Cellulose Nanocrystals as an Additive for Prestressed Concrete Slab Girders

by Sivakumar Ramanathan, Krishna Siva Teja Chopperla, Taylor Washington, O. Burkan Isgor, and W. Jason Weiss, Oregon State University

Concrete is the most widely used artificial material in the world. This widespread use is undoubtedly due in part to its low cost and long-term performance and the availability of raw materials. However, there is a need to reduce the environmental impact of concrete materials and their production. It is therefore desirable to enhance the reactions of cement to provide a possible way to reduce the amount of cement needed in concrete.[1] At the same time, it is also beneficial to reduce amounts of materials that fuel forest fires; one way to achieve that goal is by finding alternative uses for small-diameter logs and even diseased wood that need to be removed from forests and are typically not viable for commercial use.[2] Toward this end, cellulose nanomaterials (CNMs), which are made using wood products, are being researched as a potential concrete additive.[3–5] Two commonly used CNMs are cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs).

CNCs are incredibly small: 3 to 20 nm wide and 50 to 500 nm long. They are not only much smaller than the conventional cellulose fibers used in concrete but also much smaller than cement particles themselves.[6] CNCs therefore act more like an additive than a conventional fiber that can bridge a crack. Research has shown that when CNCs are used at low dosages (0.2% by volume of cement), the flexural strength of cement pastes can increase in some systems by 20% to 30%, primarily due to an increase in degree of hydration of the cement.[5] CNCs are believed to be adsorbed by the cement grains, providing paths for water to migrate through the hydrated shell and resulting in increased cement hydration. When CNCs are used in low dosages (less than 0.2% by volume of the cementitious materials) in concrete mixtures, they act as water-reducing admixtures to reduce the yield stress—the minimum required shear stress to initiate flow of concrete or cement paste—and increase flow; however, at higher dosages, the CNCs begin to entangle and increase yield stress and viscosity. Properties of fresh concrete such as bleeding and proper filling of formwork depend on the yield stress of the paste.

A recent project evaluated the commercial use of CNCs in a prestressed concrete bridge constructed in Siskiyou County, Calif. The objective of the work was to assess whether there are any potential challenges in using CNCs in conventional concrete applications.

Table 1. Concrete mixture proportions used for the Moffett Creek Bridge girders

Material	Reference concrete	Concrete with 0.1% cellulose nanocrystals
Type III cement, lb/yd³	712	718
¾ to ½ in. aggregate, lb/yd³	592	602
½ in. to no. 4 aggregate, lb/yd³	1148	1135
Sand, lb/yd³	1212	1217
Water, lb/yd³	250	250
Cellulose nanocrystals, lb/yd³	0	3.6
Air-entraining admixture, oz/yd³	7	7
High-range water-reducing admixture, oz/yd³	42	42
Workability-retaining admixture, oz/yd³	21	21
Water-cement ratio	0.361	0.355

All Tables: Oregon State University.

Precast Concrete Bridge Girders in Siskiyou County

The project consisted of both trial batches of concrete and casting conventional prestressed concrete slab girders for use in the Moffett Creek Bridge project, which replaced an existing bridge in Yreka, Calif. The prestressed concrete girders were cast at the Knife River Prestress plant in Harrisburg, Ore. Each girder was 28 ft 11.5 in. long, 3 ft 5.25 in. wide, and 12 in. deep and weighed 18,000 lb. The concrete design compressive strength was 6000 psi, and the transfer strength was 4900 psi. Standard mixture proportions approved by the Oregon Department of Transportation were used for the reference concrete. A second concrete mixture was prepared with a low dosage level of CNCs (0.1% by volume of cement). While prior laboratory research has demonstrated that CNCs can enhance the hydration of cement at later ages and reduce the amount of cement needed, this work assessed the CNC as an additive for concrete in a full-scale demonstration; therefore, the amount of cement used in the mixture proportions was not reduced for this project. **Table 1** gives the mixture proportions for both concretes. A water-cement ratio of 0.36 was used with a Type III cement to achieve a high early strength for the transfer of prestress.

The CNCs used in this study were prepared by a pilot plant at the Forest Products Laboratory—a division of the U.S. Forest Service located in Madison, Wis.—using a sulfuric acid hydrolysis process (**Fig. 1**[7,8]) and supplied as a suspension in water.[9] The CNCs were strong, lightweight, colorless, and biodegradable.[10] Air-entraining and high-range water-reducing admixtures were added in similar proportions to both concrete mixtures to achieve the required fresh properties.

The concrete was batched using conventional procedures. The CNCs were added by hand to the pug-mill mixer, with the CNCs and water slurry being added to the concrete directly through the observation hatch after the tail water (**Fig. 2**). The CNC addition did not require specialized equipment or process modifications. **Figure 3** shows the fresh concrete containing CNCs being placed. The fresh properties of concrete were measured according to ASTM C1064/C1064M-17[11] (temperature), ASTM C143/C143M-20[12] (slump test), ASTM C231/C231M-17[13] (air content using the pressure method), and ASTM C138/C138M-17a[14] (unit weight) by the quality-control personnel at the precast concrete plant. In general, the fresh properties of the CNC concrete were similar to those of conventional concrete (**Table 2**).

Hardened properties of the concrete were measured, including compressive strength (ASTM C39/C39M-21[15]), splitting tensile strength (ASTM C496/C496M-17[16]), and electrical resistivity (AASHTO TP 119-15[17]). The reference concrete had a 28-day compressive strength of 8900 ± 286 psi, while the 0.1% CNC concrete had a strength of 9480 ± 488 psi.

The compressive strengths of both concretes exceeded the design strength of 6000 psi. The average compressive strength of the 0.1% CNC concrete was 8.8% higher at day 1 and 6.5% higher at 28 days than the average strength of the reference concrete. However, at 28 days, the compressive strengths of both types of concrete were statistically similar. The fact that the 0.1% CNC concrete was of similar strength, despite the higher air content in the CNC concrete (which could be expected to reduce the strength), is attributed to an increase in the degree of hydration of the cement. The 28-day splitting tensile strength of the 0.1% CNC concrete (1321 ± 80 psi) was similar to that of the reference concrete (1273 ± 46 psi).

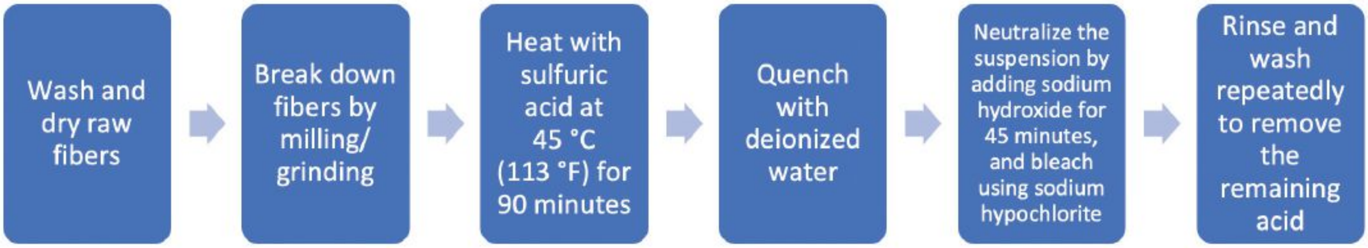

Figure 1. Flowchart describing the sulfuric acid hydrolysis process used to prepare cellulose nanocrystals for use in concrete mixtures.[7,8]

Figure 2. Addition of 0.1% cellulose nanocrystals through the observation hatch of the mixer as the concrete was being batched. Photo: Oregon State University.

Figure 3. Concrete with 0.1% cellulose nanocrystals being placed, vibrated, and finished in the prestressed concrete girder formwork. Photo: Oregon State University.

Table 2. Comparison of fresh properties of concrete with and without cellulose nanocrystals

Fresh property	Reference concrete	Concrete with 0.1% cellulose nanocrystals
Slump, in.	7.0	6.0
Air content, %	4.0	5.8
Density, lb/ft^3	143.84	141.16
Temperature, °F	72.0	72.0
Ambient temperature, °F	61.0	65.0

Table 3. Comparison of electrical resistivity of concrete with and without cellulose nanocrystals

	Reference concrete	Concrete with 0.1% cellulose nanocrystals
Resistivity, Ω-m	96.2	88.1
Standard deviation, Ω-m	2.2	1.7

In addition to compressive strength, the 28-day electrical resistivity of the samples was measured. Resistivity is increasingly being used as a potential alternative to the rapid chloride permeability test.[18] The bulk resistivities of both concretes (**Table 3**) were in the range of moderate chloride-ion permeability.

After meeting all specifications, the girders were transported to the project site in Yreka and installed by local county personnel (**Fig. 4**). The project successfully demonstrated that the addition of CNCs to concrete can result in similar or potentially improved performance. It also demonstrated the potential commercial use of these materials. Additional studies are underway to determine whether the improved hydration can be used to reduce cement content and improve the sustainability of these concretes.[1] Additionally, the use of CNCs is being tested for a wider range of cementitious materials.

Conclusion

CNCs were used as an additive to prestressed concrete used in slab girders for a bridge in Yreka, Calif. The addition of CNCs resulted in similar or slightly better concrete properties when compared with conventional concrete. While previous laboratory research has demonstrated that CNCs can enhance the hydration of cement at later ages, this work was the first full-scale demonstration of CNCs as an additive for concrete. The prestressed concrete girders cast using the CNC additive demonstrate that CNCs can be used in commercial concrete without delaying or affecting production.

Acknowledgments

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Figure 4. Successful installation of the prestressed concrete slab girders. The installation was performed using county personnel. Photo: Inland Films.

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Sivakumar Ramanathan and Krishna Siva Teja Chopperla are postdoctoral scholars, Taylor Washington completed graduate studies, and O. Burkan Isgor and W. Jason Weiss are professors at the School of Civil and Construction Engineering at Oregon State University in Corvallis.