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An Investigation on the Effects of Cellulose Nanofibrils on the Performance of Cement Paste and Concrete

Reference

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ABSTRACT

Cellulose nanofibrils (CNFs) have the potential to enhance cement and concrete properties because of the way they change both how water is distributed during mixing and how they modify the hydration process. In this work, the effects of CNFs on certain properties of cement paste and concrete were investigated. For the cement paste, workability, shrinkage properties, and compressive strength were investigated. In the cement paste study, 32 batches with variable CNF concentrations in 4 groups with different water-to-cement (w/c) ratios (0.35, 0.40, 0.45, and 0.50) were prepared and tested. Two rheological tests were performed; one used an ammeter to measure torque versus rotational speed, and a second used a standard flow table. Both tests showed a decrease in the workability of cement pastes that was due to the increase in CNF volume for all pastes, which suggests that CNF retains mix water in the fresh state. Thus, the water held in the CNF is not available during initial mixing of the cement paste. The results of the free shrinkage tests for all 32 cement pastes were collected for up to 90 days. Additional results showed that at a low w/c ratio (0.35), adding a small quantity of CNF (0.05 %) can reduce free shrinkage by 13 %. In compressive strength tests, a small dosage of CNF (0.05 %) improved compressive strength (up to 28 %), but higher dosages reduced strength. Results suggest that CNF has a good potential to be considered as a new natural plant-based internal curing agent in cement paste and concrete. For the concrete specimens, the primary focus was on workability effects and compressive strength. In the concrete study, twelve

batches with different CNF volumes were prepared, and the corresponding slump results were measured. Results showed that to preserve the slump values, extra water content of 5–8 % should be added for every 0.1 % of CNF incorporated in the concrete mixture. Based on compressive strength tests, it has been shown that CNF is the weakest link in concrete microstructures and controls the compressive strength.

Keywords

cellulose nanofibrils, internal curing, rheology, workability, cement paste, concrete, compressive strength, shrinkage

Introduction

It is known that the cement industry is huge and that about 5 % of total man-made carbon dioxide emissions come from the cement industry. Introducing any new green material in this field will be a promising new road toward sustainable development. Recently, there have been some serious environmental problems, so researchers and institutes are looking to find green materials that enhance and develop the construction industry using plant-based materials [1]. Usually, these materials are biodegradable, easy to produce, abundant, and environmentally friendly. Kawashima and Shah tried to use cellulose fibers as an internal curing agent for improving early age autogenous and drying shrinkage properties of cementitious materials [2]. Mezencevova et al. investigated the effect of Thermomechanical Pulp fibers on the internal curing of cementitious materials [3].

A concurrently developing trend in the cement and concrete industry is the use of nanomaterial additives. These nanobased materials have the potential to dramatically change traditional construction materials. Using these nanomaterials, one can modify the microstructure of cement paste, improving any number of desired properties. Thus, it may be possible to tailor mechanical and chemical properties to our particular needs. Exploring the unique advantages of plant-based nanomaterials has the potential to exploit the promise of nanomaterials with a renewable resource.

Peters et al. showed that a combination of nanocellulose and microcellulose fibers can increase the fracture energy by more than 50 % [4]. Cao et al. tried to use cellulose nanocrystals (CNCs) to improve the performance of cement paste. They found that CNCs can increase flexural strength and the degree of hydration of cement pastes [5]. In another project, they found that it is possible to improve the flexural strength of cement paste by up to 50 % [6]. Also, the influence of CNCs on the microstructure of cement paste was investigated by researchers [7,8]. Nine different CNCs were tested for improving the hydration and flexural strength of portland cement pastes in research by Fu et al. [9].

In the study described in this article, cellulose nanofibrils (CNFs) were used. Very little work has been done with this particular material; this is one of the first investigations into discovering the effects of CNF on cement paste and concrete. CNFs are nanoparticles (typically, less than 0.2 mm in length and 50 nm in width) that are often branched or forked and can be extracted from plants, trees, and renewable forest resources. They are biodegradable and less abrasive to processing equipment [10]. They are promising nanoscale hydrophilic materials that have several unique characteristics, such as high aspect ratio, low density (1.0 g/cc slurry), and high specific surface (31–33 m^2/g) that enable functionalization [10]. Most recent research has concentrated on the utilization of CNF in

traditional high-volume, low-cost products, such as paper packing, paints, composites, and food. However, these properties have led us to believe there could be a useful role for CNFs as an additive to portland cement concrete systems for shrinkage reduction, as well as an internal curing agent.

The goal of the work described in this article is to investigate the effects of CNF dosages on selected fresh and hardened properties of cement paste and concrete. We hypothesize that CNFs offer the potential for improved performance of cementitious composites using a material that is renewable, sustainable, that has low toxicity, low cost ($1.25/lb. = $2.76/kg slurry), and is suited for mass production [10]. In the work described in this article, CNFs were added into concrete and cement pastes at different dosages. Tests were designed and performed to study how the CNFs affect rheological, shrinkage, and strength properties of cement paste. Additional tests were run to measure the effects of CNF on workability and compressive strength of concrete mixes.

Materials and Specimen Preparation

CEMENT PASTE MIX

The CNF-modified cement paste composites used in this research were prepared by mixing CNF suspensions, water, and cement powder to obtain mixtures with different concentrations of each constituent CNF. Three main properties of the resulting mixture have been investigated. First, the effect of CNF on the rheology of cement paste using a flow table and kitchen mixer rheometer test was measured. Based on the results from the first part, the effect of CNF on free shrinkage and compressive strength of cement paste was investigated.

Cement Paste Specimen Preparation

The cement pastes were mixed with a conventional 8-qt rotary kitchen mixer. Traditional ultrasonication method for homogenization/dispersion of nanomaterials was not so effective for CNF; hence, the following procedure was used for mixing the pastes: (1) the CNF suspension was mixed with water in a separate 6-qt rotary kitchen mixer for 180 seconds at a speed of 95 r/min (homogenization/dispersion); (2) the solution from Step 1 was combined with cement powder and mixed at a speed of 60 r/min for 120 seconds; (3) the mix was allowed to rest for 15 seconds; (4) additional mixing for 60 seconds at a speed of 95 r/min; (5) rest for 15 seconds; (6) mixing for 60 seconds at a speed of 115 r/min; (7) rest for 15 seconds; and finally,(8) mixing at a speed of 135 r/min for 60 seconds. At each 15-second rest, a spatula was used to scrape the wall and bottom of the mixing bowl. The CNF concentrations of each batch were calculated based on volume fraction with respect to cement. Cement pastes were prepared at four different groups with different water to cement (w/c) ratios. For each group, eight different CNF concentrations were used. A total of 32 cement paste batches were prepared in 4 different groups. These groups are shown in **Table 1**.

As detailed below, the current drawn by the mixer as well as its power factor was logged during the entire mixing process. As detailed below, flow table tests were conducted immediately after completion of the mixing procedure. Portland cement Type I/II (commercial grade) that complies with ASTM C150/C150M-17, *Standard Specification for Portland Cement* [11], was used in these tests. The CNF materials used in this research were produced by the University of Maine Process Development Center. The as-received CNF materials were in a white odorless aqueous slurry form. The concentration of solids is

TABLE 1
Test matrix for CNF-reinforced cement paste.

	Mix No.	w/c (%)	CNF (% Volume)	Cement (g)	Water (g)	CNF Slurry (g)
Group 1 – w/c = 35 %	1 (Reference)	35	0.00	4,120	1,442	0
	2	35	0.05	4,119	1,421	22
	3	35	0.10	4,118	1,399	44
	4	35	0.20	4,116	1,356	87
	5	35	0.50	4,110	1,228	217
	6	35	1.00	4,101	1,014	434
	7	35	1.50	4,091	802	649
	8	35	3.00	4,062	171	1,290
Group 2 – w/c = 40 %	9 (Reference)	40	0.00	3,833	1,533	0
	10	40	0.05	3,832	1,513	20
	11	40	0.10	3,831	1,493	41
	12	40	0.20	3,830	1,453	81
	13	40	0.50	3,825	1,334	202
	14	40	1.00	3,816	1,135	404
	15	40	1.50	3,808	937	604
	16	40	3.00	3,783	348	1,201
Group 3 – w/c = 45 %	17 (Reference)	45	0.00	3,583	1,612	0
	18	45	0.05	3,583	1,594	19
	19	45	0.10	3,582	1,575	38
	20	45	0.20	3,580	1,538	76
	21	45	0.50	3,576	1,426	189
	22	45	1.00	3,568	1,240	378
	23	45	1.50	3,561	1,054	565
	24	45	3.00	3,539	503	1,124
Group 4 – w/c = 50 %	25 (Reference)	50	0.00	3,364	1,682	0
	26	50	0.05	3,363	1,664	18
	27	50	0.10	3,363	1,647	36
	28	50	0.20	3,361	1,612	71
	29	50	0.50	3,358	1,506	178
	30	50	1.00	3,351	1,332	355
	31	50	1.50	3,345	1,157	531
	32	50	3.00	3,325	639	1,056

3.0 % (3 g of nanofibrils and 97 g of water in 100 g of suspension), and the density of aqueous gel is 1.0 g/cm^3 [10].

CONCRETE MIX

Concrete mixes were prepared with the primary goal of evaluating the effects of CNF on workability. Concrete mixtures were prepared by mixing CNF slurry, water, sand, gravel, and cement to make batches with different concentrations of CNF. Twelve different concrete batches prepared in four groups are described in Table 2.

Concrete Specimen Preparation

The following procedure was used to mix the concrete and slump test: (1) CNF suspension was mixed with water in a separate 6-qt rotary kitchen mixer for 180 seconds at a speed of 95 r/min (homogenization/dispersion); (2) the solution from the previous step was mixed with cement, sand, and gravel at a speed of 95 r/min for 180 seconds; (3) after completing the mixing procedure, a slump test was done. The cement and CNF used for concrete

TABLE 2
Test matrix for CNF-reinforced concrete.

Mix No.	CNF (% volume)	w/c (%)	Cement (g)	Water (g)	Sand (g)	Gravel (g)	CNF Slurry (g)
1	0	45	2,600	1,170	5,119	6,143	0
2	0	50	2,600	1,300	4,971	5,965	0
3	0	55	2,600	1,430	4,823	5,788	0
4	0.1	55	2,600	1,346	4,823	5,788	87
5	0.1	60	2,600	1,476	4,676	5,611	87
6	0.1	65	2,600	1,606	4,528	5,434	87
7	0.2	60	2,600	1,392	4,676	5,611	173
8	0.2	65	2,600	1,522	4,528	5,434	173
9	0.2	70	2,600	1,652	4,380	5,256	173
10	0.3	65	2,600	1,438	4,528	5,434	260
11	0.3	70	2,600	1,568	4,380	5,256	260
12	0.3	75	2,600	1,698	4,233	5,079	260

specimens were the same as that used for preparing cement paste. All-purpose sand and bulk gravel (passing a 3/8-in. sieve) was used in the concrete specimens.

Experimental Testing Procedures

CEMENT PASTE RHEOLOGY TESTS

The goal of the work described in this section was to quantify the rheological properties of cement paste with varying w/c ratios and CNF contents. To realize this goal, two methods were employed. The first method consisted of using a conventional rotary mixer connected to a data-logging ammeter such that torque could be measured as a function of rotational speed. The second method employed a standard flow table test. Details of these methods are presented below.

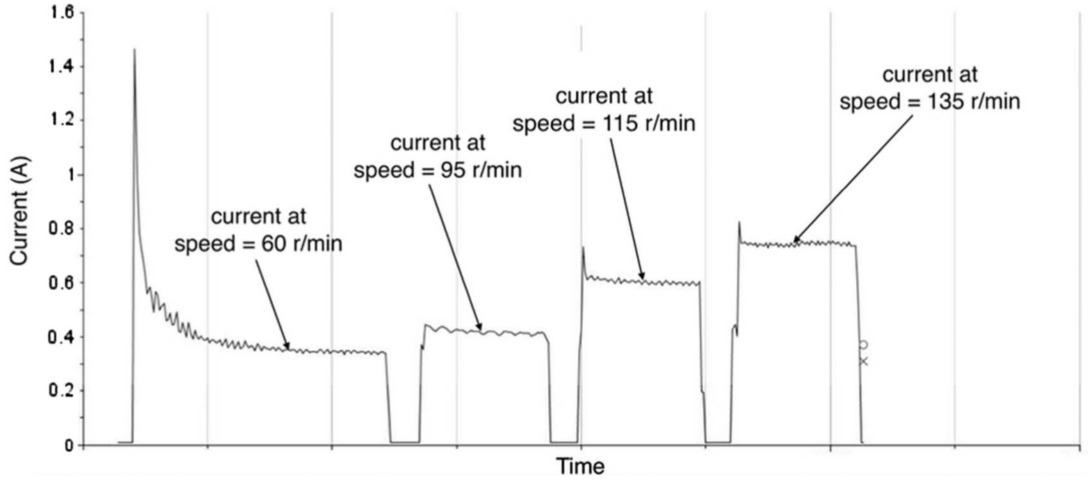
Kitchen Mixer Rheometer

There are a number of commercially available instruments for measurements of concrete rheology. A comprehensive study at the National Institute of Standards and Technology showed that the different instruments actually produced widely different values for both yield stress and viscosity [12]. Since the basic goals of this study were to measure relative differences in rheological properties between different paste mixes with CNF additions, a simple method was developed using a conventional rotary kitchen mixer.

The torque required to move the fresh paste at different mixer speeds was used to develop a torque–rotational speed relationship. The basis for this method was recognition that a higher viscosity cement paste would require more torque to drive the electric mixer to a given speed. Hence, a data-logging ammeter was connected to the mixer so that the current could be monitored as the mixer ran at different speeds. Through the application of basic electrical machinery principles, the current and voltage measurements could be converted to a torque applied to the mixing paddle. As shown below, the relationship between torque and rotational paddle speed serves a proxy for viscosity.

The ammeter used in this work was a HOBO Plug Load Logger (Onset Computer Corporations, Bourne, MA), which includes a computer interface. An 8-qt rotary kitchen mixer was used to mix the cement paste. Four speeds were used for mixing the paste in this study, 60, 95, 115, and 135 r/min. A detailed mixing procedure can be found in previous

FIG. 1 Typical current versus time results.



sections. Currents and power factor were measured during mixing at each of the different speeds, as illustrated in Fig. 1.

The calculation of mixer torque required several additional electrical measurements, namely voltage and resistance. Both these measurements were made using a handheld multimeter while the instrument was operating at different speeds.

The torque required to turn the mixer paddle was calculated using the following relationship:

$$T = \frac{P_m}{\omega * \frac{2*\pi}{60}} \tag{1}$$

where T is the torque (N · m), ω is the rotational speed in r/min, and P_m is the mechanical power (VA), which can be estimated by the following:

$$P_m = P_e - P_{losses} \tag{2}$$

where the P_e is the electric power (VA) calculated as follows:

$$P_e = V * I * PF \tag{3}$$

and P_{losses} is the power losses defined as follows:

$$P_{losses} = I^2 * R \tag{4}$$

In these last two expressions, I is the current in amperes, V is the voltage (volts), and PF is the measured power factor. R is the resistance in ohms.

Recognizing that a certain amount of torque is required to turn the mixing paddle without any paste in the mixing bowl, a net torque, T_{net}, is defined as the difference between the torque measured with paste, and the torque measured without paste, or:

$$T_{net} = T_{meas} - T_0 \tag{5}$$

where T_{meas} is the measured torque for paste ($N \cdot m$), and T_0 is the torque for paddle only ($N \cdot m$).

Cement Paste Flow Table Test

A flow table test based on ASTM C1437-15, *Standard Test Method for Flow of Hydraulic Cement Mortar*[13], was performed for each batch directly after finishing the mixing procedure. The result is the flow in percentage, for each batch.

CEMENT PASTE FREE-SHRINKAGE TEST

After mixing the mixture, two cold-rolled steel molds with dimensions of 1 by 1 by 11.25 in. (25.4 by 25.4 by 285.75 mm) were used to mold the specimens. ASTM C157/C157M-17, *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete* [14], was used to cast the specimens. After 24 hours of curing in a wet room, the specimens were demolded and stored in an enclosed plastic chamber throughout the data collection period. Length measurements were made using Dial Indicator H-3250 (Humboldt Manufaturing Inc., Raleigh, NC), a length comparator. This device meets the requirements of both ASTM C157/C157M-17 [14] and ASTM C490/C490M-17, *Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete* [15]. The specimens were named and marked for the upper and lower ends to ensure that all specimens are placed in the same direction and at the same position in the length comparator device at each measurement.

The initial reading (reference) of the specimen's length was taken directly after demolding the specimens, which means after 1 day after water was added to the cement. Subsequent readings were taken at 3, 5, 7, 11, 14, 21, 28, and 90 days of aging. At each reading, the temperature and relative humidity were recorded.

CEMENT PASTE COMPRESSIVE STRENGTH TEST

After mixing the paste, two 2-in. (50.8 mm) cube molds were used to mold two specimens for each batch. Molds were kept inside zipped bags (sealed condition) for 24 hours. Then, specimens were demolded and cured inside other zipped bags (sealed condition) for 28 days. ASTM C109/C109M - 16a, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)* [16], was used to break the specimens and measure the compressive strengths aged at 28 days. Results are the average value of the compressive strengths of two specimens for each batch.

CONCRETE SLUMP TESTS

A slump test, which was based on ASTM C143/C143M-15a, *Standard Test Method for Slump of Hydraulic-Cement Concrete* [17], was performed for each batch directly after finishing the mixing procedure. The result is the slump in centimeters, for each batch.

CONCRETE COMPRESSIVE STRENGTH TEST

After mixing the concrete, four 3 by 6 in. (76.2 by 152.4 mm) cylinder molds were used to mold four specimens for each batch. Molds were kept inside a wet room for 24 hours. Then specimens were demolded and cured inside a wet room for 28 days. ASTM C39/C39M-18, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*[18], was used to break the specimens and measure the compressive strengths aged for 28 days. Results are the average value of compressive strengths of four specimens for each batch.

Results and Discussions

CEMENT PASTE RHEOLOGY

Cement Paste Kitchen Mixer Rheometer

Using measured parameters by ammeter and the equations mentioned before, net torque for each batch at different rotational speeds was calculated. Fig. 2 shows the relationship between the net torque (N · m) and the rotational speed (r/s) for each group (different w/c ratios) at different CNF ratios. It was observed in all mixtures that torque is increased when the rotational speed is increased. If one assumes that cement pastes follow the Bingham model, then we need to determine yield stress and viscosity for each mixture. Initiation torque (torque at first rotational speed) can be interpreted as an index of yield stress, and the slope of each line can be seen as an index of viscosity for that particular mixture. Results for initial torque and relative viscosity versus CNF in different groups are shown in Fig. 3. It can be seen that, in all groups, increasing CNF leads to increasing initiation torque as well as relative viscosity. These results show that increasing CNF dosage leads to poorer workability. Furthermore, the effects are more severe at lower w/c ratios.

FIG. 2 Net torque versus rotational speed: (a) Group 1, w/c = 0.35; (b) Group 2, w/c = 0.40; (c) Group 3, w/c = 0.45; and (d) Group 4, w/c = 0.50.

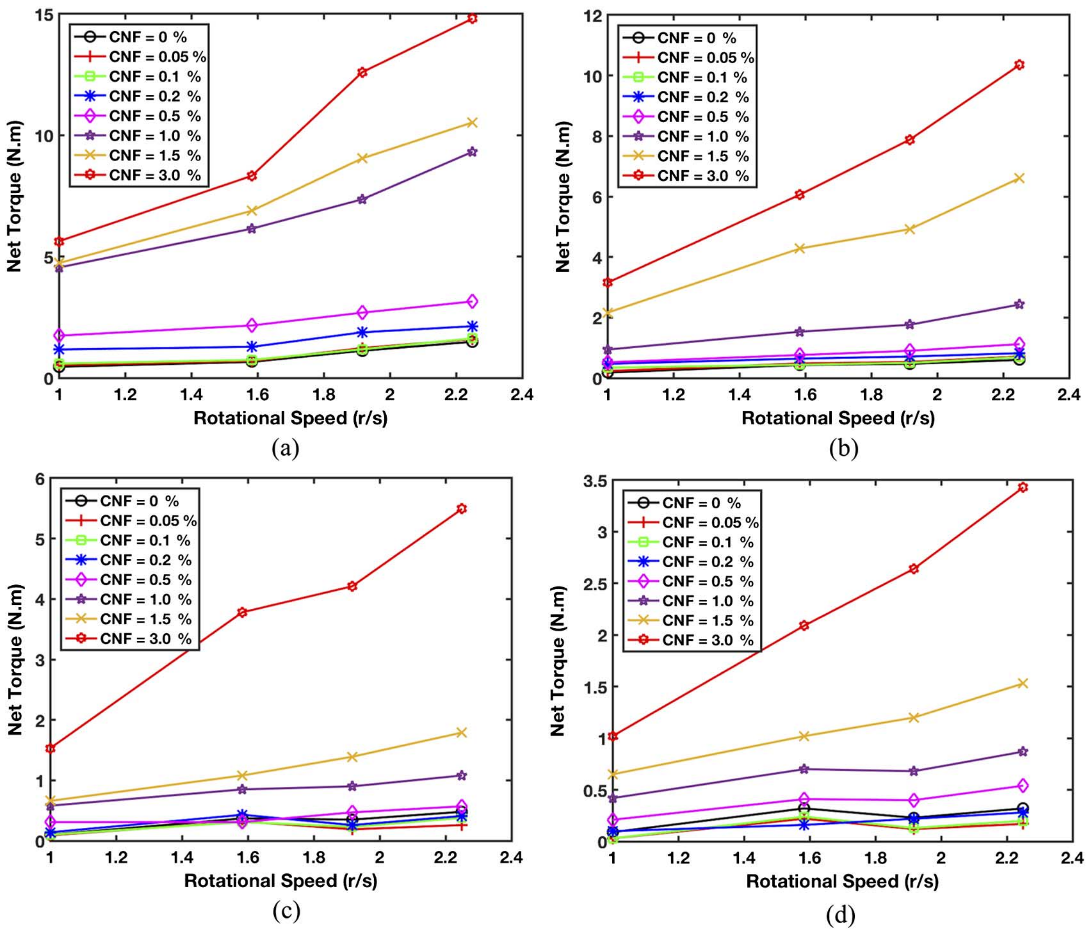
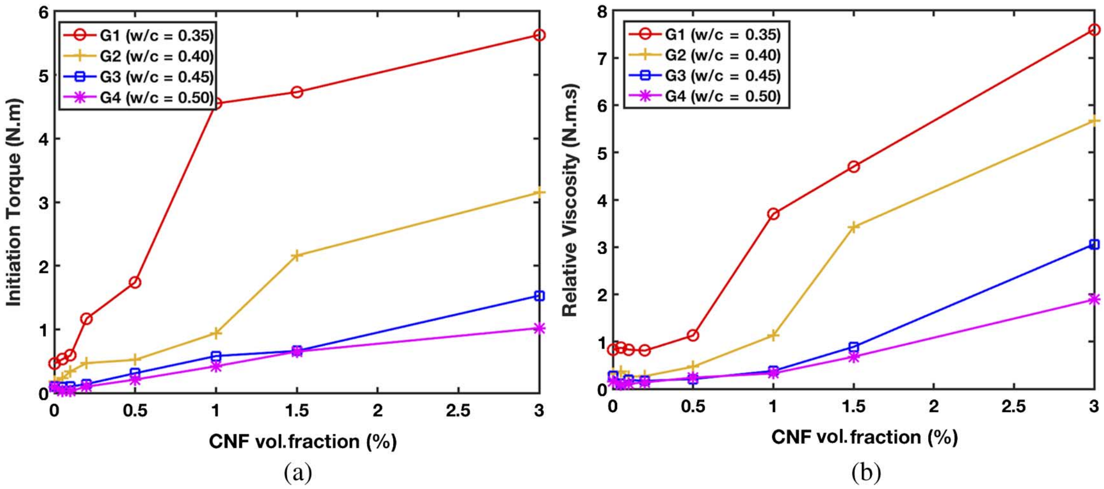


FIG. 3 Relative rheological parameters: (a) initiation torque and (b) relative viscosity.

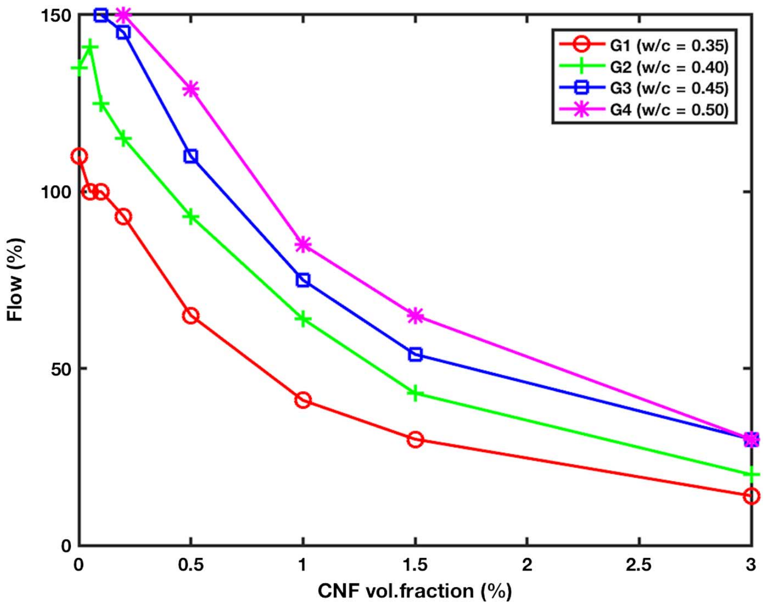


Cement Paste Flow Table

Fig. 4 shows the effect of CNF on the flow table results of different batches in four groups with various amounts of CNF. The results show that the flow decreased by increasing the amount of CNF for each group, which means that adding CNF decreased workability for all groups. These results support the results found using the kitchen mixer rheometer described in the previous section. A possible interpretation for these results is that the CNF may be agglomerating in such a way to decrease workability. Results from the flow table

FIG. 4

Flow versus CNF volume fraction.



tests and kitchen mixer rheometer tests give a prediction that water in CNF slurry is not available as the water of the mixture is in fresh cement paste.

CEMENT PASTE FREE SHRINKAGE

Fig. 5 shows the results of free shrinkage versus time for 90 days. When aged for 28 days, the results showed that at higher w/c ratios (w/c = 0.40, 0.45, and 0.50) an increase in the CNF dosage led to an increase in the free shrinkage. At the lowest w/c ratio (w/c = 0.35), however, small dosages of CNF led to a reduction in free shrinkage when compared with the reference batch of this group. Using a small rate of the CNF, such as 0.05, 0.1, 0.2, and 0.5 %, has helped to decrease the free shrinkage. However, no benefit was found in adding other rates, such as 1, 1.5, and 3 %.

This result might be explained if one assumes that the shrinkage can be broken down into autogenous and drying shrinkage. Recognizing that, for w/c ratios less than 42 %, autogenous shrinkage can be significant [19,20], we can assume that for the higher w/c mixes, we are observing only drying shrinkage. The fact that the addition of CNF only increases the shrinkage for these mixes suggests that the interaction of CNF and mix water

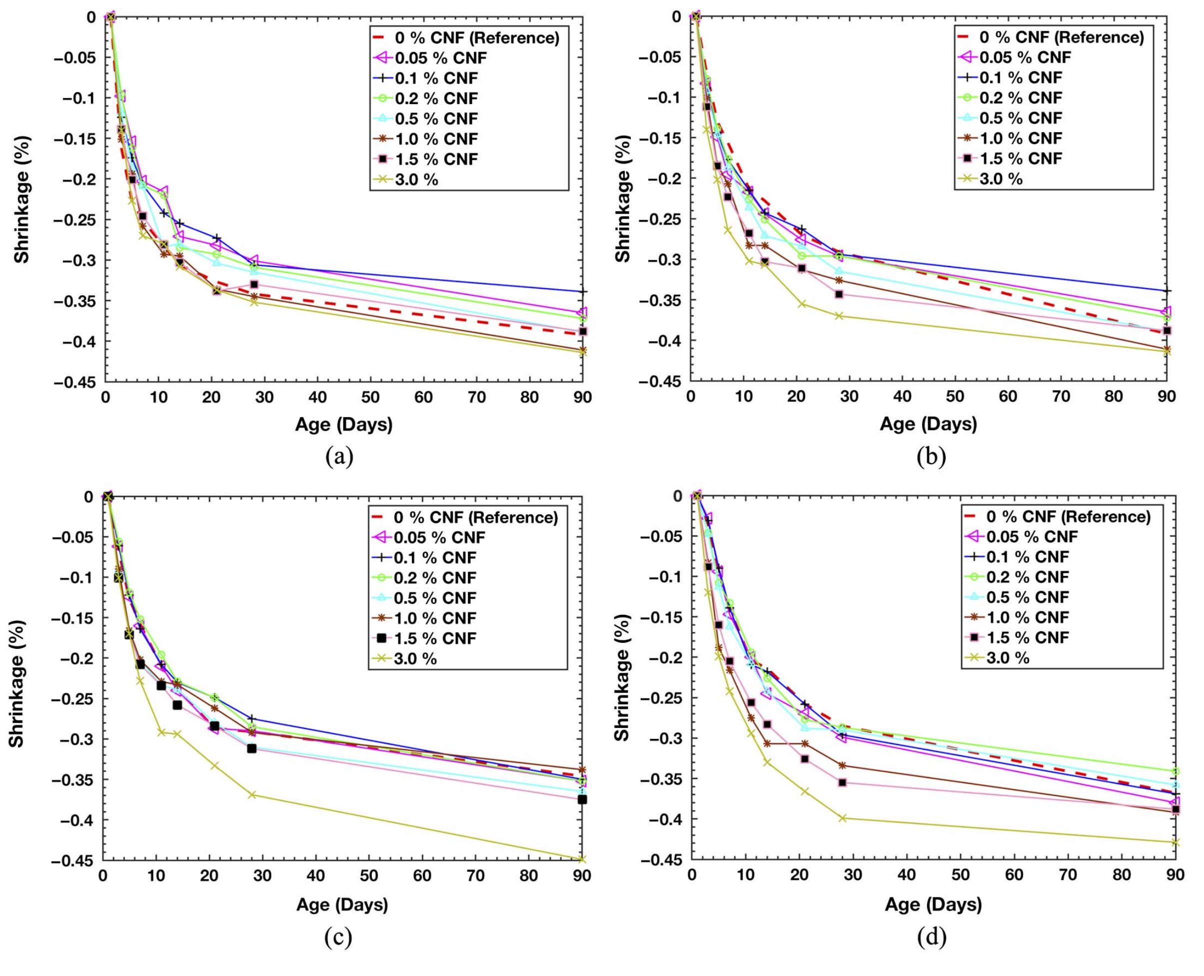


FIG. 5 Shrinkage versus age: (a) Group 1, w/c = 0.35; (b) Group 2, w/c = 0.40; (c) Group 3, w/c = 0.45; and (d) Group 4, w/c = 0.50.

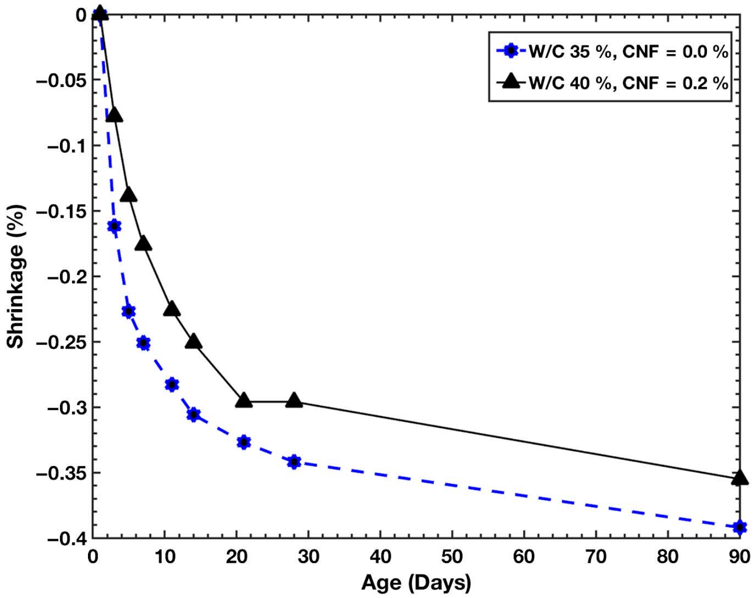


FIG. 6
Shrinkage versus age for two batches with the same workability (flow).

perhaps leads to an increase in capillary porosity and hence greater drying shrinkage. However, the reduced shrinkage for low w/c ratio pastes could suggest that the CNF may be holding back mix water in a way that resembles an internal curing agent. That is, the low w/c ratio allows the formation of a low-porosity hardened paste, but the water held by the CNF is later drawn into the hydration reaction, minimizing self-desiccation, and reducing autogenous shrinkage. Effects of CNF on shrinkage of cement pastes are very similar to the effects of cellulose nanopulps on cement-based composites, as obtained by Ferrara et al. [21].

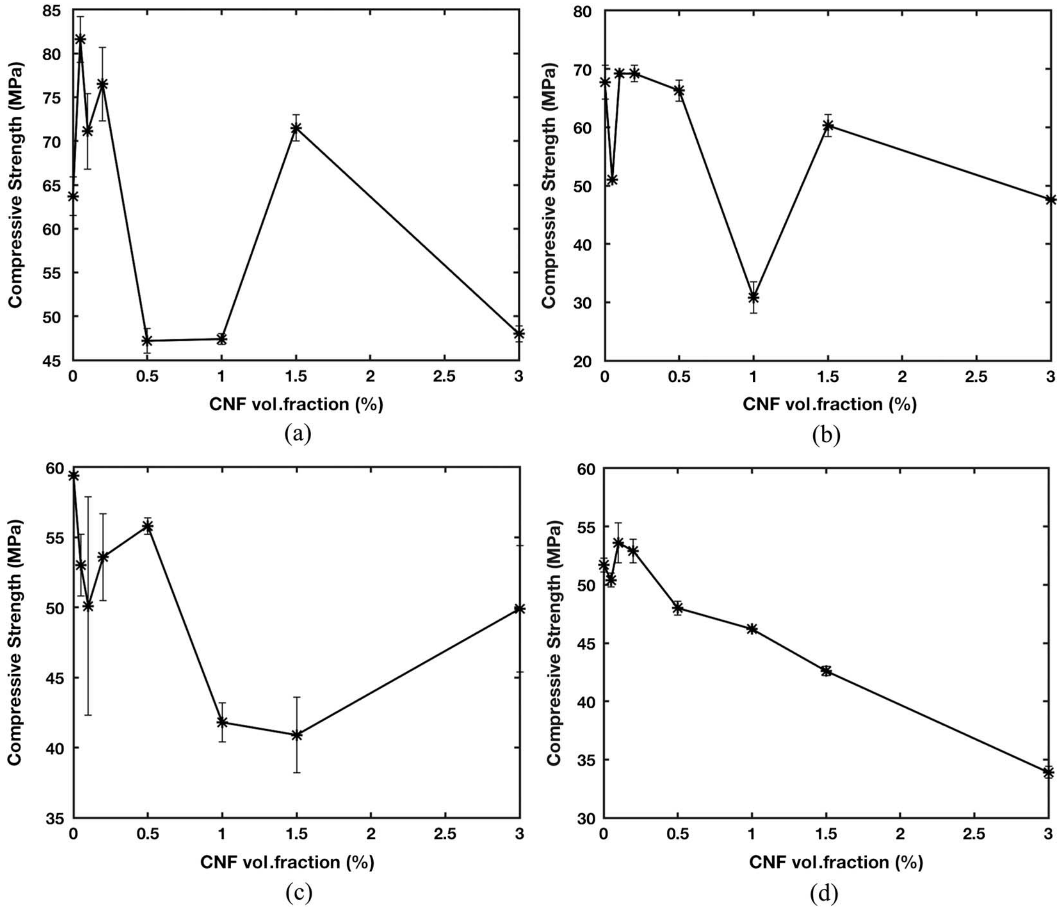
One other interesting way to consider the shrinkage measurements is to put them in terms of mixes of similar workability. Fig. 6 shows the shrinkage profile of two mixes that had the same flow table response. One mix had a w/c of 0.35 with no CNF, and the other mix had a w/c of 0.40 with 0.2 % CNF. At 28 days, the mix with CNF had 13 % less shrinkage than the mix without CNF.

CEMENT PASTE COMPRESSIVE STRENGTH

Results of compressive strength tests for cement pastes in Table 1 can be seen in Fig. 7. Again, the results in Group 1 (w/c = 0.35) are different from results in other groups. It can be observed that small quantities (0.05, 0.1, or 0.2 %) of CNF in Group 1 (w/c = 0.35) are effective and can improve the compressive strength. Using 0.05 % of CNF in cement paste increases compressive strength up to 28 % with respect to the reference paste (without CNF). No clear trend is observed with the higher w/c mixes, except that in all cases, high dosages of CNF reduce the compressive strength.

The improvement in strength observed in the low w/c ratio mixes can possibly be explained once again by an effect of internal curing. However, looking at Fig. 7a shows that this improvement disappears at higher dosages. The possible explanation for this result is that the CNF may be agglomerating in such a way to increase flaw sizes in the pastes. At low dosages, such an effect is small, but it likely dictates ultimate strength at high

FIG. 7 Cement pastes compressive strength results: (a) Group 1, w/c = 0.35; (b) Group 2, w/c = 0.40; (c) Group 3, w/c = 0.45; and (d) Group 4, w/c = 0.50.



dosages. It is interesting to note that in these four plots there is no clear trend for intermediate CNF dosages. An explanation for these erratic results requires further study.

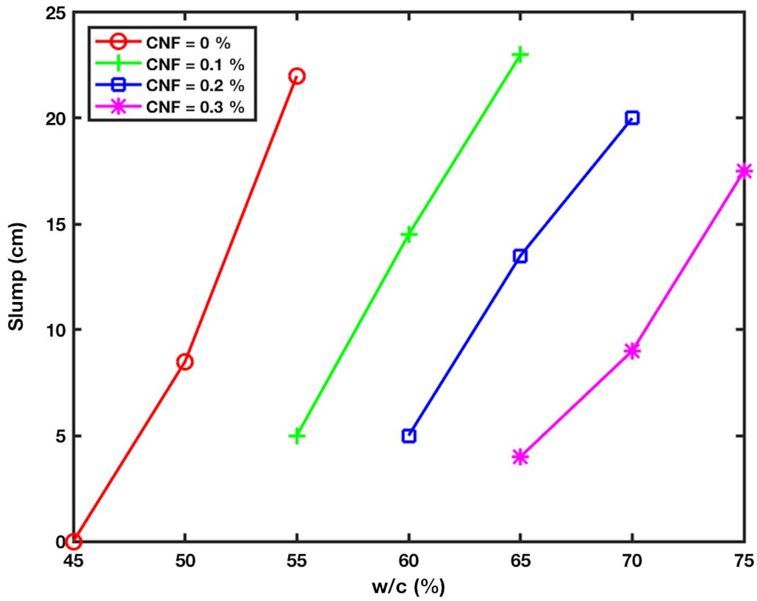
The positive effects at low w/c ratios on both shrinkage and compressive strength led us to believe that the CNF is acting as an internal curing agent in a manner similar to a super absorbent polymer [22]. That is, some of the mix water is being captured and held by the CNF during mixing but is released later on as hydration progresses. Such a mechanism would explain both the strength and shrinkage improvements as it would play a role in minimizing self-desiccation and autogenous shrinkage.

CONCRETE SLUMP

Fig. 8 presents the results obtained from the concrete slump tests. This figure shows slump results for batches in **Table 2** versus w/c ratios, displayed in different volumes of CNF. The plot highlights the observation that increasing CNF dosage leads to reduced workability. It can be seen that to preserve the slump values, extra water content of 5–8 % has to be added for every 0.1 % of additional CNF volume incorporated in the concrete mixture. As was suggested with the results from cement paste, the results here suggest that the water in

FIG. 8

Concrete slump test results.



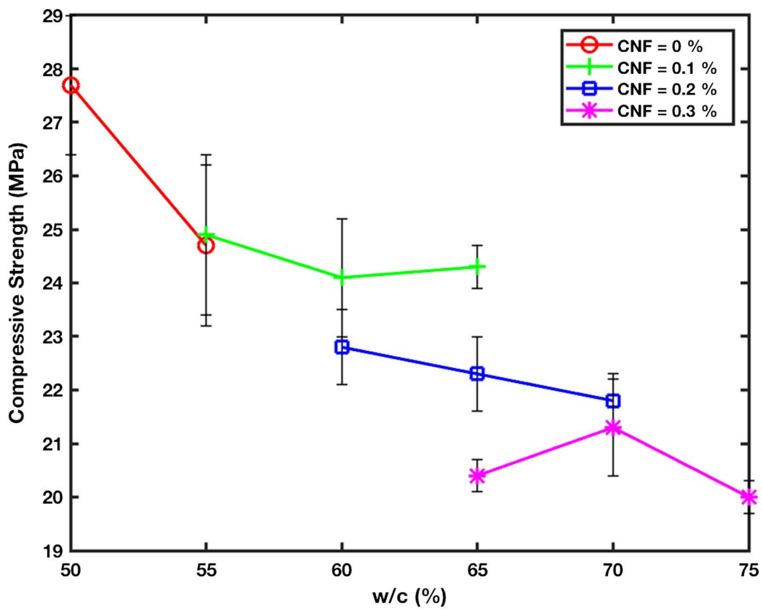
CNF slurry is not available as the water of the mixture in fresh concrete, and CNF agglomeration can play a role in decreasing workability.

CONCRETE COMPRESSIVE STRENGTH

Results of compressive strength tests for concrete batches in Table 2 can be seen in Fig. 9. It is clear from the plot that, in general, increasing the CNF dosage leads to a reduction

FIG. 9

Concrete compressive strength results.



in compressive strength for a given w/c ratio. However, it is also interesting to note that unlike traditional concrete, which loses strength at higher w/c ratios, the CNF-modified concrete is not so sensitive to the w/c ratio. That is, at a fixed dosage of CNF, the changes in strength with increasing w/c ratio is very small. This observation suggests that at higher w/c ratios, the additional porosity set up by the additional water no longer controls the compressive strength, but rather the changes in microstructure induced by the CNF control the compressive strength.

Conclusions

An array of tests were conducted with cement paste and concrete modified with CNFs. Two sets of rheological tests (torque and flow table) on cement pastes show that increasing CNF dosages decrease workability, which suggests that CNFs have the ability to retain water in fresh cement paste. Thus, the water in CNF slurry can't be counted as mixing water in fresh cement paste mixture calculation. This is very similar to the effect of Superabsorbent Polymers on cement pastes [22]. Free-shrinkage tests showed that at low w/c ratio (w/c = 0.35), small dosages of CNF reduced free shrinkage, while at higher w/c ratios, shrinkage was not improved and indeed was more severe with higher dosages of CNF. Likewise, with the compressive strength tests, at a low w/c ratio, small dosages (0.05, 0.1, or 0.2 %) of CNF led to an improvement in compressive strength. For example, adding 0.05 % CNF increased the compressive strength of a 0.35 w/c mix up to 28 % compared to the reference paste. However, at higher w/c ratios, the addition of CNF led to a reduction in compressive strength. Finally, the results from free shrinkage tests showed that the addition of CNF typically led to additional shrinkage beyond the control specimen, with the exception of the low w/c ratio mix in which shrinkage was reduced with the addition of CNF.

For concrete specimens, the study focused only on workability and compressive strength. Tests showed that the addition of CNF had a detrimental effect on workability. Slump tests showed that to preserve workability, w/c has to be increased by 5–8 % and has to be added for every 0.1 % of CNF incorporated in the concrete mixture. Regarding compressive strength, CNF addition did not have a positive effect. At a given w/c ratio, additions of CNF generally led to lower compressive strengths. One interesting finding is that when CNF was added to the mix, the compressive strength became less sensitive to changes in w/c ratio, which suggests that CNF changes the way critical flaws manifest themselves in higher w/c ratio mixes.

So overall, a general conclusion is that additions of CNF to concrete mixes can have both a positive and negative effect on properties. The current work is aimed at better understanding the status of water during mixing as well as better ways to disperse the CNFs. The former will allow us to better optimize CNF dosages, while the latter will allow us to better control both the effects on workability and the effects on strength at higher w/c ratios.

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