



Concrete Plant International North America Edition

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SPECIAL PRINT
CPI 01/14



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The 6.8 magnitude Nisqually earthquake that struck eastern Washington State in 2001 shook a wide area of the U.S. Northwest, damaging numerous structures including many roads and bridges. The damage and subsequent repairs of a 1950s era reinforced concrete double-decker highway led to an ambitious replacement plan that includes the world's largest diameter highway tunnel. On July 30th, an \$80 million tunnel boring machine (TBM) departed its 80-foot deep launch pit near the Seattle waterfront. The TBM – the world's largest – arrived in April 2013 from Osaka, Japan, and its 41 pieces were lowered into the launch pit for assembly. At speeds of up to 35 feet per day, the earth-worm-like TBM will burrow its way below nearly 200 buildings and a maze of subsurface infrastructure for nearly two miles, surfacing just south of Lake Union in the fall of 2014.

■ Hank Giles,
Advanced Concrete Technologies (ACT), USA ■

Reinforcing world's largest highway tunnel

The 7,000-ton 326-foot-long by 57.5-foot-diameter self-contained TBM will advance along its course by using hydraulic jacks to push against successive precast concrete reinforcement rings, each consisting of ten segments (see figure 1) weighing about 37,500 pounds each. Most segments measure 18.5 feet long, 6.5 feet wide and two feet thick. Several smaller segments combine to form a key section at the top of each ring. A complete tunnel reinforcement ring weighs in at approximately 375,000 pounds. The reinforcement rings are 2.65 inches narrower on the keystone side, allowing the builders to curve the tunnel in almost any direction by rotating and aligning each nonsymmetrical ring.

According to Jason Lien, EnCon United's vice president of design, the firm was chosen for the tunnel project because the contractor wanted a facility with a long track record and PCI certification. The 21.5-acre EnCon Washington, LLC, precast facility in Puyallup, Washington, just 35 miles from the tunnel location, was an ideal choice.

EnCon Washington has been in continuous operation as a PCI certified plant since 1999 and is a wholly owned subsidiary of EnCon United, based in Denver, Colorado. EnCon Washington was already a long-time producer of precast retaining walls, median barriers, sound barrier panels, and commercial wall panels—most products pro-



Figure 1: The system shown above is used to install a gasket on each newly cast tunnel segment prior to yarding. Each segment weighs approximately 37,500 lbs.

duced to Washington State DOT standards. EnCon site's proximity to the tunnel construction site, large storage yard, and EnCon's existing fleet of gantry cranes was a critical advantage.

"We learned we won the business in late 2008 and began planning immediately for the expanded facility we would need to produce the tunnel segments," explains Lien, project manager for the expansion of the EnCon Washington plant.

The plant will produce thousands of individual segments to meet the need for more than 1,400 complete reinforcement rings. The total volume of concrete required by the tunnel liner will amount to approximately 118,000 cubic yards.

Advanced batching system required

EnCon Washington's original plant relied on ready mix to meet its needs. "We were already in the process of moving a dry batching plant from our Atlanta operation up to Washington and using our own mixer truck," Lien notes. "Our existing ready mix arrangement was really not meeting our needs in terms of production scheduling, mix consistency and costs. Once we learned we had been selected for the tunnel, and saw what was required, we knew we needed a high volume, highly precise batch plant."

The plant expansion includes nearly 41,100 additional square feet of enclosed



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Figure 2: Under construction. The new ACT MobilMat Mo4500-5-PCS batching solution is positioned to feed EnCon's new tunnel segment production line as well as its preexisting precast retaining walls, median barriers, sound barrier panels, and commercial wall panel production lines. The new batch plant arrived from the Wiggert factory pre-assembled, pre-tested, wired and plumbed (air and water). One of the two cement silos shown here is dedicated to Portland Type 1 cement, and the other silo is split with one side containing silica fume and the other ground-granulated blast-furnace slag (GGBFS).

space, a rail-based carousel production line and flying bucket concrete delivery system, a sophisticated segment mold system, and highly automated concrete batching system from Advanced Concrete Technologies (ACT). There are also specially designed trailers to transport the finished segments. "The equipment and specifications for the tunnel segments were specified in the contract; however, the selection of the batching system was up to us," Lien says.

"We needed a system that could produce a large volume of concrete in a short period with high levels of consistency and would allow us to easily break into the tunnel liner production cycle now and then to pull out mix for our other DOT precast operations." Lien and his team looked at several batching systems, but ultimately chose the MobilMat Mo4500 system from ACT/Wiggert (see figure 2). "Other batch plant vendors were somewhat competitive on

price; however, we had greater confidence in the ability of ACT to deliver on time and meet our specific needs," Lien explains. "We knew we had a carousel production system coming, the building laid out, and we had a delivery mechanism. We needed a batch plant vendor that could work within the confines of those specifications and deliver on demanding requirements. It had to be a design-build solution—essentially a turnkey plant."



Figure 3: The new EnCon batch plant features a five-compartment, 885-ton capacity aggregate storage system from ACT that includes drive over dump hopper and conveyor system (shown here) that automatically ensures the correct aggregates are loaded into associated bins.



Figure 4: Shuttle belt above aggregate storage bunkers provides automated distribution of aggregates into one of five aggregate bins.

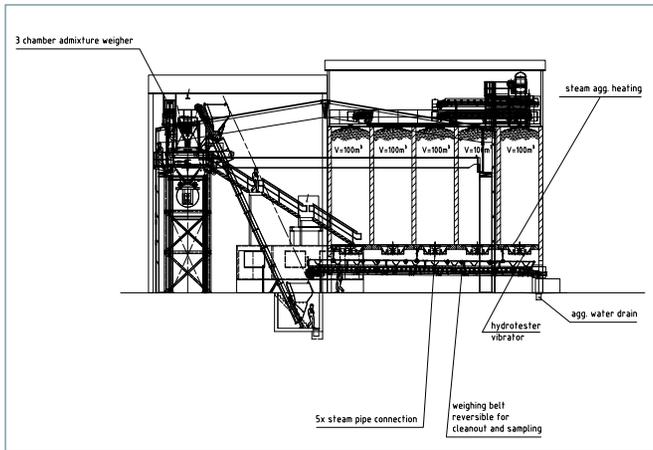


Figure 5: At left in this diagram is the ACT MobilMat Mo4500-5-PCS batch/mixing plant. At right, five steam-heated aggregate bins hold up to 900 tons and discharge onto weigh belt that in turn empties into a skip hoist to feed the HPGM 4500 high-shear planetary mixer from ACT/Wiggert. Steam heating is required to meet exacting temperature requirements for the high early strength tunnel segment mix. This extra moisture is accounted for by the batch plant's PCS computer control system and moisture probes in the aggregate bins and mixer.

The ACT automated MobilMat Mo4500-5-PCS batching solution provides four cubic yard output with continuous cycle times of just a few minutes per batch. The plant is pre-assembled, wired and plumbed (air and water) at the factory and tested prior to shipping. The system includes the following elements:

- HPGM 4500 high-shear planetary mixer from Wiggert & Co. with true four-cubic-yard consolidated concrete output. Mixer equipped with two discharge gates to enable easy distribution to both the tunnel segment production via flying bucket or to the precast panel production area via Tucker delivery vehicle.



Figure 6: Weigh belt and galvanized dual-gate batching cones below aggregate storage bins for precision batching of aggregate components.

- Five-compartment aggregate bins with 885-ton capacity automatically charged via a drive over dump hopper and a conveyor system (see figure 3). An automated aggregate handling system (see figure 4) ensures correct aggregates are loaded into associated bins. The bins were fabricated on site from precast panels according to ACT drawings (see figure 5) to provide sufficient capacity within predetermined footprint. Galvanized cones have dual batching gates for precision fast/slow aggregate batching onto a weigh belt (see figure 6).
- Steam heated aggregate bins ensure precise batching temperatures. Aggregate moisture levels are automatically monitored and compensated for in the mixer to maintain the perfect water/cement ratio. Temperature probes in each aggregate bin and the mixer ensure concrete temperature is maintained ensuring fast stripping strength.
- Continuous level monitoring of aggregate bins and cementitious silos prevents overfilling and enables suppliers to log in online to check stock levels for just-in-time restocking.
- Two cement silos contain approximately 300 tons of cementitious material. One silo is dedicated to Portland Type 1 cement, the other is a split double wall silo, one compartment stores silica fume and the other stores ground-granulated blast-furnace slag (GGBFS).
- PC-based PCS Control system with user-friendly interface and remote call stations provides flexible control, maintenance reminders, recipe recall, complete production history, and real-time batch control. "Batching history and quality control are critical," Lien says. "Through the ACT PCS controls, we can track everything, including aggregate temperature, batch weights. With the connection to our system for vendors, the ordering process has basically gone away, which is a huge savings in time and coordination when you're dealing with the volumes we are."
- Hydrateser aggregate moisture probes automatically adjust batch weight compensating for varying moisture in order to maintain mix design and batch yield.
- Hydromat microwave mixer probes automatically measures mix moisture and calculates final batch water quantity to maintain perfectly consistent W/C ratio for each batch.
- Automatic high pressure mixer and flying bucket cleaning system reduces cleanout time and extends equipment life. "We have defined automated cleaning times that fall within employee break windows and we could not clean the system in the allotted timeframe without this automated system," Lien notes.
- Centrally located Eco-Clean water reclaim system treats approximately 10,000 gallons of process water daily. The plant generates about 3,000 gallons of grey water from plant cleaning and an additional 7,000 gallons from steam curing operations. The process water is automatically treated to meet tough Washington State turbidity and pH standards before discharging.
- Precision admixture metering system pumps precise admixture doses by weight.

Project management

The Denver-based Lien served as project manager on-site at the EnCon Washington facility during plant construction and start-up. "I

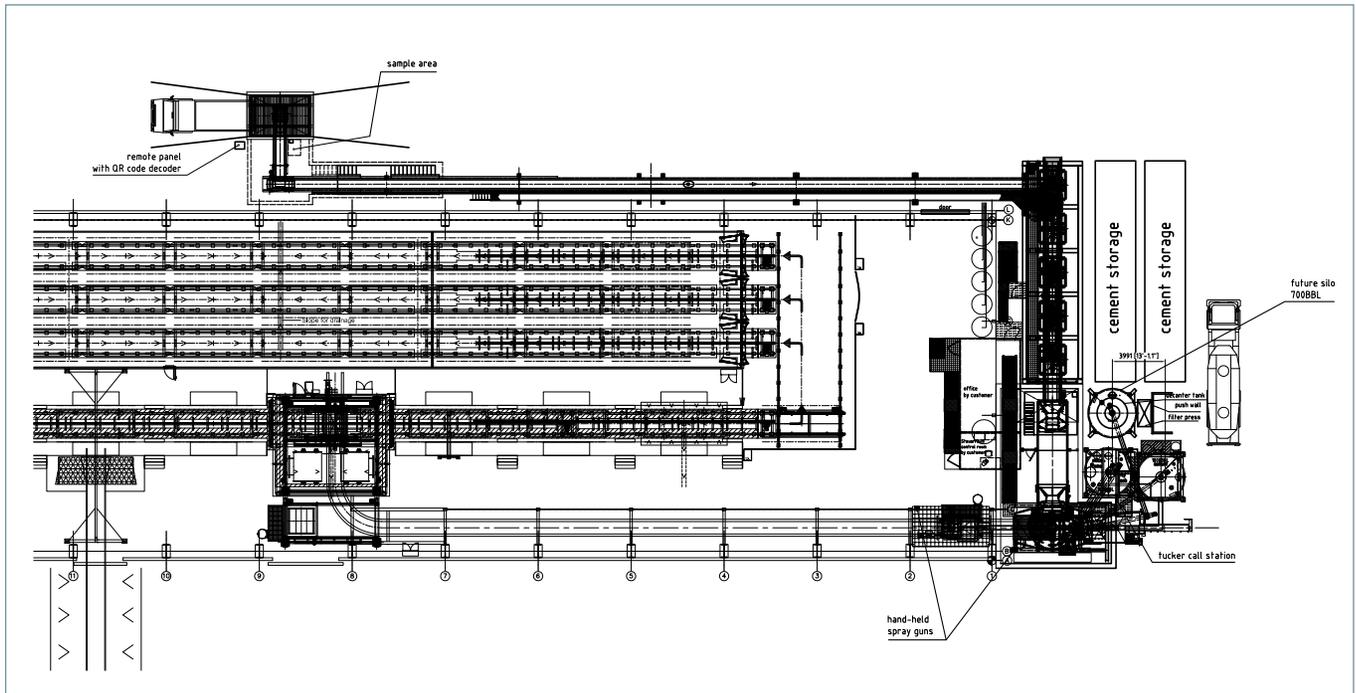


Figure 7: From above, the new EnCon plant is a model of efficiency with many automated features to save on labor and enhance quality. From the automated aggregate loading and batching system, to the automated ACT MobilMat batching system, computer control and continuous moisture monitoring ensures that they dry mix required for tunnel segment production always meets & exceeds design requirements.

acted as the liaison between the various vendors and the general contractor," Lien explains. "I worked closely with ACT. The batch plant was essentially a perfect fit upon delivery. ACT provided layout and design assistance, including complete drawing and specification (see figure 7) that were made part of the drawings kept by the engineer of record."

One challenge in particular—aggregate storage—required a creative solution. "We had a predetermined space for about 900 tons of aggregate storage and the metal bins we originally specified would not provide the storage volume within the allotted footprint," Lien notes. "EnCon Design engineered and detailed the prestressed/precast aggregate silos and ACT provided review of bins for compatibility into the overall batch plant plan. We not only achieved the space/storage objective we needed, but also saved about \$200,000 building them on site."

The tunnel liner segment plant has been in full production since February 2013 and has already produced thousands of segments. The segments are transported via truck from the Puyallup plant to the southern tunnel portal at varying rates. The special-

ly designed trucks can carry two segments at a time due to their extreme weight. The segment production line includes 11 main workstations. The segments ride on special rail carts through each workstation, which include:

- Opening Mold – open the form
- Stripping – remove product from Form
- Cleaning – Clean Form / Oiling
- Insert Placement – place insert in form, includes bolting hardware for purpose of attaching the segment to others at the job site.
- Reinforcement Placement – place cage in mold
- QA – quality assurance position where the finished mold is inspected for compliance before casting.
- Casting – place concrete in mold and vibrate using seven built-in vibrators in each mold (see figure 8).
- Screeding – remove excess concrete from surface
- Finishing – hand finishing of exterior surface of segment
- Wash – Final clean of mold exterior prior to curing chamber
- Curing Chamber – segments cure for seven hours and 12 minutes to achieve minimum 2,500 psi stripping strength

Critical mix parameters

The concrete mix used to produce the tunnel liner segments is engineered to provide stripping strength of 2,500 psi after seven hours of curing, and a minimum strength of 7,000 psi after 56 days. The segments are stored in the EnCon Washington yard during that time (see figure 9). According to Lien, the company is actually achieving 56-day strengths in the range of 10,000 to 12,000 psi, which provides an extra level of confidence that the segments can easily withstand the demands of transportation, and the extreme hydraulic pressure exerted on them to drive the TBM forward.

Each segment requires approximately nine cubic yards of concrete. The mix is delivered via a flying bucket system to the casting station. Every 50th segment is carefully measured using a 3D laser-based scanning system.

"The high shear mixing precision batching we see with the ACT/Wiggert batching plant is definitely helping us exceed the early strength and 56-day strength goals," Lien says. "We are using a very stiff mix with a one inch slump, so the speed and consistency of the batching system is critical. Given



Figure 8: Skilled operators watch over every step in the tunnel production process. Here, a flying bucket has just filled the segment form. Powerful vibrators, built into the form system, ensure complete and thorough consolidation.

the water contained in the aggregates, we only add about 39 pounds of water to each yard to hit our target water/cement ratio. We have a very short window—a short pot life—and fast mixing and delivery speed is essential."

Lien notes that even if it were possible to get the volume and particular mix design from a ready mix supplier, the consistency and quality would not be sufficient. "Quality and record keeping is paramount—we can only get that using our own batch plant," he notes. "Not to mention, our cost to produce concrete with our own batching system is about \$25 less per yard compared to delivered ready mix. That's a saving of about \$3 million over the life of the project."

Segment assembly

Rail mounted carts haul the tunnel segments from the southern portal along the completed section of the concrete tunnel to an overhead conveyor that transports them to the lining system. The TBM system uses two vacuum powered erector arms to place the tunnel liner segments. Bolts and dowels are used to secure the segments to form a complete ring. The TBM then moves forward using massive hydraulic jacks that push off the latest ring.

With the new ACT/Wiggert concrete mixing batching plant, EnCon is able to deliver the highest quality precast concrete with significant production savings over conventional methods.

"With this plant expansion we are achieving improvements in quality, lower labor and material production costs at the same time achieving increased product strength," Lien notes. "This investment positions our company for future growth and flexibility to deliver precast concrete products that meet market demands. We're extremely proud to be playing a key role in the development and delivery of this important transportation system. Thanks to all our vendors and our dedicated crew, we are producing the highest quality precast products possible."



Figure 9: Completed tunnel segments are stored in the EnCon yard for about 56 days before delivery to the tunnel construction site in Seattle. The fully enclosed plant addition, shown here, enables continuous production in all types of weather.

FURTHER INFORMATION



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