Innovations Deserving
Exploratory Analysis Programs

NCHRP IDEA Program

Nano-Enabled Multifunctional Concrete for Transportation Infrastructure

Final Report for
NCHRP IDEA Project 197

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August 2019

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NANO-ENABLED MULTIFUNCTIONAL CONCRETE FOR TRANSPORTATION INFRASTRUCUTRE

IDEA Program Final Report

NCHRP Project #197

Prepared for the IDEA program

Transportation Research Board

The National Academies

Dr. Rouzbeh Shahsavari

C-Crete Technologies

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We greatly thank the support of NCHRP-IDEA program, the panel committee, and Dr. Inam Jawed, and the project advisors including Richard Meininger, Colin Lobo, and Charles Nmai, as well as Bill Brudnick and Mark Woodridge from the Houston District of the Texas Department of Transportation for volunteering their times and providing valuable technical insights and practical guidance on this project.

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1. EXECUTIVE SUMMARY

Concrete is the most widely used synthetic material on earth. In the US, more than 75% of bridges and over 60% of interstate highways are made of concrete. There is no other bulk material on the horizon that could replace concrete as the backbone for our increasing demands in infrastructures. Despite several decades of studies, concrete bridges, highways and infrastructures still significantly suffer from fracture, deterioration and external chemical attacks (e.g., chlorides/sulphates) with maintenance costs that amount to multi-billion dollars annually.

To address the above critical needs, this project developed a new class of ultra-high performance, multifunctional concrete using emerging two-dimensional (2D) materials. The core strategy lies in mixing ultra-thin exfoliated nanosheets of 2D materials such as hexagonal boron nitride, hBN, as small as few atoms in thickness, in the bulk concrete (Figure 1). hBN exhibits several exotic properties (ultrahigh mechanical and thermal properties, chemical inertness, hydrophobicity, etc) that are highly desirable for a complex matrix such as concrete. These features, combined with the double surface area per mass of hBN sheets - compared to conventional 1D fibers - can act as template (seeds) to regulate the hydration processes and maximum contact between the sheets and the matrix, thereby providing an effective reinforcement from the bottom up. The overarching goal of this project was to study and identify the optimum experimental conditions and parameters for delivering the maximum mechanical properties and durability in hBN/concrete while economically and commercially being viable.

We studied several different routes to investigate the degree of exfoliation and reduction in size of hBN (to increase surface area) as well as their functionalization and water solubility in effectively mixing them in concrete. We synthesized various concrete coupons with variety of weight percentages of 2D materials. Notable among our results are the compressive strength of the concrete cylinders that can increase by >71%, with only a very small fraction of the 2D materials. Furthermore, we found the tensile strength of the concrete samples increases by >100%. The measured durability properties of the concrete samples also showed ~35% increase, compared to the control sample devoid of hBN. The origin of the improved properties stem from two key factors: 1) Ultrahigh surface area of hBN (ideally >2200 m^2/g for mono layer 2D materials), which effectively connect and bridge several phase of the concrete matrix, and 2) a charge transfer from Boron of hBN to Oxygen of Silicate groups in the concrete matrix, creating strong electrostatic bonds between 2D materials and the matrix.

Following discussions with TxDOT and implementation requirements, we determined a patch/repair job on a surface of a road/highway to be a good starting point for field testing. Upon consultation with TxDOT, we examined the compatibility of our formula with common accelerators such as $CaCl_2$ and found no negative cross-effect between our technology and common accelerators while exhibiting compressive strength of 1800 psi in only ~5 hours, making the technology suitable for rapid construction and/or maintenance in transportation applications.

Figure 1. An atomistic image of a mono-layer of hBN and Representative coupons of hBN/Concrete.

2. IDEA PRODUCT

The IDEA product is a nano-enabled concrete technology with enhanced mechanical and durability properties for transportation infrastructures. This is possible via a carefully synthesized nanosheet, which is added as a water soluble additive into concrete. This strategy allows creating nano-reinforced microstructures with minimal pores (due to filing effect of 2D materials) and more structural integrity of the matrix, contributing significantly to enhanced compressive and tensile strength as well as durability (i.e. blocking passage of deleterious ions). Such improved strength and durability allow "*to do more with less*". For example, a more durable concrete indicates lower maintenance costs. Similarly, a higher strength concrete translates to lower volume for construction of transportation infrastructures, which entail lower CO_2 emissions associated with concrete manufacturing.

3. CONCEPTS AND INNOVATION

The project's concepts, strategies, and methodologies have a radical departure from standard design of concrete materials. The main driving force of this project is that in spite of its very small fractions, hBN nanosheets mixed in concrete act as 2D nanotemplates to regulate hydration processes and microstructural features of concrete, resulting in significant improvements in mechanical and durability properties. This is original in cementitious materials and is enabled by the 2D nature of hBN as well as its exquisite multifunctional properties such as ultra-high surface area, chemical inertness, super mechanical properties, lubricity, etc. The unique attribute of this project is that 2D nanomaterials are more effective fillers for composites (than 1D conventional fibers/fillers) when prepared with high surface areas and high aspect ratios. For example, imagine an unzipped 1D tube to make a flat 2D sheet where the latter has double surface area per mass. Furthermore, such 2D materials, even randomly dispersed in concrete, can better block the passage of deleterious ions than 1D counterpart fibers (e.g. carbon nanotubes), thereby imparting less permeability and higher durability.

Based on our fundamental studies, the origin of such property enhancement in hBN/concrete mixes stem from two main factors: i) Ultrahigh surface area of hBN (ideally >2200 m^2/g for mono layer 2D materials), which effectively connect and bridge several phases of the concrete matrix (hydrated cement products such as calcium-silicate-hydrates, portlandite, and sands, gravel, etc), and ii) a charge transfer from Boron of hBN to Oxygen of Silicate groups in the concrete matrix, creating strong electrostatic bonds between 2D materials and the matrix (Figure 2). Together, this strategies open up a plethora of opportunities to tailor these distinct material classes (hBN and concrete) into a hybrid composite from the nanoscale up.

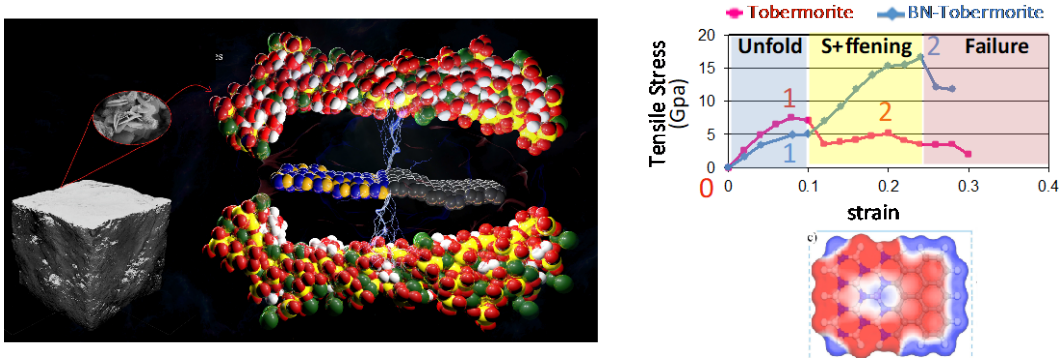

Figure 2. Two key sources of property enhancement: 1) ultra high surface area of 2D materials, 2) charge transfer from Boron to Oxygen of concrete ingredient.[11-12] Left: An atomistic image of intercalated cement/hBN. The thin middle layer represents a single hBN sheet, which is sandwiched between two calcium-silicate-hydrate phases as hydrated cement product. Right: stress versus strain in tobrmorite (a crystalline mineral of cement hydrate) and hBN/tobermorite composites. Bottom:

charge density around B and N atoms in the vicinity of silicate groups.

4. INVESTIGATION

4.1 Introduction

Boron nitride (BN) is a synthetic material made of boric acid or boron trioxide that is being increasingly investigated for novel applications. Among various crystalline forms of BN, its hexagonal allotrope, hBN, is similar to graphite in structure and layered form but with alternating boron (B) and nitrogen (N) atoms. BN has notable thermodynamic (stable up to 1000 °C) and chemical stability, exceptional hardness, corrosion resistivity, lubricating effect, and great thermal conductivity while electrically insulating [1-2, 11-12]. These properties make hBN a promising 2D nanofiller suitable for many technological applications. In the next section, first, we describe our exfoliation processes, and then we show mechanical and durability results.

4.2 Investigation of process parameters and properties

The exfoliation and functionalization of 2D materials such as hBN is a challenging task because of the inertness of the materials. A harsh chemistry (either acidic or basic) needs to be employed in order to break hBN down and functionalize them. The B atoms in the hBN are acidic in nature while N are basic. One needs a strong medium to drive the B and N atoms into the reaction as they are already participating in the aromatization. The π- cloud of electrons in the ring makes the atoms completely engaged.

Here, by avoiding the carcinogenic materials, we attempted a simple and inexpensive process to exfoliate and hydroxyl functionalize the hBN that were in the size of ~15 um. We systematically investigated various routes [1-10] to study the effects of:

A) Two different solvents
B) Combination of solvents.
C) Hot and cold temperatures.
D) Thermal treatment on the hBN up to 1000 ˚C
E) Other factors

In what follows, we review the results. Our goal is to exfoliate the large flakes of hBN into the smaller sizes and lower thicknesses while inducing hydroxyl functionalization.

4.2.1 Using solvent A (Isopropyl Alcohol) as the medium

a) Method A1. Methods A1 and A2 refer to different variation of an external exfoliation force such as sonication.. In method A1, we sonicated 50 mg/mL of hBN flakes in IPA for 200 minutes. Significant quantity of flakes (aggregates) is obtained, indicating that the exfoliation was not efficient. Figure 3-left shows flakes with minimal amount of exfoliation. As indicated by the arrows, however, there is an exfoliation to a certain extent.

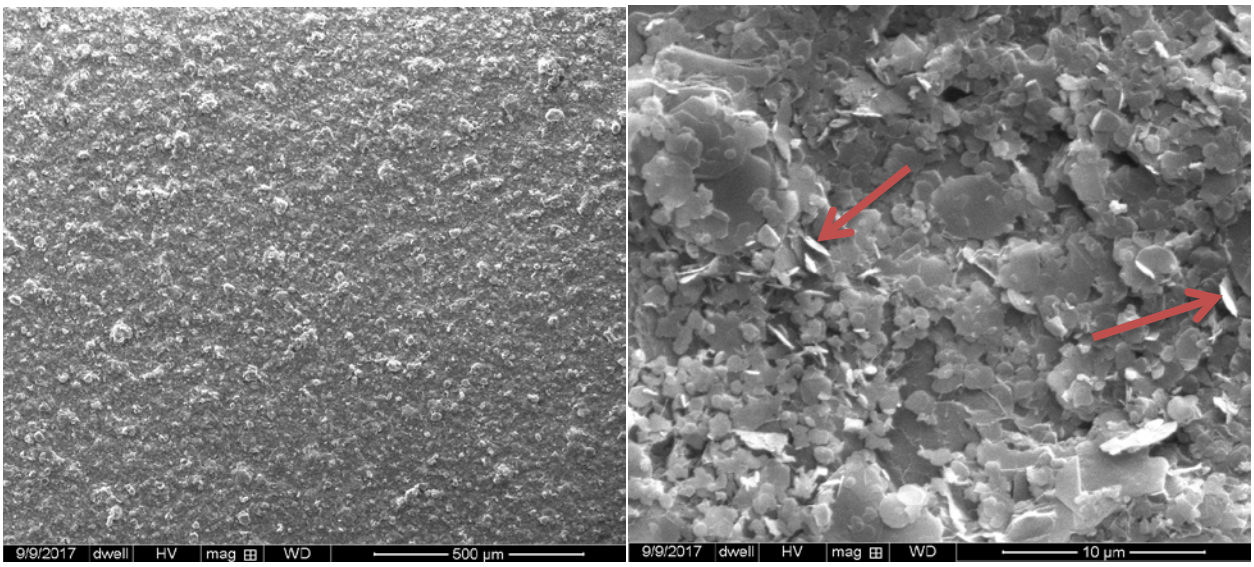

Figure 3. SEM images of exfoliated hBN using method A1: 50 mg/mL in IPA

<u>b) Method A2</u>. In method A2, we sonicated 25 mg/mL of hBN flakes in IPA for 100 min. The hBN in this case are better exfoliated compared to Method A1. The image on Figure 4-left shows the smoothness and homogeneity of the hBNs and the right image displays numerous smaller particles compared to the Figure 3. There are still aggregates present that could potentially be reduced. Figure 5 shows a zoomed-in image of Figure 4.

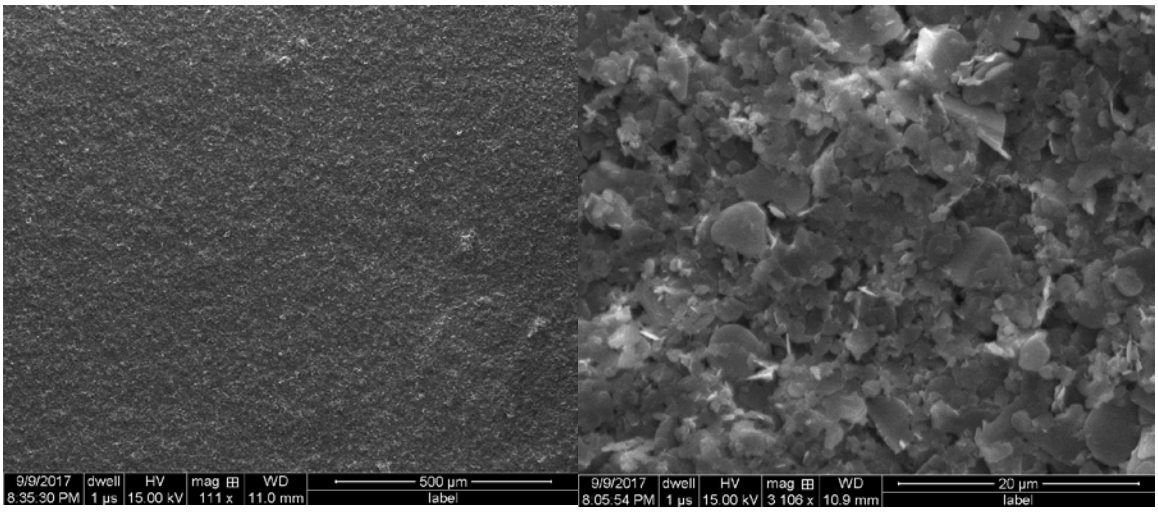

Figure 4. SEM images of exfoliated hBN using method A2: 25 mg/mL in IPA

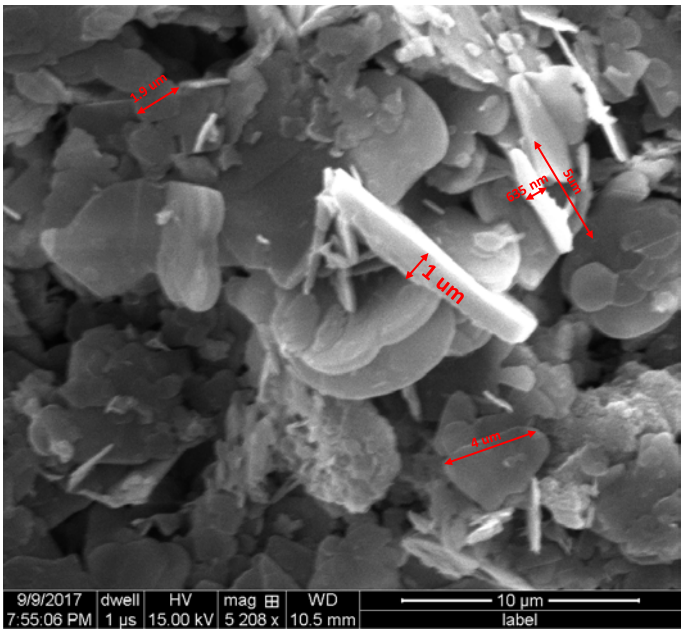

Figure 5. Zoomed SEM images of exfoliated hBN using method A2: 25 mg/mL in IPA.

4.2.2 Using solvent B (**Dimethylformamide)** *as the medium*

a) Method B1. In this method, 50 mg/mL of hBN flakes with sonicated in Dimethylformamide (DMF) for 200 min. hBN sheets were obtained (Fig 6) with a great exfoliation.

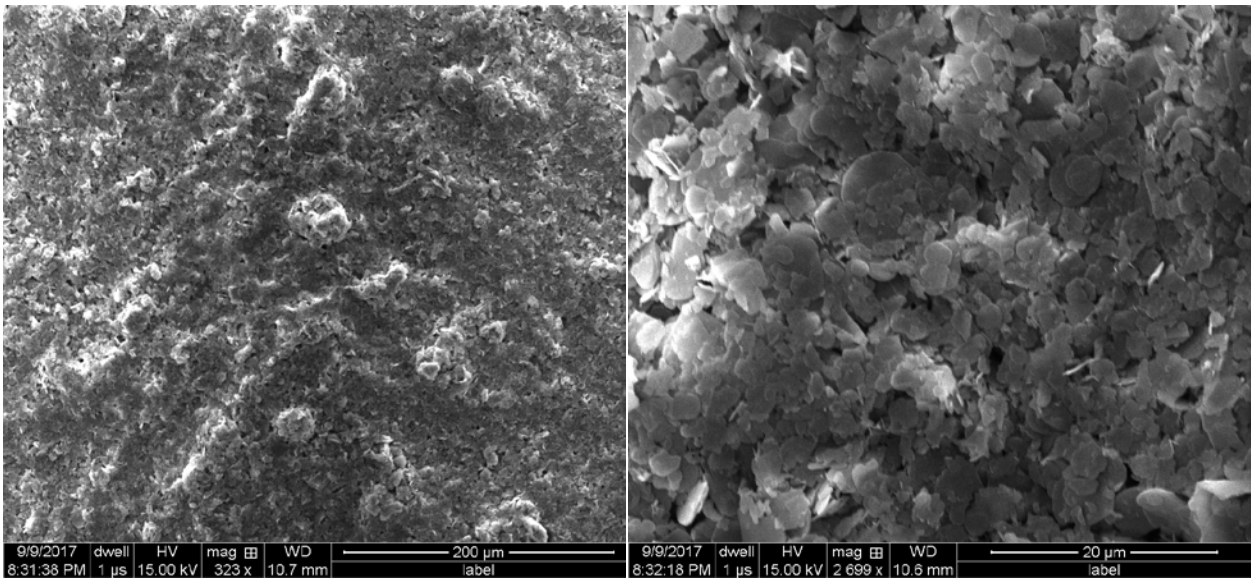

Figure 6. SEM images of exfoliated hBN using method B1: 50 mg/mL in DMF

b) Method B2. In this method, 25 mg/mL of hBN flakes were sonicated in DMF for 100 min. These results (Figure 7) are similar to the ones obtained using method A1 (with IPA). The hBNs seem to be exfoliated to a certain extent with the significant amount of large size particles.

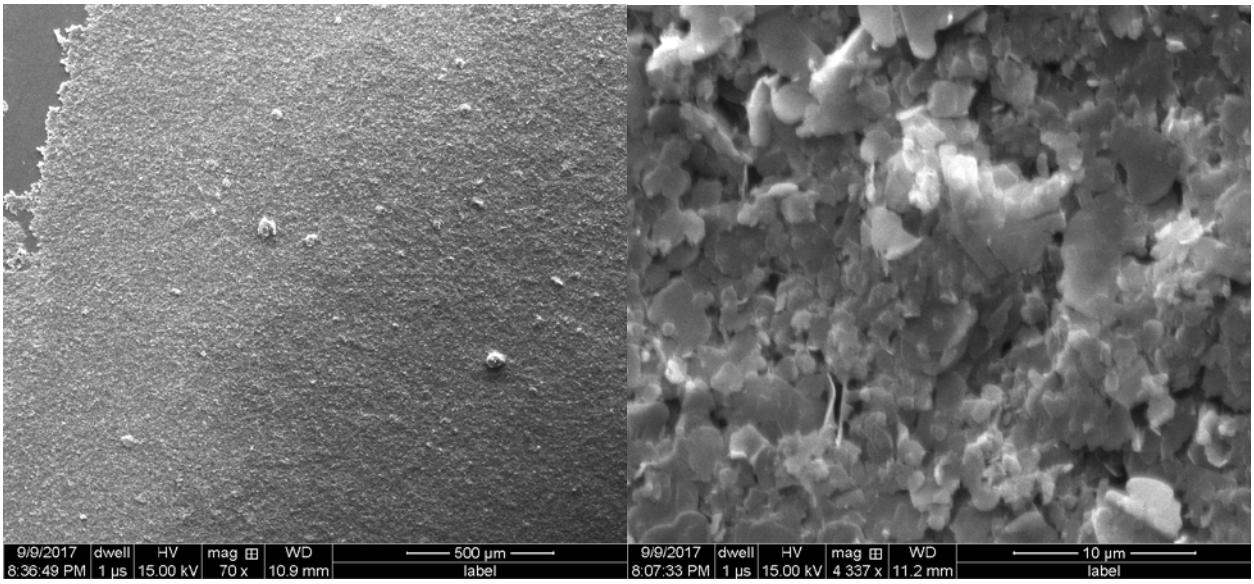

Figure 7. SEM images of exfoliated hBN using method B2: 25 mg/mL in DMF

4.2.3 Mixture of solvent (Method A+B)

In this method, we used 50 mg/mL of hBN flakes in the mixture of the IPA: DMF with a ratio of 1:1. The results indicated that the mixture of solvents did not help exfoliate the hBN. It could be because of the compatibility between the two solvents, they may have engaged among themselves (Figure 8). Changing the ratio of solvents and the amount of hBN per mixture of solvent can make the exfoliation more effective. This is because the right solvent will reduce the surface energy of hBN sheets, thereby smallest external forces (e.g. mixing, sonication, etc) can exfoliate them.

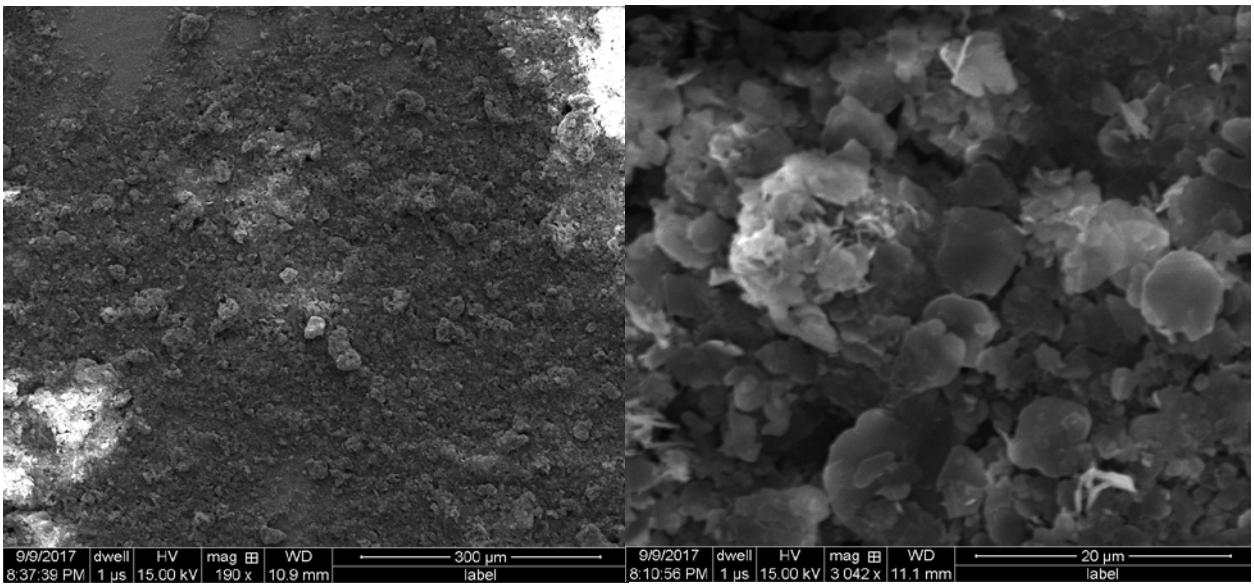

Figure 8. SEM images of exfoliated hBN using solvents A+B: (50 mg/ML in IPA+DMF)

4.2.4 Exfoliation at higher (45 °C) and lower (8 °C) Temperature using solvent A and B:

Exfoliating the hBN at higher (45 °C) or lower (8 °C) temperature did not make noticeable difference. Figure 9 to Figure 12 are the images obtained at lower (8 °C) and higher (45 °C) temperatures. For lower

temperatures, we put the samples in a container with ice cubes. The results are very similar (with slight aggregations) to the ones obtained at room temperature. This indicates that the variation in temperature from 8 °C to 45 °C does not really make a difference in exfoliation. Arrows on the images indicate the effectively exfoliated sites.

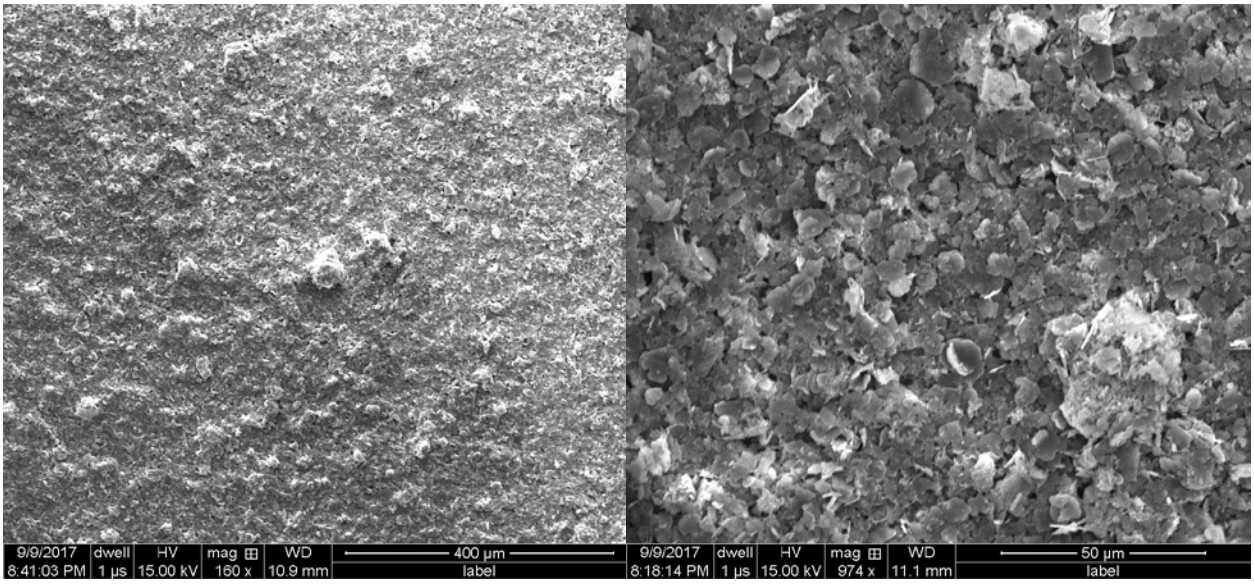

Figure 9. SEM images of exfoliated hBN at 45 °C (solvent A)

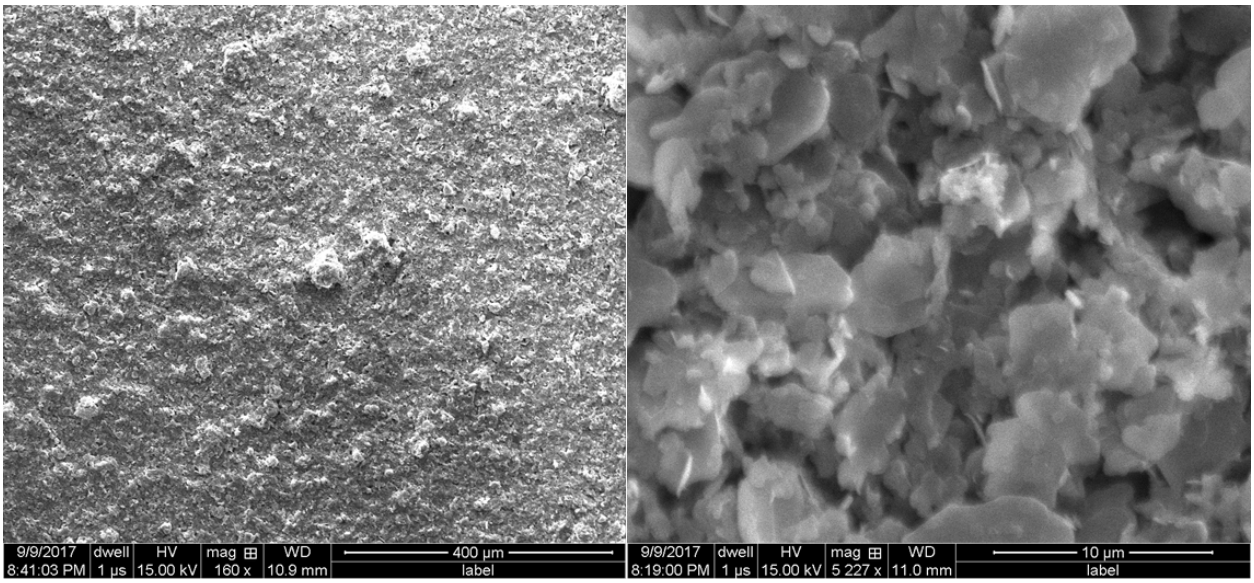

Figure 10. SEM images of exfoliated hBN at 8 °C (solvent A)

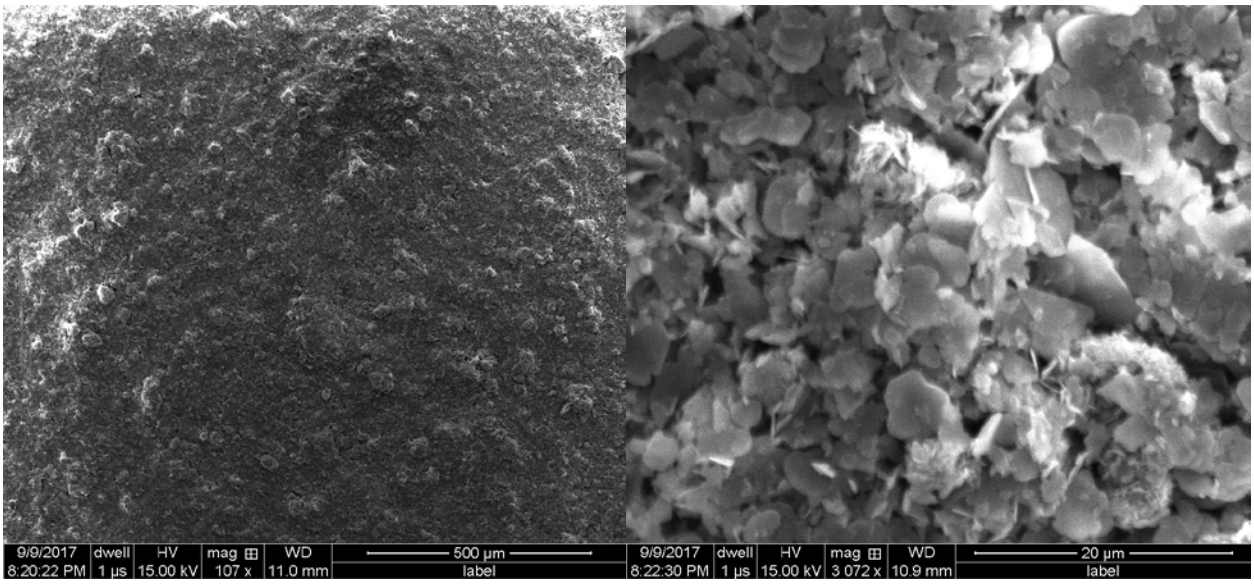

Figure 11. SEM images of exfoliated hBN at 45 °C (solvent B)

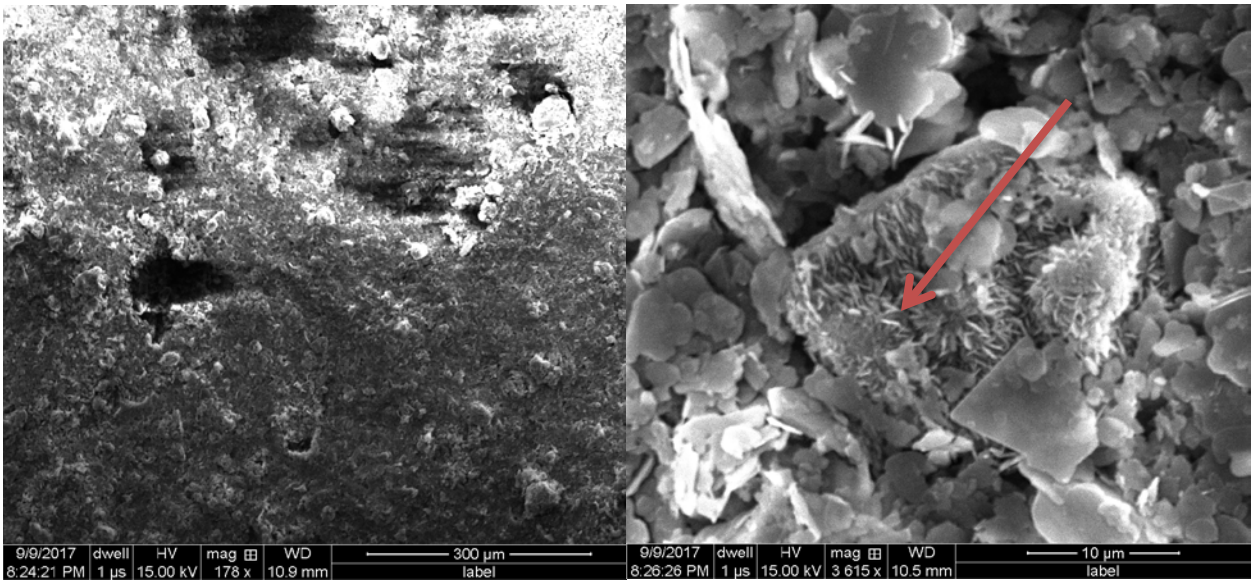

Figure 12. SEM images of exfoliated hBN at 8 °C (solvent B)

4.2.5 Thermal exfoliation method

The hBN samples were loaded in a quartz glass tube (stable at 1400+ °C) and heated in an oven for 2 hours at 1000 °C (at the rate of 10 °C per minute). The sample cooled down at the same rate. This method is based on the procedures outlined in ref [6]. This method also resulted in aggregation. However, there is likely a different chemistry occurring here during the heating and cooling processes. Looking at the image on the right (Figure 13) the morphology looks quite different than any other methods employed here. One possibility is that the hBN were exfoliated at higher temperature but during the cooling process they got aggregated back again.

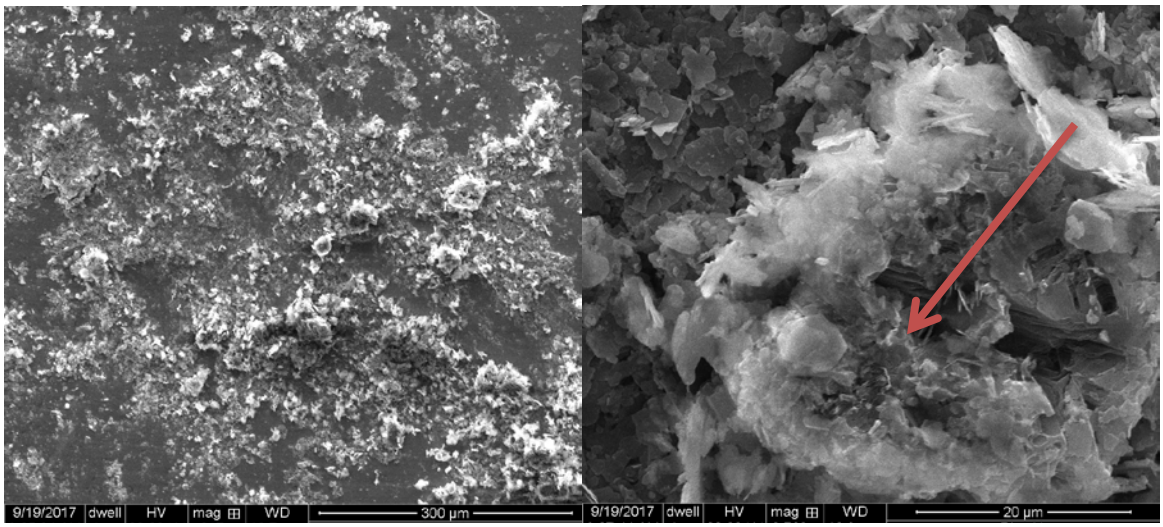

Figure 13. SEM images of exfoliated hBN obtained after heating at 1000 °C in an Oven for 2 hours

4.2.6 OH group functionalization

Besides exfoliation, the majority of the above methods also functionalized the hBN with –OH bonds, which is highly desired for mixing with water and dispersibility. The innate water-insolubility of hBN prevents its homogeneous mixture in concrete as well as its effective bonding to concrete constituents. By synthesizing OH bonds on hBN sheets and optimizing their amount, it is expected that the solubility and effective bonding to concrete increase. These hydroxyl functionalized hBN are expected to act as a lubricant in slurry and also play as a bridging agents, connecting the concrete constituents together resulting into better mechanical properties.

4.2.7. Testing mechanical properties

Using a proprietary combination of the above methods that resulted in the best exfoliated and functionalized hBN, we created several 4”x8” concrete cylinders using sand, gravel, water, Portland cement types II/I, and hBN (up to ~2% by weight). We used a cement: sand:gravel ratio of 1:2:3 to create Portland cement concretes (e.g. water to cement ratio of 0.4). The sand was natural, washed and dried (procured from Sakrete). The stone will all purpose stone procured from Vigoro. After casting concrete coupons, the curing was done via 24 hours in the mold, then the sample were taken out of the molds and kept in water for the desired period (e.g. 27 days for the 28 day testing). The mechanical strengths were measured after 7, 14, and 28 days following ASTM C 39 and ASTM C496 for compressive and Brazilian testing, respectively. After several trials and failed tests, Figure 14 shows a representative plot with promising mechanical properties at 28 days using exfoliated bulk hBN and extensively exfoliated hBN (hBN sheets with much lower thicknesses). Here, the homogenous dispersion of hBN in concrete was a crucial factor in achieving the best results. Numerous initial trials did not show improved properties due to lack of proper dispersions.

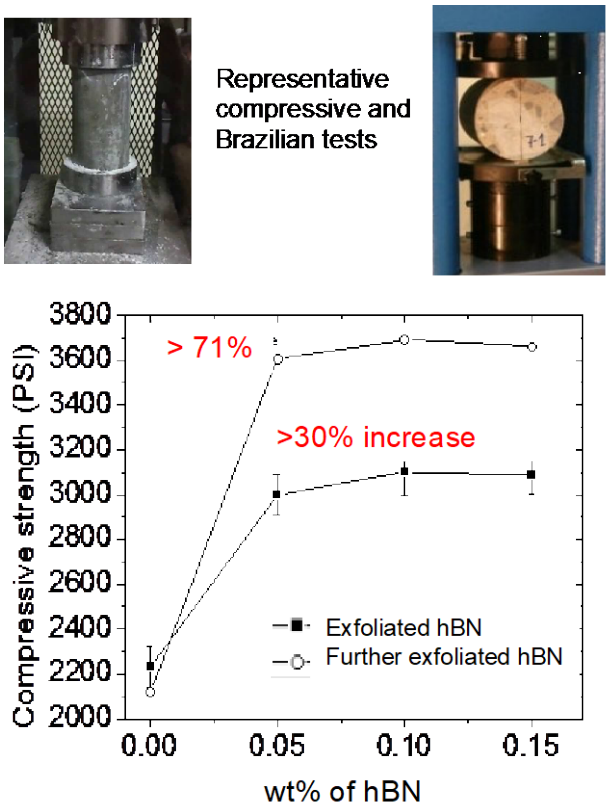

Figure 14. Mechanical Characterizations at 28 days using bulk or centrifuged hBN.

In particular, the compressive strength can increase by >71%. Further, tensile strength (measured by Brazilian testing) showed >100% increase. These results are quite encouraging given the very small fraction of 2D materials used. As the functionalized hBN have –OH functional groups they may interact with silicate and other oxides in cement, sand and gravel during hydration reactions and act as a bridge to connect the various particles together. Additionally hBN are known to be "solid lubricants" [11-12], thus they help to make a homogeneous slurry resulting into a material that has minimum pores and voids, thus maximum structural integrity and enhanced durability described next.

Note that our control sample (reference point) was not optimized to use the best quality sand, gravel, water/cement ratio, etc. For instance, if we use a reference concrete mixture with a compressive strength of 3600 psi (without any hBN), we expect to obtain analogous improvement upon minor addition of hBN. The improvement may not be exactly 71% elaborated above but more or less similar (e.g. maybe 65% or 75%, etc.). This is because the fundamentals of the property improvement are the same, *i.e.* ultra high surface area of hBN and charge transfer between Boron atoms of hBN and Oxygen atoms of cement oxide/sand/gravel, which together lead to better microstructural integrity of the concrete matrix (Section 3).

4.2.8 Durability testing of concrete cylinders

To investigate durability, the surface density and bulk density were screened following the ASTM C29 and AASHTO T19 standards. As shown in Figure 15, Concrete cylinders were cast using hBN as a filler. The slurry was casted in plastic molds and taken off after 48 hours. The cylinders were kept in the water for next 26 days and tested for resistivity using Resipod durability tester. The data are shown in Figure 16. Interestingly, the durability of the samples with hBN increased by ~35%. Note that given the very small

weight fraction of such 2D materials in the concrete samples, the density of the proposed concrete composite was measured to be almost equivalent to normal concrete.

Figure 15. Measurement of surface and bulk resistivity on concrete cylinders.

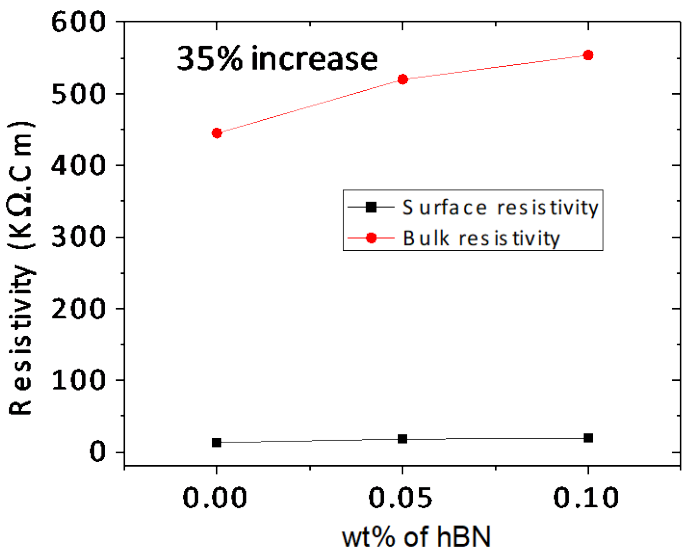

Figure 16. Durability results of concrete cylinders versus weigh % of hBN.

Overall, we demonstrated that great results can be achieved by using a very small fraction of 2D materials, which are properly exfoliated, functionalized and integrated into concrete.

5. PLANS FOR IMPLEMENTATION

We held several discussions with the TxDOT (Houston District) and they suggested that testing our product with patch/repair jobs would be a good start (Figure 17). However, TxDOT initially required ~4-8 hours curing to open the road to traffic. Thus, we used three of our formula (cement/hBN with three wt% of hBN) and tested addition of various wt% of accelerators (such as $CaCl_2$), and various curing temperatures (at room temperature, at 40 °C and 45 °C) to evaluate the performance and potential negative cross-effects of accelerators with our formula (e.g. accelerators may cause aggregation of exfoliated hBN to themselves or prevent their dispersion in water). The amount of accelerator did not exceed 2 wt% according to the ASTM D98.

Figure 17. Representative area of a road to be poured with our concrete product.

In a typical syntheiss, first, a desired amount of hBN and $CaCl_2$ were suspended in a suitable quantity of water and mixed with the cement in a ratio of 0.40. The cement cubes were cast and molds were carefully removed after 8 hours. For every experiment, the 4 hour samples were cast separately and taken out the mold very carefully to prevent the damage. The 8 hours, 12 hours and 72 hours samples were taken out after 8 hours. No water was used to cure the samples. The cubes were tested for their mechanical strength after 4 hours, 8 hours, 12 hours and 72 hours (Figure 18).

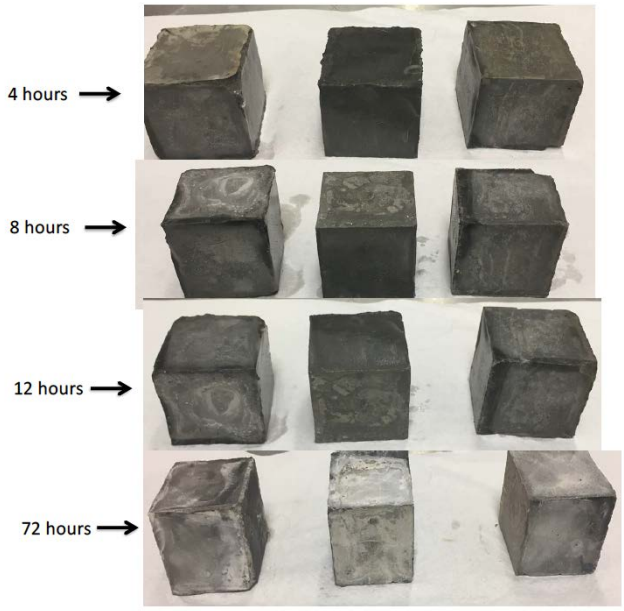

Figure 18. Representative 2" cement/hBN cubes over a period of 72 hours, containing 1 wt% of CaCl2 and hBN cured at 45 °C.

Figure 19-20 shows our results for representative wt% of accelerator and hBN.

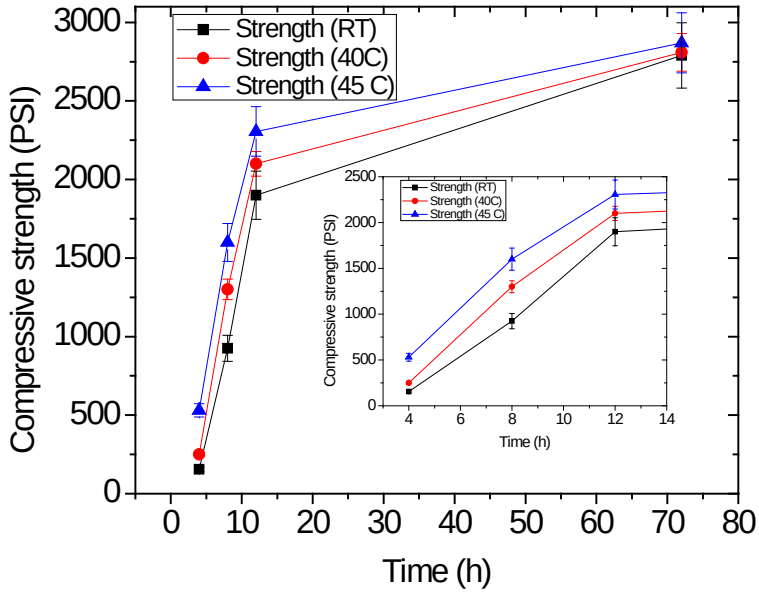

Figure 19. 2" cube cement curing with 1 wt% accelerator and hBN

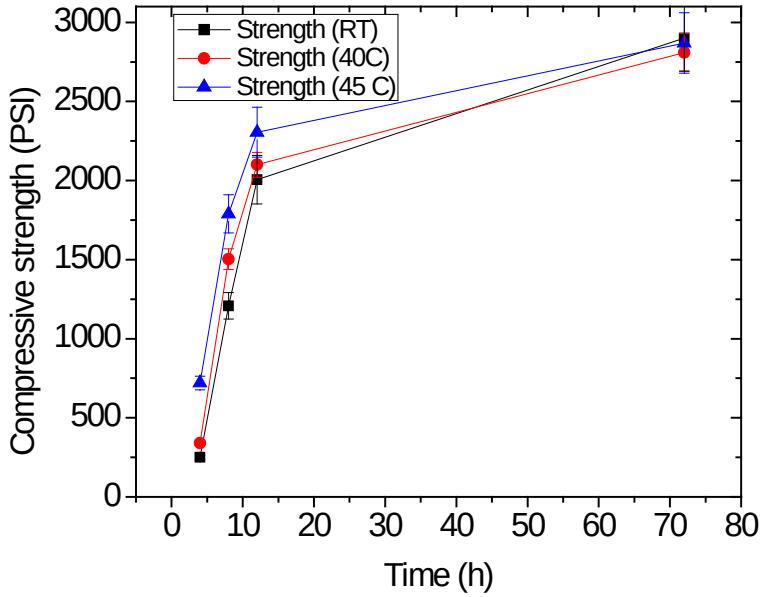

Figure 20. 2" cement cubes curing with 2 wt% accelerator and hBN.

In brief, the mechanical strength of the cement cubes increased by 4-6 times within first 8 hours at room temperature and by 2-3 times within first 8 hours if cured at 45 °C. No adverse cross-effect was observed with our cement/hBN formula.

Next, we casted several 4"x8" concrete cylinders as a function of time and hBN wt%. The goal (dictated by TxDOT) was to achieve 1800 psi in ~5 hours to be able to open the road to the traffic. After several trials and failed tests, we successfully achieved this requirement, making our technology ready for the field

test (Figure 21). The logistics of the field test are currently being finalized by TxDOT (pending approvals).

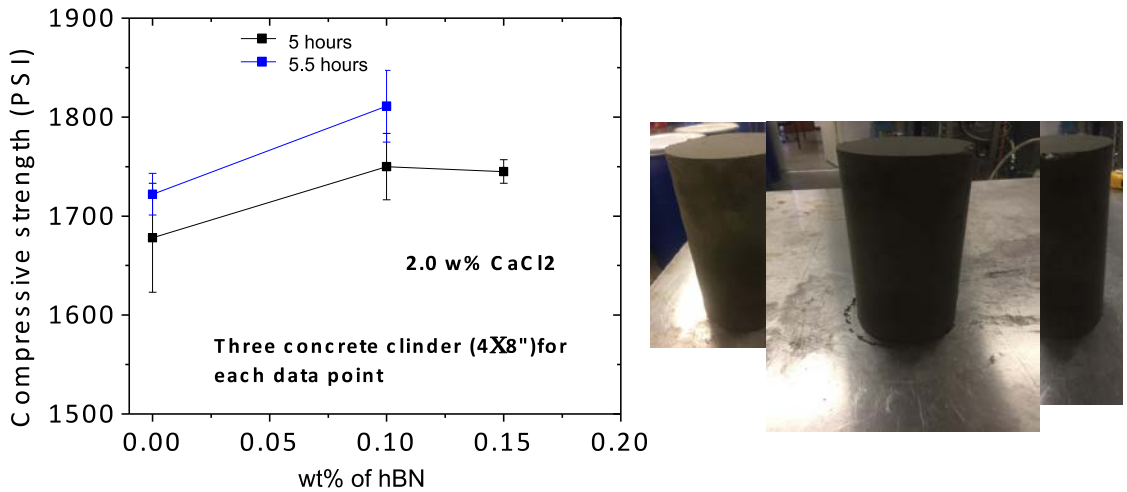

Figure 21. 4"x8 concrete cylinders curing with 2 wt% accelerator, achieving ~1800 psi compressive strength with only a minor fraction of hBN.

5.1. Cost Analysis.

We currently buy the hexagonal Boron Nitride (hBN) in small quantities from a manufacturer for ~$50 per kg with supply capacity of >100 tons per month. Assuming projected cost of 5X lower upon scale-up to tonnage quantities, we anticipate the cost of hBN ~$10/kg. Given this cost and use of 0.05% wt% hBN in cement, the additional cost for a metric ton of concrete will be only ~$1-2. The detailed calculation is as follows: 1 tone of concrete weighs ~2400 kg. Assuming 10% of it is cement, the weight of cement is 240 kg and the weight of hBN will be 0.12 Kg (0.005*240 Kg). Thus, the additional cost per ton of concrete will be $1.2 (0.12 kg *$10/kg). This small premium for a concrete that currently sells ~$100/ton in the US is quite insignificant, specially compared to what it offers (enhanced strength, durability, etc.). Simply put, the premium is within ~1-2% of the concrete price and lower than conventional additives.

We note that our exfoliation processes of hBN will add to the above cost but this processing cost becomes significantly reduced when scaled-up, as is common with any manufacturing technique for additives in the market. For example, some of our chemicals for hBN exfoliation can be recycled back for repetitive use. Given that we aim to use very low weight fractions of hBN in cement, these processing costs will become minimal upon scale-up.

To put the above numbers in perspective, we remind that "cost per performance ratio" is a key factor for commercialization. The cost for High Performance Concrete (HPC) and Ductal™ products are much higher than normal concrete (e.g. the price of Ductal™ might be up to 20X higher than normal concrete!) but given their superior properties, each have their own applications and market interests that render them as commercially viable solutions, compared to normal concrete.

5.2 Potential Payoff on Practice for Highways, Bridges, and Pavements

Our innovative technology for improved strength and durability of concrete have a significant impact on designing concrete highways, bridges, pavements and infrastructures with improved safety and sustainability, which entail economic growth in the US. To illustrate the potential payoff of this project,

let's consider a simple example: the US interstate highways. According to [13], 60% of the 73,000-km of four lanes (3.7 m each lane) interstate highways in US are paved with concrete that is 28 cm thick; thus ~400 Mt (million tons) of concrete is used in highways. Given the average lifetime of concrete highways 30 years [14] and assuming that at year 30, 10% of concrete highways are replaced and 90% employ overlay of 6 cm for repair, each year 400/30*0.1=1.3 Mt concrete is used for replacement and 400/30*0.9*(6/28)=2.6 Mt is used for repair (thus total of 3.9 Mt concrete is used annually for maintenance).

If our research results in novel methods to increase the concrete durability by 35%, only 2.8 Mt concrete will be needed annually for maintenance (*i.e.* 2.8=1/1.35* 3.9 Mt concrete). This immediately translates into **~$110** million/year cost saving in just US interstate highways, i.e. (3.9-2.8) *$100/t; assuming concrete to be $100/t.. There are also additional cost-saving due to less greenhouse gas emissions due to concrete manufacturing and use. For instance, each ton of concrete produces about 0.12 ton of CO_2 [15]. Assuming the current cost of carbon capture and sequestration to be $50/t, the aforesaid saving in concrete volume will translate into an additional ~$6.6 million/year cost-saving (1.1 Mt * 0.12 * $50/t) due to less CO_2 emissions. Similarly, a higher strength concrete translates into lower volume, less labor, less rebar, etc. for constructing transportation infrastructures and hence lower manufacturing cost and greenhouse gas emissions (due to lower needed volumes) associated with concrete use and transport. In essence, being able *to do more with less* has a significant impact on reducing the use of virgin materials and their associated handling (transport, use, etc).

Furthermore, one must also consider broader societal issues associated with concrete failure such as road accidents, environmental blight, public confidence, and reduction in future developments in transportation infrastructure, which could be avoided if our new concrete is used. From these analyses, the underlying investment of our new technology (hBN cost, processing cost, etc.) must be subtracted, which we estimate to be minimal (see Cons Analysis in Section 5.1). With this rough analysis, it is easy to realize that the net benefits from the new technology are worth the underlying investment.

6. CONCLUSION

This project developed a new class of high performance, multifunctional hexagonal Boron Nitride (hBN)-concrete for various transportation infrastructures. Conventional methods of mixing typical additives in concrete are known, but the introduction of the emerging 2D sheets with ultra-high surface area such as hBN in concrete is a challenge. In particular, proper dispersion and homogeneity of the mixture is of a paramount importance. Furthermore, creating such composites in a cost-effective way is another difficulty. Our novel technology focused on creating a water-soluble ultrathin functionalized hBN as an additive in concrete. This was done via effective exfoliation of hBN via solvents (IPA, DMF, etc), tuning their concentration (e.g. 25-50 mg/mL) and exposure time, etc. Among their unique attributes, such ultrathin hBN sheets can act as 2D templates to (i) promote the growth of cement hydration products, (ii) bridge the different concrete constituents, (iii) fill the pores of concrete, and (iv) block the passage of deleterious ions (via their 2D nature). Together, preliminary laboratory results indicate such features impart multiple desired properties in concrete (hence the name multifunctional) such as enhanced structural integrity, more than 71% increase in compressive strength, >100% increase in tensile strength, and >35% increase in durability.

To implement our technology, we held several discussions with the TxDOT to perform and evaluate the first application of this new product on a surface of a road/highway. A patch/repair job was found to be an appropriate starting application with TxDOT requirement of 1800 psi compressive strength in ~5 hours to be able to open the road to traffic. We incorporated and tested several accelerators with various percentages in our hBN formula and optimized the mix, meeting the 1800 psi requirement in 5 hours. This makes our technology ready for the next step in large-scale implementation. Regarding cost and

scalability, we note that compared to other flagship nanomaterials such as graphene or carbon nanotubes, hBN is several orders of magnitude lower in cost and is available in bulk (tonnage) quantities. These attributes, combined with our proposed low volume fraction of hBN in concrete (less than 1%), would facilitate the low-cost implementation and large-scale commercialization of our technology.

Overall, tuning concrete chemo-mechanics as performed in this project provides a substantial opportunity to produce a superior concrete product while reducing the maintenance cost and concrete environmental footprint. This strategy enables *to do more with less;* for example, a higher durability concrete translates into lower maintenance cost. Similarly, a higher strength concrete translates into lower volume, less labor, less rebar, etc for constructing transportation infrastructures and hence lower cost and GHG emissions associated with concrete. From these perspectives, this project is a significant first-step in altering concrete materials landscape and could potentially lead to a new line of commercialization for transportation infrastructures. The immediate next steps for future efforts will be (i) Scaling up our wet chemistry synthesis procedures of exfoliated hBN to large batches to provide our additive as a water soluble additive, (ii) Conducting field studies to assess durability in real environments and demonstrate ease of application, and (iii) Performing more specific tests to transportation such as ASR, Freeze-Thaw, Abrasion, etc (via ASTM AASHTO/ACI codes).

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8. APPENDIX: RESEARCH RESULTS

Sidebar Info:

Program Steering Committee: NCHRP IDEA Program Committee

Month and Year: July 2019

Title: Nano-enabled multifunctional concrete for transportation infrastructure

Project Number: 197
Start Date: 11/20/2016
Completion Date: 07/31/2019

Product Category: New or Improved Materials

Principal Investigator: Dr. Rouzbeh Shahsavari
President, C-Crete Technologies
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TITLE:
Enhancing concrete properties via two-dimensional (2D) nanosheets

SUBHEAD:
Emerging 2D materials enables developing a new class of high performance, multifunctional concrete for various transportation infrastructures.

WHAT WAS THE NEED?
Concrete is the most widely used synthetic material on earth. In the United States, more than 75% of bridges and over 60% of Interstate highways are made of concrete. There is no other bulk material on the horizon that could replace concrete as the backbone for increasing demands in infrastructures. Despite several decades of studies, concrete bridges, highways and infrastructures still significantly suffer from fracture, deterioration, and external chemical attacks (e.g., chlorides/sulfates) with maintenance costs that amount to multi-billion dollars annually.

WHAT WAS OUR GOAL?
The goal was to leverage the recent decade long knowledge developed over exotic 2D materials such as hexagonal boron nitride (hBN), as small as one atom in thickness, to effectively enhance the mechanical and durability properties of concrete from the nanometer scale up.

WHAT DID WE DO?
The research studied and identified the optimum experimental conditions and process parameters for enhancing the mechanical and durability properties of concrete while economically and commercially being viable. In particular, the research studied (i) several different routes to investigate the degree of exfoliation and reduction in size of hBN to increase surface area and bonding to concrete, and (ii) their functionalization and water solubility in effectively mixing them in concrete. The research also started collaborating with the Texas Department of Transportation (Houston District) for incorporating practical considerations in regards to implementation of the technology on a surface of a road/highway.

WHAT WAS THE OUTCOME?

Notable among the research results are the compressive strength, tensile strength and durability of the concrete cylinders that increase by >71%, >100% and 35%, respectively, via strategic addition of a very small fraction of hBN in concrete. Furthermore, the research shows that the treated hBN nanomaterials are compatible with the common concrete accelerators such as $CaCl_2$, enabling ~1800 psi in compressive strength of concrete within only ~5 hours, making the technology suitable for rapid construction and/or maintenance in transportation applications.

WHAT IS THE BENEFIT?

This research provides a substantial opportunity to produce a superior concrete product while reducing the maintenance cost and concrete environmental footprint. This is because the technology allows *to do more with less;* for example, a higher durability concrete translates into lower maintenance cost. Similarly, a higher strength concrete translates into lower volume, less labor, and less rebar for constructing transportation infrastructures, and hence lower cost and GHG emissions associated with concrete. Regarding implementation cost and scalability, hBN is several orders of magnitude lower in cost and is available in bulk (tonnage) quantities as compared to other flagship nanomaterials such as graphene or carbon nanotubes. These attributes, combined with the proposed low volume fraction of hBN in concrete, would facilitate the low-cost implementation and large-scale commercialization of the technology.

LEARN MORE

Provide link to final report or other pertinent info, such as how to access an online tool.