Using nanotechnology to improve concrete admixture for a lower carbon footprint

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Abstract: Today admixture is an essential component of most concrete and other cement-based materials. Continued efforts have been made to further enhance the performance of admixtures to obtain higher quality of concrete which can allow to reduce its carbon footprints by cutting down the cement content. This paper introduces our newly developed technology to apply nanomaterials in improving concrete and cement admixtures. Experiment is conducted with this new technology for typical concrete having a water to cement ratio of about 0.4 and backfill liquid paste for mining having 5–6% of cement content. Comparison is made with the current technology of polycarboxylate ether (PCE). It is found that compared with the use of only PCE, the nanotechnology can help further increase the compressive strength of concrete and backfill up to 15% and 64%, respectively. The mechanism for improving strength of the nanotechnology is not based on how much water reduced and thus it can lead to promising advantages when combined with traditional water reducing admixture. The addition of nano-additive can help reduce further up to 40 kg cement per 1 m^3 of concrete or over 17% cement content per 1 m^3 of backfill compared with the current admixture technology.

Keywords: concrete admixture, nanotechnology, polycarboxylate ether, backfill, cement reduction

1. Introduction

High range water-reducing admixtures can significantly decrease the essential water demand to obtain similar consistency of concrete mixture compared with that of one without admixture. With lower water content resulting in lower porosity, the mechanical properties of concrete are improved accordingly. Water reducers play a prominent role in the modern concrete technology thanks to this benefit.

Too much reduction of water, however, may have certain adverse effects on the workability of concrete. In addition, increasing concrete strength by reducing the water to cement ratio (w/c) does not follow a linear regression model and it has a certain limit depending on other factors such as cement type, aggregate quality, or the required workability.

Besides water reducer, efforts have been made to improve the mechanical properties of concrete with different approaches such as early carbon dioxide mineralization or inclusion of micro silica, graphene, or other nano materials in concrete. The sources and types of nano materials are becoming more numerous with the advancements of nanotechnology.

Nanotechnology can be considered as the fifth industrial revolution because of its impact on different industry sectors from pharmaceutics to aerospace, not excluding construction (1). For example, titanium oxide nanoparticles can be used for building coating for easy cleaning and ultraviolet protection. Another example is using nano-based catalyst for bitumen concrete to improve its strength, surface abrasion resistance, and anti-stripping properties (2).

The potential for further development of nanotechnology is still enormous. According to GlobeNewswire, the global market of nanomaterials was of USD 10.89 billion in 2022 and it is expected to grow up to USD 43 billion in 2030 with the high demand in electronics, biomedical, drug delivery, and optical fields. In the next section, we take a brief but closer look at typical nanotechnologies for cement concrete.

2. Typical nanotechnologies for cement concrete

It is generally known that nanoparticles act at the molecular scale of concrete resulting in enhanced properties such as compressive strength, thermal insulation, durability, resistance to corrosion, contraction, and crack, depending on the type of nanomaterials.

The grain size of a cement particle normally ranges from 7 to 200 microns (0.007–0.2 mm). The size of nanoparticles is at a significantly lower scale, 15–500 nm or 0.015–0.5 microns (3,4). A small quantity of nano materials can have plenty of super fine particles and thus they can be thoroughly dispersed in the cement paste. During hydration, the hydrate products of cement will deposit on nanoparticles to form conglomerations. The nanoparticles act as nucleus and allow more and evenly dispersed conglomerations to be formed. This will improve the nanostructure and microstructure of the cement phase leading to improved mechanical properties of concrete.

Different types of nano materials are considered for using in concrete. Their effects on mechanical properties of concrete vary from study to study.

Li et al (3) indicated that the addition of nano silica and nano ferric oxide can increase the compressive strength of cement mortar in the ranges of 12–26% and 3–19%, respectively. The dosage of the nano materials, however, is quite high in that study, e.g., 3–10% and 3–5% by weight of cement for nano silica and nano ferric oxide, respectively. They explained that other than acting as nucleus, nano silica can react with calcium hydroxide to form C-S-H to improve concrete strength.

In another study which one of the authors participated (5), we investigated effects of organic additives from silane nanoparticles on the hydration and mechanical properties of cement-based mortar compared with that of the original silane monomers. It is found that while silane monomers retard the cement hydration, silane nanoparticles do not cause retardation due to the combined effects of silane (retarding) and nano size (accelerating). The nanomaterials seem to improve the mechanical properties of mortar to a certain extend compared with the control sample without any silane. Such an effect, however, is less significant compared with that of the original silane monomers.

In this paper, we introduce the use of a nanomaterial in two applications, typical concrete and backfill for mining. Considering the cost efficiency and the convenience of using admixtures, the nanomaterial is pre-mixed with the available polycarboxylate-based admixtures.

3. Experimental study

3.1 Experimental details

Studies are conducted with concrete and backfill. Experiment details and test results of these concrete and backfill materials are given in Table 1 and Table 2 below, respectively.

Table 1. Experimental details and test results of concrete

Mix No.	Cement type	PCE admixture, %	Nano-additive, %	Slump flow, cm	Initial setting time, hr	Final setting time, hr	Compressive strength, MPa		
							1 day	7 days	28 days
M0	M	0.20	0	66.0	10:15	11:45	25.1	53.0	61.0
M1		0.20	0.05	62.0	10:05	11:35	25.2	53.5	62.6
M2		0.20	0.10	60.5	10:45	12:15	27.0	60.0	70.0
M3		0.20	0.20	62.0	11:15	12:45	27.0	54.0	63.0
H0	H	0.20	0	61.0	07:20	08:50	30.1	55.0	67.5
H1		0.20	0.05	62.5	08:00	09:30	32.0	56.9	68.4
H2		0.20	0.10	62.0	08:10	09:40	30.6	60.0	74.0
H3		0.20	0.20	60.0	08:35	10:05	31.0	56.0	67.0
C0	C	0.20	0	50.0	07:55	09:25	28.0	47.0	58.0
C1		0.20	0.05	58.0	08:10	09:40	28.0	49.0	60.0
C2		0.20	0.10	56.0	08:30	10:00	30.0	52.0	65.0
C3		0.20	0.20	56.0	09:10	10:40	28.3	48.5	60.0

Note: M, H, C are three types of cement from different cement suppliers

Portland cement, andesite fine aggregate, basalt coarse aggregate, and three types of cement from different suppliers are used for concrete. Other than Portland cement, mine tailings are used in backfill. Two types of polycarboxylate ether (PCE) admixtures are used in the study, one for concrete and the other one for backfill which are customized for these specific purposes. A special nanotechnolgy-based additive (nano-additive) is used for both concrete and backfill. Details of the mix proportions and chemical formula of related additives and admixtures are not provided in this paper. The experiment is conducted in Mexico.

A water to cement ratio (w/c) of 0.40 and a dosage of PCE admixture of 0.2% over cement weight are used for all concrete mixtures. For each cement type, nanotechnolgy-based additive (nano-additive) is used with different dosages at 0.05, 0.10, and 0.20 to compare with the control mixture without nano-additive. Concrete consistency is assessed via slump flow test. Initial and final setting time are also determined to see the effects of the nano-additive content. Compressive strength of all mixtures is tested at 1, 7, and 28 days.

Two cement contents of 5% and 6% are used for backfill. The respective w/c is 9.3 and 7.6, respectively. For each cement content, only PCE admixture and a combination of PCE admixture and nano-additive are used to compare with the control mixture without any admixture/additive. Compressive strength is determined at 7 and 28 days after mixing.

Table 2. Experimental details and test results of backfill

Mix No.	Cement content, %	w/c	PCE admixture, %	Nano-additive, %	Compressive strength, MPa	
					7 days	28 days
A1	5.0	9.3	0	0	0.44	0.88
B1			4.4	0	0.59	1.09
C1			4.4	0.1	0.59	1.47
A2	6.0	7.6	0	0	0.49	0.98
B2			3.8	0	0.64	1.16
C2			3.8	0.1	0.98	1.90

3.2 Results and discussion

3.2.1 Concrete workability

As shown in Figure 1, concrete slump flow does not seem to change significantly with the increase in dosage of the nano-additive. Note that the water content and water to cement ratio remain the same, the workability of concrete mixtures is mostly similar after including different dosages of nano-additive up to 0.2%.

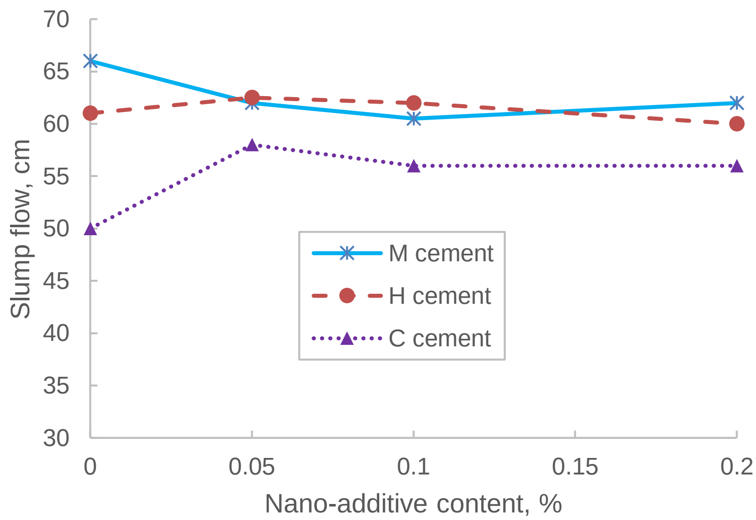

Figure 1. Effect of nano-additive on concrete flow

3.2.2 *Concrete setting time*

The addition and increasing dosage of nano-additive seem to lead to an increase in setting time, for both initial and final setting time. The trend can be noticed in all three cement types as shown in Figure 2.

For M cement, when the nano-additive dosage increases from 0 to 0.2%, the setting firstly decreases (-) 10 minutes, which may be attributed to the test tolerance, and increases (+) up to 60 minutes. For H cement, the setting time increases with the increase of the nano-additive dosage, i.e., from +40 to +75 minutes compared with that of the control mix H0. Similarly for C cement, the setting time also increases from +10 to +70 minutes compared with that of the control mix C0.

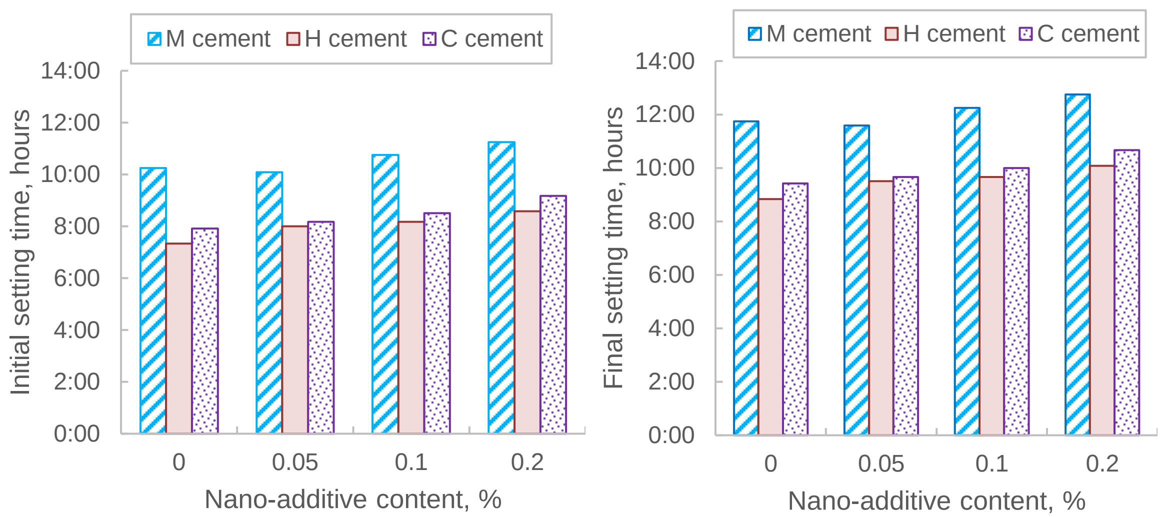

Figure 2. Effect of nano-additive on initial and final setting time

In literature, however, the addition of nano-additive often leads to a slightly shorter setting time of concrete. Ramezani et al. (6) explain that the additional surface area and nuclearation seeding sites caused by nanomaterials will facilitate faster the hydration process of mineral components in cement. In the current study, the nano-additive is used together with a water reducing admixture. The effect on the setting time is thus more complex. The delayed setting can be related to the interaction between the nano-additive and PCE and/or other components in the admixture. In comparison with the control sample and with the optimum nano-additive dosage of 0.1% as discussed in the next section, the extended setting time is in the range of 30–50 minutes for all cements. When using for applications requiring short setting time, this can be conveniently compensated by our current technology of accelerator which will be performed in the next phase of the project.

3.2.3 *Concrete compressive strength*

Effect of nano-additive dosage on the compressive strength of concrete over the ages of 1, 7, and 28 days is shown in Figure 3.

Generally, the 1-day strength of concrete is not much changed with different dosages of nano-additive, for all three cements. The amount of hydrated products is not significant at this early age and the strength is mainly influenced by the setting time.

At 7- and 28-day ages, the differences in strength are more noticeable. While the nano-additive dosage of 0.05% only leads to an increase of 1–4% in concrete strength, the dosage of 0.1% leads to a much more significant increase, in the range of 9–15% compared with the control one. Further increase in dosage up to 0.2%, however, does not provide benefit to the compressive strength.

It can be explained that the optimum dosage of 0.1% is the most favourable for the nano materials to provide sufficient seeding sites for the hydration of cement. Further increase in dosage leads to difficulties in the dispersion of nano-additive which can result in adverse effects on the mechanical properties of concrete material as reported by Adhikary (7).

In terms of absolute values, the addition of nano-additive increases the compressive strength of concrete 6.5–9 MPa at 28 days. This means that the addition of nano-additive may allow to reduce the cement content about 29–40 kg/m^3 of concrete, provided that the average cement content needed per 1 MPa for similar grade of concrete at 28 days is about 4.5 kg/m^3 according to Golaszewski et al. (8). With our typical PCE admixture reducing 15–20% water, the combination of nanotechnology and PCE technology can surely reduce over 100 kg cement per 1 m^3 concrete having w/c of 0.4 compared with that of plain concrete without any admixture.

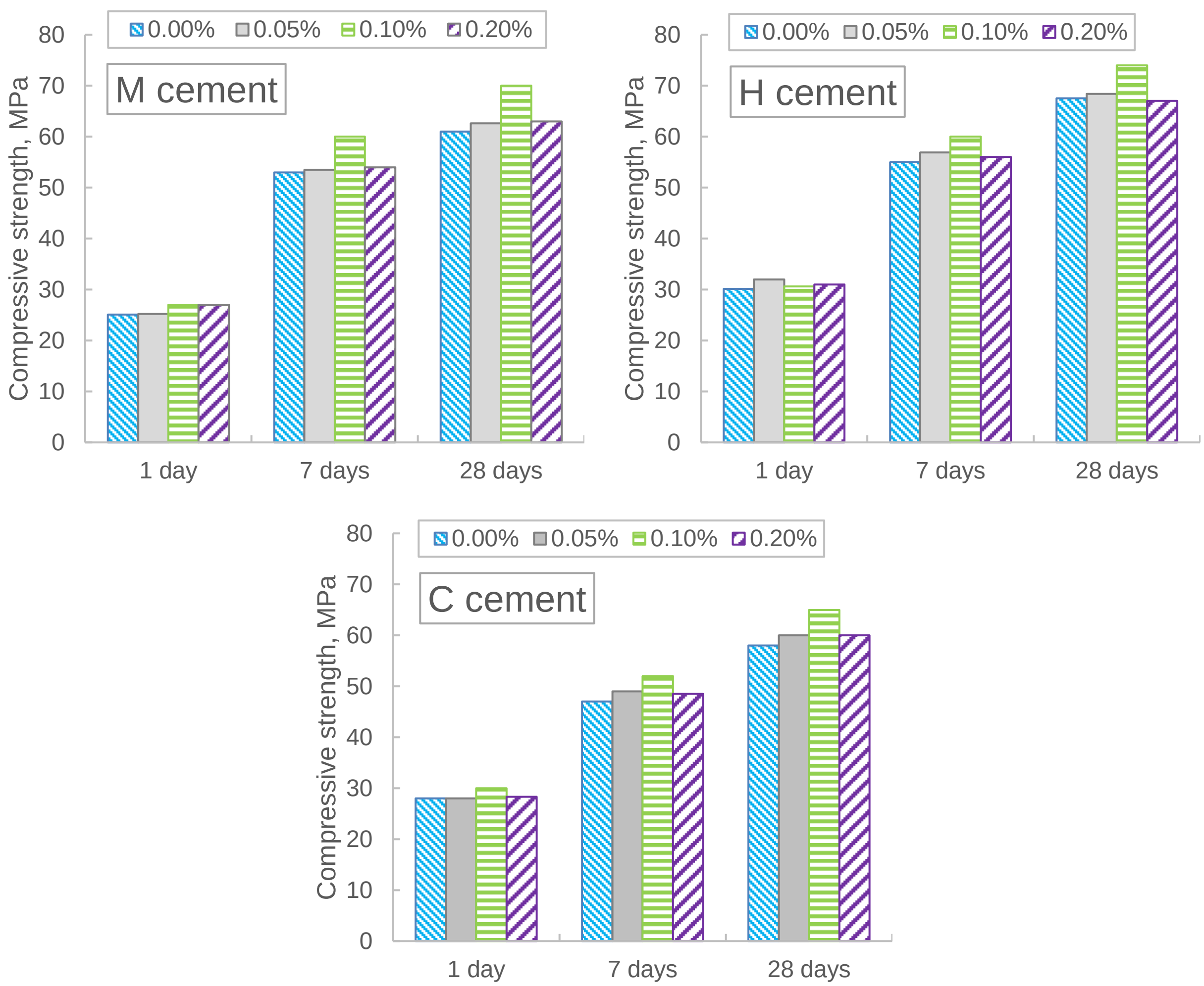

Figure 3. Effect of nano-additive on compressive strength of concrete

3.2.4 Backfill compressive strength

In Figure 4 below, the compressive strength of backfill at 7 and 28 days is plotted with three groups: (A1 & A2) backfill without admixture, (B1 & B2) with only PCE admixture, and (C1 & C2) with PCE admixture plus nano-additive.

In each group, the increase in cement content from 5% to 6% leads to an increase in strength of the material. The increases are more significant with group (C) having both PCE admixture and nano-additive. This can be attributed to the greater hydration process of higher amount of cement when there is a presence of nano-additive.

When comparing the backfill with a certain amount of cement, i.e., from (A1) to (C1) with 5% cement content or from A2 to C2 with 6% cement content, it is obvious that the inclusion of admixture leads to a significant increase in strength. The addition of nano-additive together with the admixture further increases the strength, even with greater magnitude.

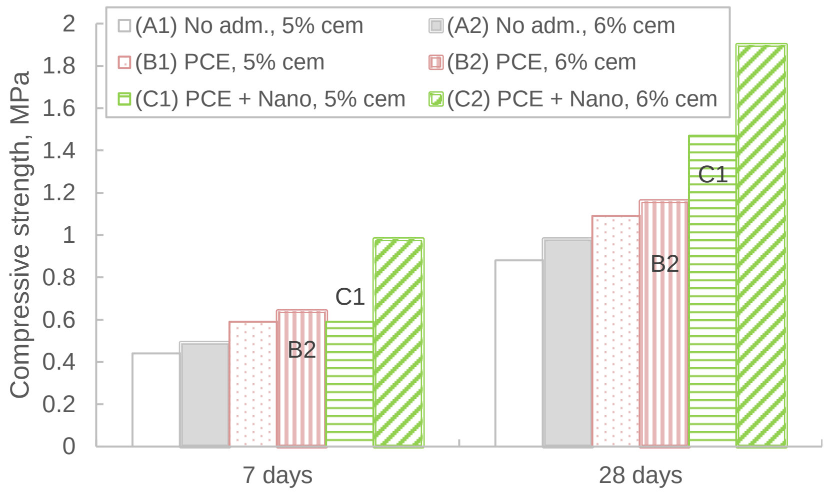

Figure 4. Effect of nano-additive on compressive strength of backfill

It is also of interest that the 28-day strength of mix C1 (having PCE + nano, 5% cement) is much better than that of B2 (having only PCE, 6% cement) although the 7-day strength is not much different. It means that compared with the single use of the current admixture, the addition of nano-additive can help save over 17% of cement content to obtain even better final compressive strength. Considering the large amount of backfill material for mining projects, this saving amount of cement is significant leading to considerable impact on the carbon-footprint of the project.

4. Conclusions

The application of nanomaterials for improving the performance of polycarboxylate ether admixtures is examined in this study. Results of the study show that it is feasible and practical to further increase the compressive strength of concrete and backfill by the improved structure at nanoscale in addition to the typical water reduction approach.

The inclusion of the nanomaterial in our commercial admixtures leads to the greater strength growth, especially at 28 days for both concrete and backfill. This can result in a saving of 29–40 kg cement per 1 m^3 of typical concrete and over 17% cement in the mixture of backfill for mining. The inclusion does not change much the workability of concrete while the setting time is slightly increased.

Results of the study have been granted a patent. The commercialization of this nanotechnology in Australia and further improvement in its performance are being performed.

5. Acknowledgements

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6. References

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