of the Seattle concrete mix yielded compressive strengths over 30,000.

This confinement has two additonal benefits. It changes the compression failure mode from sudden (very high strength samples have been known to explode in the testing machine) to more gradual, and it makes a rather brittle material more ductile.

Says Russell, "We should be looking at strengths of 20-30,000 psi." Others have said these strengths are attainable, but perhaps only with special aggregates. Seattle's Bryce Simons predicts 30,000 psi will be exceeded without confinement, but with special aggregates such as chunks of scrap steel.

But caution. The concreting guidance documents were prepared when few if any structural concretes exceeded 6,000 psi. The Seattle concrete is over three times as strong.

Last June, at a conference in Norway, Arthur Nilson of Cornell University cautioned, "Extrapolation of empirically based design equations, such as are found in most national codes, far beyond the limits of the original test data on which they are based, is not a safe practice. A thorough review of the codes is mandatory...."

At least two groups, ACI and ASTM, are now developing relevant standards and guidelines to practice. Hester and Simons are on ACI's Committee on High Strength Concrete, so it will be no surprise if some of the procedures and quality assurance requirements developed for or used at Seattle find their way into national codes and recommended practices. ASTM recently formed a Silica Fume in Concrete Committee, and Simons says it's a good thing: "Presently, there's no way to write a spec for concrete using silica fume that will precisely control concrete quality—strengths vary considerably."

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