Investigation of Macro-Defect-Free Concrete for ABC including Robotic Construction

Final Report
February 2018

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16. Abstract

Accelerated Bridge Construction (ABC) has grown tremendously over the past several years, due in part to the maturation of new materials that have properties conducive to working in an ABC environment. In recent years, Caterpillar Inc. has developed several formulations of a cementitious material for building purposes called CEMPOSIT, which is a variation of macro-defect-free (MDF) concrete.

This material is unlike any cement-based material currently available and is much more closely related to various types of rubber—although with vastly different properties than rubber. These favorable properties include high strength (comparable to ultra-high-performance concrete), rapid early strength, extremely low permeability, and the ability to be extruded on-site to fit specific project needs.

The goal of this work was to assess important material characteristics of MDF concrete and to develop conceptual uses for the material with a specific focus on accelerated/robotic bridge construction. The findings from the material tests are presented, along with discussion of applicability for usage in the accelerated bridge construction field, in this report.

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INVESTIGATION OF MACRO-DEFECT-FREE CONCRETE FOR ABC INCLUDING ROBOTIC CONSTRUCTION

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INTRODUCTION

Accelerated Bridge Construction (ABC) has grown tremendously over the past several years, partly due to the maturation of new materials that have properties conducive to working in an ABC environment. In recent years, Caterpillar Inc. has developed several formulations of a cementitious material for building purposes called CEMPOSIT, which is a variation of macro-defect-free (MDF) concrete.

This material is unlike any cement-based material currently available and is much more closely related to various types of rubber—although with vastly different properties than rubber. These favorable properties include high strength (comparable to ultra-high-performance concrete), rapid early strength, extremely low permeability, and the ability to be extruded on-site to fit specific project needs.

Prior to this work, only a limited number of very basic material tests have been performed with MDF concrete, so there is a significant void in understanding what the material is capable of and what its limitations are.

The goal of this project was to serve as the first step in determining whether this material could be used in ABC projects and, if so, how. This required the assessment of important material characteristics, with the goal of developing conceptual uses for the material with a specific focus on accelerated/robotic bridge construction.

The findings from the material tests are presented in this report, along with a discussion of applicability for usage in the accelerated bridge construction field.

LITERATURE REVIEW

This chapter summarizes previous findings pertaining to macro-defect-free cement. This includes a discussion of typical MDF cement manufacturing processes and material properties. In addition, background information is provided on the unique material, CEMPOSIT, developed by Caterpillar Inc., which served as the basis for this research.

Typical Macro-Defect-Free Cement

MDF cements were first developed in the early 1980s and had properties similar to those of ceramics, plastics, and metals. MDF cements require high shear mixing of polymers and hydraulic cements at low water to cement (w/c) ratios. W/c ratios of 0.08 to 0.20 are typical for MDF mixes, in contrast to w/c ratios of 0.4 to 0.6 for traditional concrete mixes. The typical manufacturing process for MDF materials is also quite different from that of traditional concrete, the outline of which is shown in Figure 1.

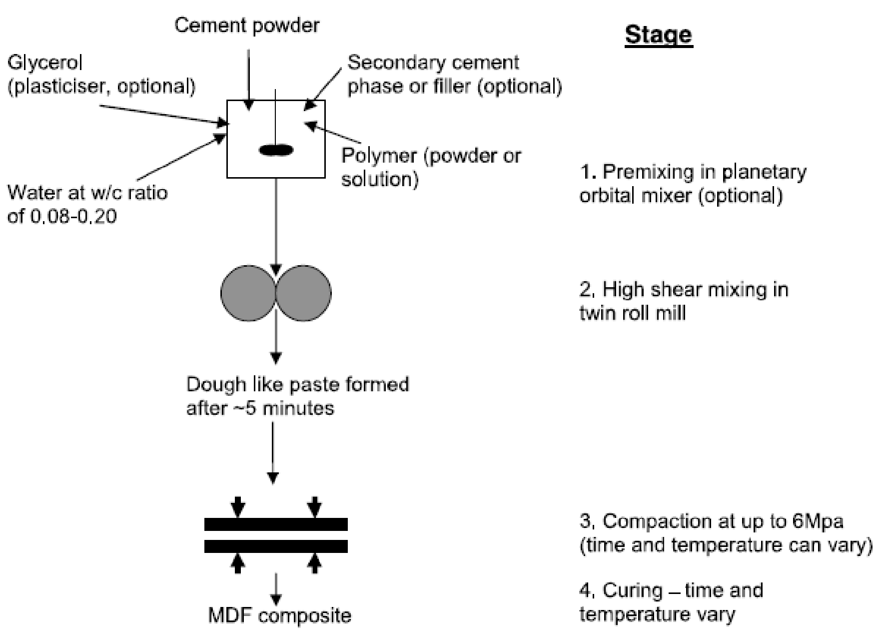


Figure 1. Typical manufacturing process for MDF cements

This process involves the premixing of all components, which typically include water, glycerol, polymer, and cement powder. This mixture is then subjected to high shear mixing via a twin roll mill to create a material with dough-like consistency. Once the paste has been formed, it can be compacted at high temperatures and cured—with this process varying depending upon the type of material properties desired.

The material properties of MDF cement, as well as ordinary portland cement (OPC), aluminum, glass, and wood, are shown in Table 1.

Table 1. Material properties for MDF concrete and other comparative materials

Material	**Young's Modulus (ksi)**	**Flexural Strength (ksi)**
Ordinary Portland Concrete	2,900-3,600	700-1,500
MDF Concrete	5,500-6,500	>21,000
Aluminum	10,000	21,000-58,000
Glass	10,000	10,000
Wood	1,500	14,500

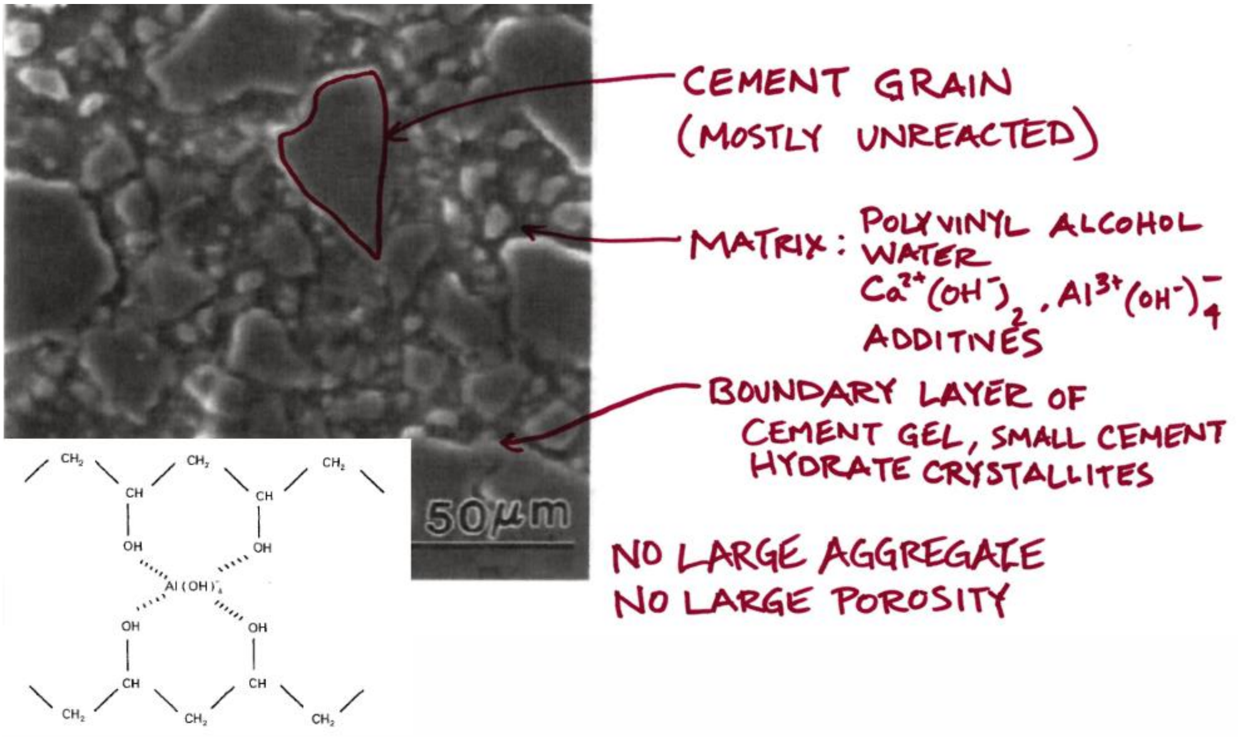
Modified from Bennett 2002.

As shown in this table, OPC and MDF have vastly different flexural strength and Young's modulus properties. As far as flexural strength, MDF concrete is comparable to aluminum, although with a much lower fracture energy. While the material properties shown in Table 1 highlight the strengths of MDF concrete, there have been observed limitations associated with the material as well. These limitations include low moisture resistance, shrinkage, and difficulties in processing on a large or commercial scale. Traditionally, MDF cements have shown a loss of strength when exposed to moisture or humidity. More recent modifications to the manufacturing process, as well as specialized polymer selection, have helped to overcome some of these issues. The nature of the polymer used has a drastic effect on the material's susceptibility to moisture, and significant moisture resistance can be achieved when materials are dried 24 hours after finishing the pressure application phase of production (Mojumbar 2001). However, economical large-scale production remains an important limitation that has yet to be overcome (Donatello et al. 2009).

Given the limitations outlined above, the suggested applications for MDF have been typically residential in nature and include roofing tiles, fire-resistant doors, shutters, sewage pipes, and plastic molds. These applications typically involve the replacing of metals or plastics due to the corrosion resistance associated with MDF cements.

CEMPOSIT Material

In 2013, work began at Caterpillar to research the applicability of macro-defect-free cement as a possible material for valve covers. This work led to improvements to the material's chemistry to solve water ingression problems by using novel additives. Additional work then allowed for improvements to strength, cost reduction, decreases in shrinkage, and increased toughness. The composition of the material is roughly 80% by weight cement, with the remaining 20% comprised of water, additives, and polyvinyl alcohol. The microstructure can be seen in Figure 2. The lack of porosity is thought to be the cause of the high-strength performance of the material.



Correspondence with Aaron Amstutz, Caterpillar Inc. 2016

Figure 2. Microstructure of CEMPOSIT

To manufacture CEMPOSIT, the polymer and water are combined to form a paste or gel, the consistency of which can be seen in Figure 3.

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Figure 3. CEMPOSIT paste prior to shear mixing

This paste is then subjected to high shear mixing via a rubber mixer between two revolving drums with variable speeds, as shown in Figure 4.

Figure 4. High shear mixing of CEMPOSIT

The mixing process allows for incorporation of fillers and additives (as shown in Figure 5), which includes the opportunity to dye the material to any desired color.

Figure 5. Addition of fillers during mixing process

After mixing, the material can be cut or shaped into the desired form, and then either air cured or molded to shape in a heated hydraulic press. An example of the material after mixing is complete can be seen in Figure 6.

Figure 6. CEMPOSIT remnant after mixing, showing an edge that has been cut with a razorblade

This image shows the cut edge of the remnant material, which in this case was formed into a block for the application of heated pressure (as shown in Figure 7), achieved using a razorblade for trimming.

Figure 7. Mold and heated press process

The two variations of CEMPOSIT include CEMPOSIT Create, which is air cured, and CEMPOSIT Dura, which is molded to shape in a heated hydraulic press. The heated press variation of the material allows for improved material property performance, which is discussed in the laboratory testing section along with other material test results. CEMPOSIT exhibits high early-age strength, with half strength achieved instantly when heat curing is utilized. After 8 hours, full strength is usually achieved. For ambient curing, the material is not hard or rigid for 3 to 4 hours after forming.

To illustrate improvements to MDF that were made via Caterpillar technology, Figure 9 shows the flexural strength with respect to age for five different MDF mixtures with various additives.

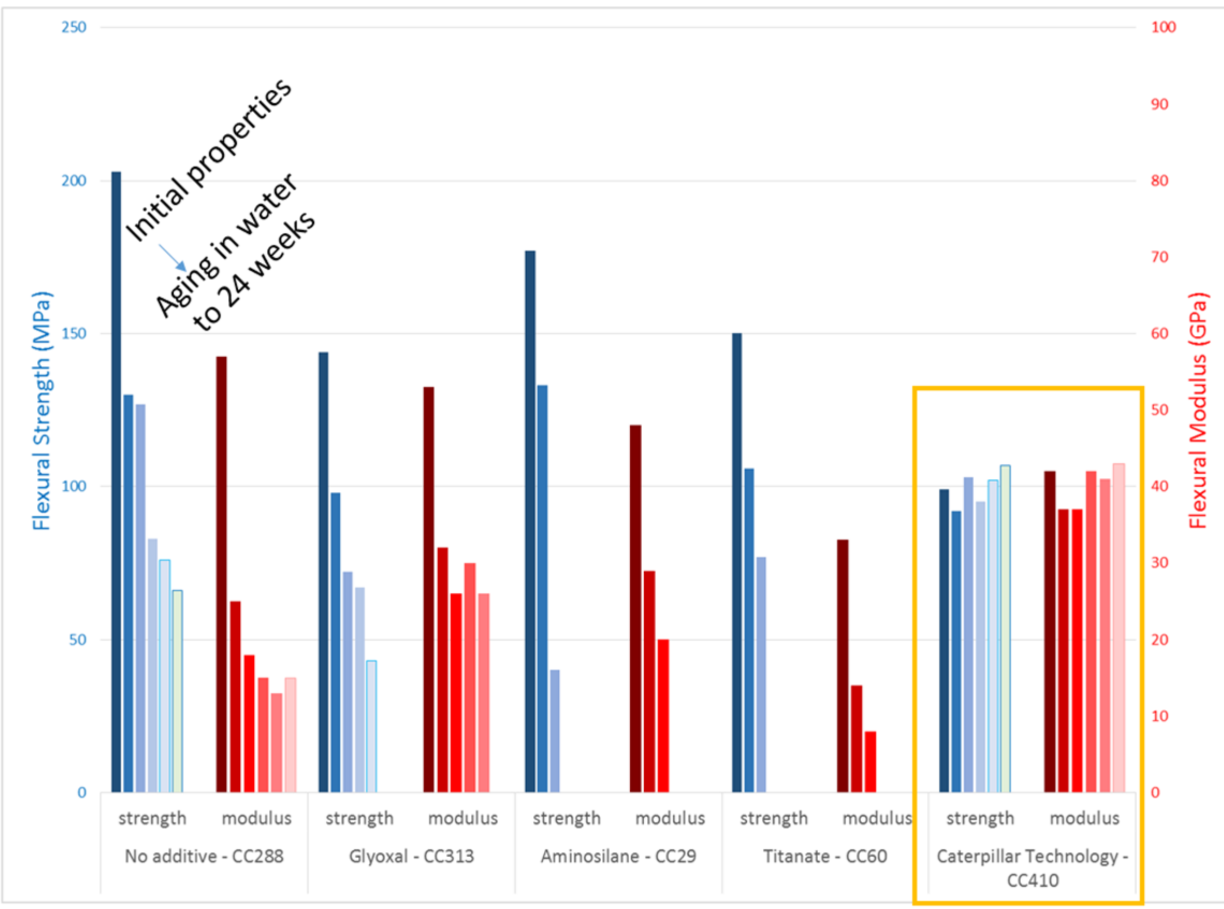

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Figure 8. Varying recipes and their respective strength performance with age

As can be seen in Figure 8, typical MDF materials (CC288 in the figure) show a loss of strength after exposure to water over time. Additives help to improve this performance, with CEMPOSIT exhibiting greatly improved strength performance after exposure to moisture.

Many iterations of CEMPOSIT mixes have been developed at Caterpillar in an attempt to improve material properties via changes in key components and additives. More than 700 recipes were explored based on polyvinyl alcohol, using heat and pressure molding. The following additives were considered:

- Fillers and pozzolans: alumina, alumina trihydrate, talc, whiting, kaolin clay, metakaolin clay, coal dust, coke, Class C and Class F fly ash, ground granulated blast furnace slag, ordinary portland cement, ground soda glass, iron oxide, and precipitated silica

- Reactive resins, monomers, and co-polymers: phenolic resins, melamine resins, epoxy silane, amino silane, titanates, glyoxal, phosphoric acid, polyacrylic acid, metallic coagents, and peroxides

- Fiber reinforcement: aramid-melamine fiber, acrylic fiber, glass fiber, carbon fiber, cotton cloth, sheet molding compound (SMC) over-molding, woven fiberglass/carbon pre-preg overmolding, steel fiber, steel wool, and continuous wire/cordage

The Iowa State University research team played a role in this process by communicating ideal material characteristics to the manufacturer to spur refinement and innovation of the material. Once sufficient improvements were made, a suite of material tests were needed to ascertain key material characteristics necessary for determining applicability for structural engineering purposes.

LABORATORY TESTING

To determine key material properties of CEMPOSIT, a number of laboratory tests were performed on heat-molded, black-dyed samples, which were held until the cementitious reactions were complete. Subsequently, all samples were subjected to an 80-degree, 64- to 72-hour, thermal post-cure without pressure. The tests that were performed included split tensile, compression, freeze-thaw, and air permeability. All of these tests were performed at the Iowa State University Civil, Construction, and Environmental Engineering laboratories and represent the tests that were needed to understand engineering-based applicability.

Sample Types

For the compressive and tensile strength tests, specimens were made of multiple types and layer orientations. The first type of samples was made using a split clamshell-type mold, with the individual plies either perpendicular or parallel to the lengthwise direction of the cylinder. The material was cut in strips and extra material flashed through the parting line of the mold. These samples are referred to as clamshell, either parallel or perpendicular. The other formulation of samples was made via a vertical spring-form mold that was loaded with a stack of disks (each roughly 1/4 in. thick and 3.75 in. diameter). The stack was then compressed in the heated mold. These samples are referred to as spring-form samples. Regardless of the type of form used, water was applied to the faces between each layer to ensure a good bond between surfaces, as the material dries out rapidly when exposed to air. The samples used for the freeze-thaw and air permeability tests are much smaller and did not require these same forms for molding. A discussion of each test that was performed on the samples, as well as the test results, is presented in the following sections.

Compressive Strength

Compressive strength tests were performed on 6 cylinders, according to the ASTM C39 specifications. The specimen dimensions were 4 in. diameter and 8 in. tall. Two layer orientations were considered: clamshell and spring-form, with three samples of each type. The compressive strength results for the 6 cylinders are shown in Table 2.

Table 2. Compressive strength results (in ksi)

Specimen	Compressive Strength (ksi)	Average Compressive Strength (ksi)	
Clamshell 1	24.7	21.8	21.8
Clamshell 2	19.1		
Clamshell 3	21.7		
Springform 1	22.5	21.7	
Springform 2	22.1		
Springform 3	20.5		

The average compressive strength of the clamshell orientation was 21.8 ksi, while the average for the spring-form specimens was 21.7 ksi, indicating that the layer orientation did not have an effect on compressive strength performance. Therefore, the overall average compressive strength of all samples was approximately 21.8 ksi. For comparison, standard concrete typically has a compressive strength of 3 to 6 ksi.

Failure planes of cylinder remnants from a spring-form specimen are shown in Figure 9 and from a clamshell specimen in Figure 10.

Figure 9. Spring-form compression test remnants

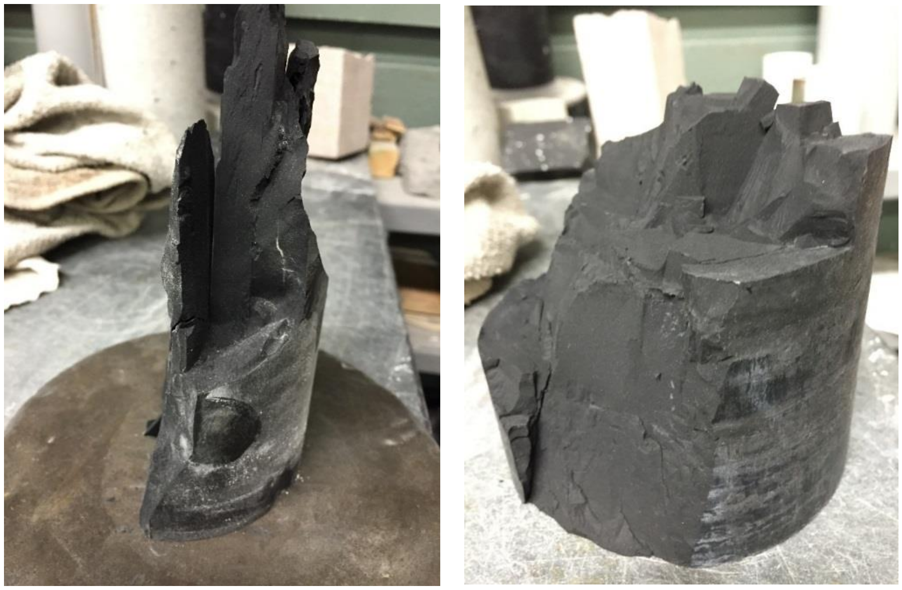


Figure 10. Failure planes of clamshell specimens after failure

Tensile Strength

Splitting tensile strength tests were performed on nine cylinders, according to ASTM C496 specifications. The cylinders had dimensions of 4 in. diameter and 8 in. height. In addition, varying layer orientations were used to determine any effect on strength, with three cylinders formed of each type. The three orientations of layers considered in these tests were clamshell, both parallel and perpendicular, and spring-form. The results of the splitting tensile strength tests for all cylinders are shown in Table 3. The table also includes the average splitting tensile strength for each orientation type, as well as the standard deviation.

Table 3. Splitting tensile strength results (in psi)

	Clamshell						**Spring-Form**		
	Parallel			**Perpendicular**					
Splitting Tensile Strength (psi)	1074	1352	620	647	1613	1939	2387	2374	1068
Average (psi)	1015			1400			1943		
Standard Deviation (psi)	369			672			758		

Figure 11 shows the failure planes of spring-form specimens, and Figure 12 shows the clamshell specimens.

Figure 11. Failure planes for split tensile test specimens made via spring-form mold (shown in the testing apparatus on the right)

Clamshell Perpendicular

Clamshell Perpendicular

Clamshell Parallel

Clamshell Parallel

Figure 12. Failed clamshell cylinders with perpendicular (top) and parallel (bottom) layer orientations

The splitting tensile strength results show that the layer orientation does affect the tensile strength of the specimen, with the spring-form specimens exhibiting the greatest strength. Of the two clamshell orientations, greater strength was seen in the perpendicular orientation. However, there is large variability in strength results, as seen in the results for all layer orientations. Typical splitting tensile strength values for ordinary concrete are 300 to 700 psi. In most cases, CEMPOSIT exhibited greater tensile strength than ordinary concrete, and often by a large factor.

Air Permeability

Air permeability tests were performed on a sample of CEMPOSIT, according to the University of Cape Town specifications. The results of the test provide time-dependent pressure data which is used to calculate the air permeability index (API). The API is the negative log of the D'Arcy coefficient of permeability (Buenfeld and Okundi 1998). This index uses a log scale, with lower air permeability indexes associated with higher permeability.

The permeability index values can be interpreted using the following guidelines (Alexander and Beuschausen 2010):

Table 4. Air permeability index interpretation guidelines

API	Performance
> 10.0	Excellent
9.5 < API < 10.0	Good
9.0 < API < 9.5	Poor
AP I< 9.0	Very Poor

The API results from the CEMPOSIT sample were in the excellent range, with an API above 10. This indicates that the material has low permeability, or excellent performance with respect to permeability. This is an advantageous material property, and is likely due to the low porosity of the material, combined with the heat-pressed forming technique. This air permeability performance has also been seen in other types of concrete paste systems (Taylor et al. 2015).

Freeze-Thaw

Freeze-thaw tests were performed on 10 samples of CEMPOSIT, according to ASTM C666 specifications. The data from these tests can be used to determine the relative dynamic modulus of elasticity after 0, 30, 60, 180, and 300 freeze-thaw cycles. After the entirety of the freeze-thaw cycles are complete, the durability factor at 300 cycles can also be calculated. The relative dynamic modulus values for all 10 samples is shown in Figure 13, and results for a typical concrete mix are shown in Figure 14 for comparison purposes.

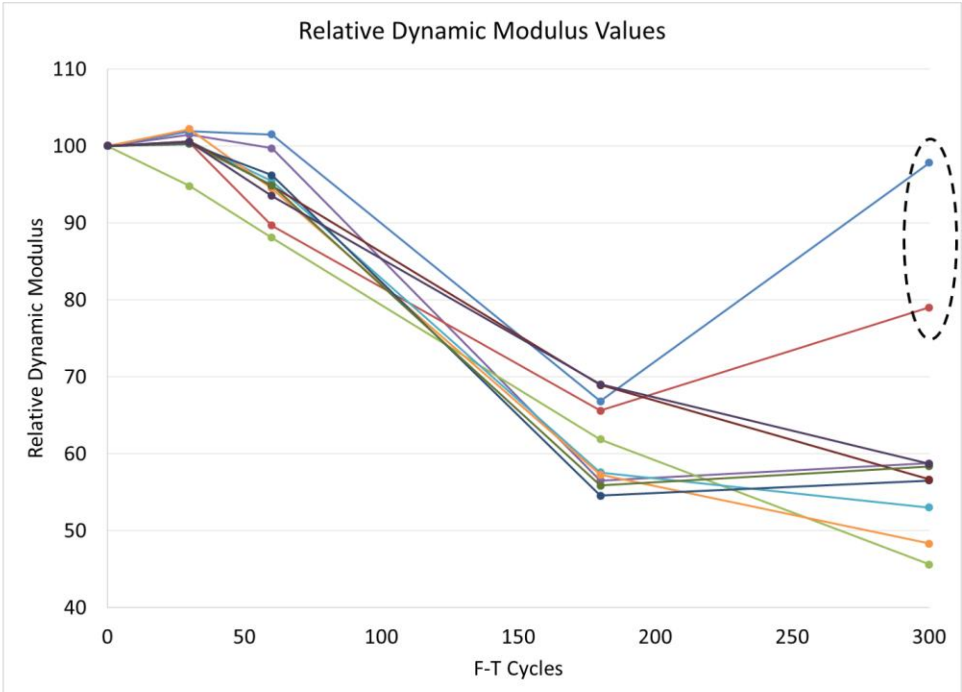
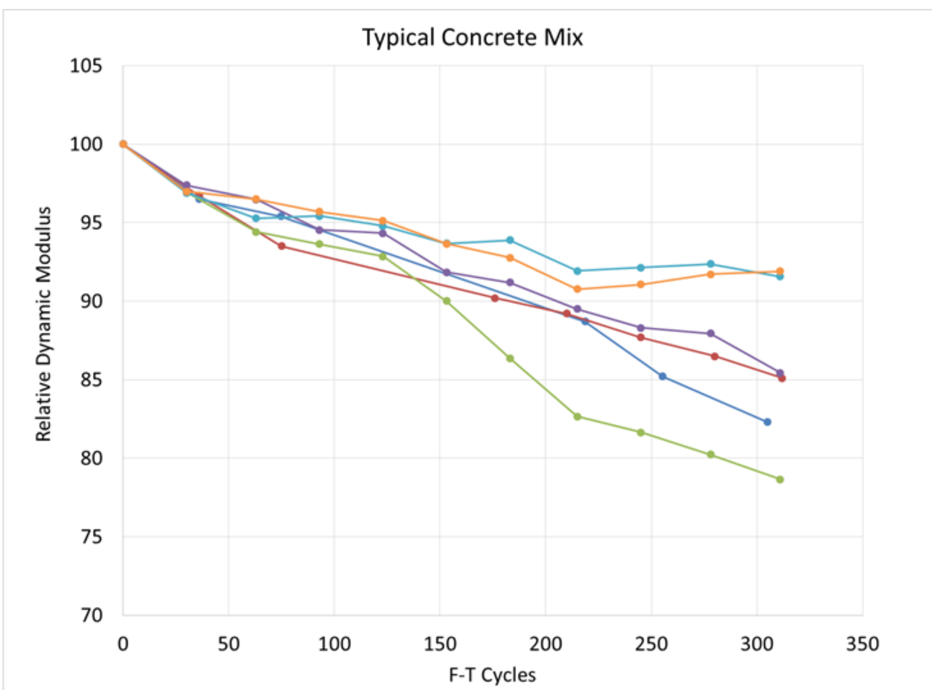


Figure 13. Relative dynamic modulus values for all 10 CEMPOSIT samples, with outliers circled



Wang et al. 2016

Figure 14. Relative dynamic modulus values for a typical concrete mix

Two outliers were recognized in the CEMPOSIT data, identified by the dashed black oval in Figure 13. These values are the result of testing errors and were removed for the average relative dynamic modulus of elasticity value calculations. These averages (excluding outliers) are shown in Figure 15.

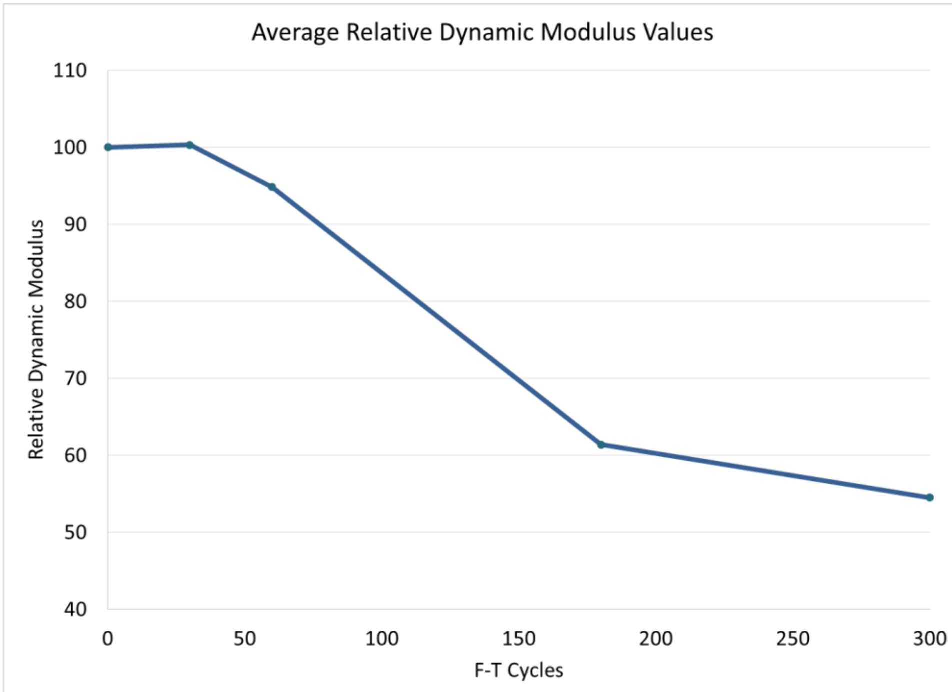


Figure 15. Average relative dynamic modulus values, excluding outliers

Based on the average results, and according to ASTM C666 specified calculations, the average durability factor (DF) for the samples after 300 cycles was 54.

Concrete mixes with good concrete performance typically have DF values of above 80 (as shown previously in Figure 14). This indicates that CEMPOSIT does not have ideal freeze-thaw resistance, and would be susceptible to the associated distress mechanisms.

Performance Summary

After the laboratory testing was complete, the results were compared and analyzed to determine strengths and weaknesses of the material. The compressive strength of CEMPOSIT was seen to be very high, with an average of 21.8 ksi and low variability in test results. This strength is considerably greater than that of traditional concrete, indicating that the material performs well under compression loads, regardless of layer orientation. The splitting tensile strength results showed considerable variation, but in most cases were higher than those of typical concrete.

Based on the results of these two tests, CEMPOSIT performed well with regard to strength but did have brittle failure mechanisms. Several iterations of mixes were attempted using fibers to reinforce the mix and improve toughness. However, to achieve the performance desired, an inefficient amount of fibers had to be added, which, in turn, made the mix unworkable and proved to be an unrealistic modification.

The air permeability test showed that CEMPOSIT has excellent performance with respect to permeability, indicating that the material has low air permeability traits. Greater air permeability is associated with reduced concrete durability due to the ability of gases and liquids to infiltrate the concrete matrix. The presence of liquids leads to concrete deterioration, and, therefore, low permeability is an attractive material property for concrete applications. For normal concrete, several studies have examined concrete permeability, as well as the effect of mix design characteristics such as w/c ratio on permeability performance (Sanjuan and Munoz-Martialay 1996). The excellent permeability performance of the material is as expected due to the lack of aggregates and air voids in the material, combined with the heated press formation technique, which further reduces permeability into the matrix.

The freeze-thaw testing resulted in a durability factor of 54 after 300 cycles. This signals poor performance with respect to resilience to freezing and thawing, as typical concrete is associated with durability factors of above 80 (Wang et al. 2009). To predict the durability of a mix, both the air permeability and freeze-thaw test results are needed to understand performance. The air permeability index reveals the material's resistance to permeation of external gases and liquids. The durability factor reveals the material's ability to resist deterioration once excess liquids are present. Thus, while CEMPOSIT performed well with regard to air permeability, the overall durability of the material is not as robust as desired due to its low durability factor.

Overall, the material has attractive material properties, but also has drawbacks associated with implementation limitations. These strengths and weaknesses are discussed in the next chapter, which explores the applications for ABC projects.

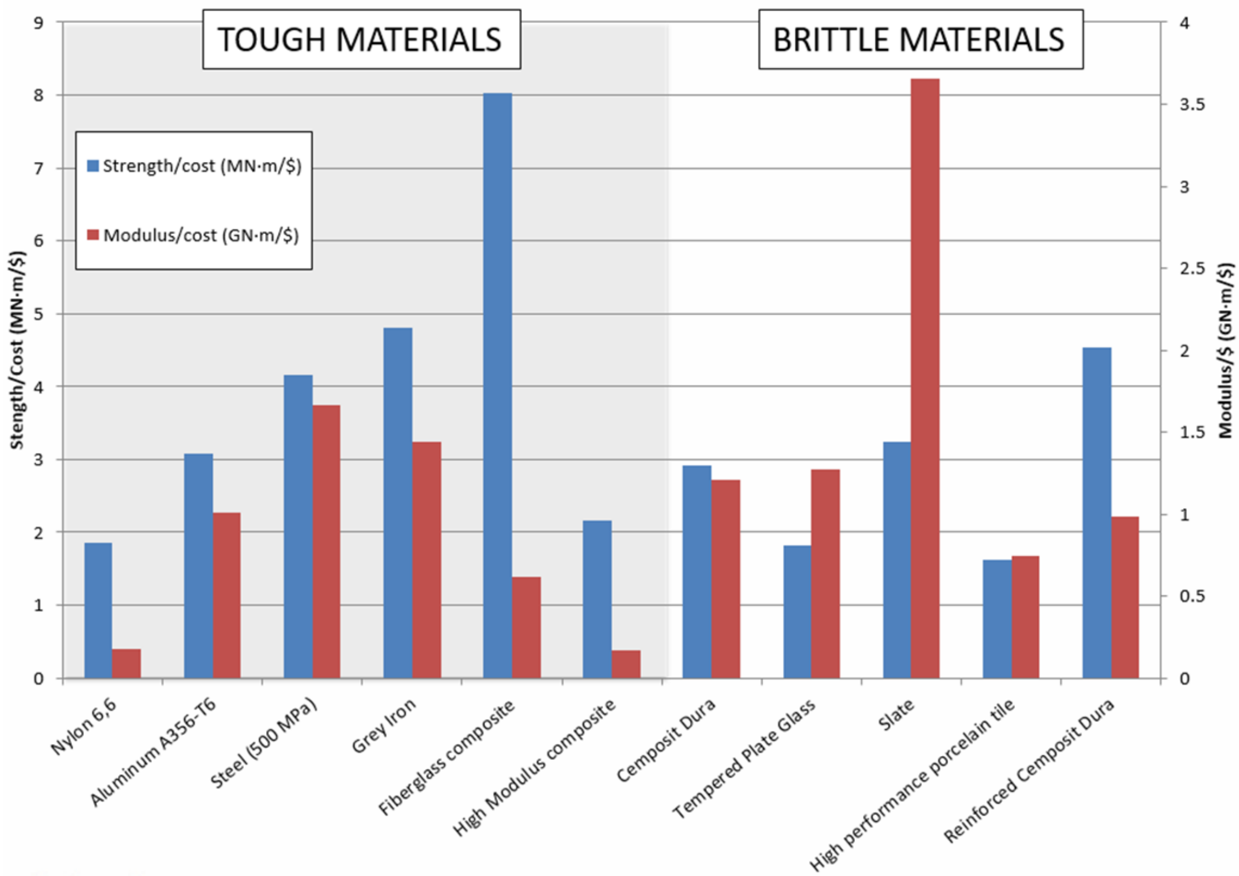
EXPLORATION OF ABC APPLICATIONS

ABC projects achieve reduced road closure times via preformed members and new construction methodologies. CEMPOSIT is attractive for these types of projects because it can be extruded to any shape. As discussed previously, the heat-pressed version of CEMPOSIT offers much more desirable material properties and thus would be preferred over the air-cured formulation.

Because of the nature of the forming process, ABC bridge elements that are cast on-site (such as joints) would probably not be a potential application for the material unless special delivery tools could be developed (perhaps by the CEMPOSIT developers themselves).

Preformed elements such as beams, bearing pads, and other structural elements that have been prefabricated and historically made of other materials would also be possible applications for CEMPOSIT with respect to the methods through which the material is fabricated. However, the use of CEMPOSIT for large-scale members (such as beams) would not be realistic at this time due to the nature of the fabrication process and the need for high shear mixing and heated press of the material. However, should fabrication issues be resolved in a cost-effective manner, it appears that large-scale elements may be a viable opportunity for the use of MDF cement. Aside from fabrication limitations, the other properties determined by the laboratory tests must be considered.

The high early-age strength, along with ultimate compressive and tensile strengths, and extremely good air permeability seen in the laboratory testing, also make CEMPOSIT an appealing material. However, the limitations must be considered. Both cost and strength are shown for a number of materials in Figure 16, grouped by toughness properties.



Modified from correspondence with Aaron Amstutz, Caterpillar Inc. 2016

Figure 16. Strength and modulus versus cost for a variety of materials

This figure shows how CEMPOSIT, both unreinforced and reinforced, compares to the value of other materials. Additional materials are shown for comparative purposes in Figure 17.

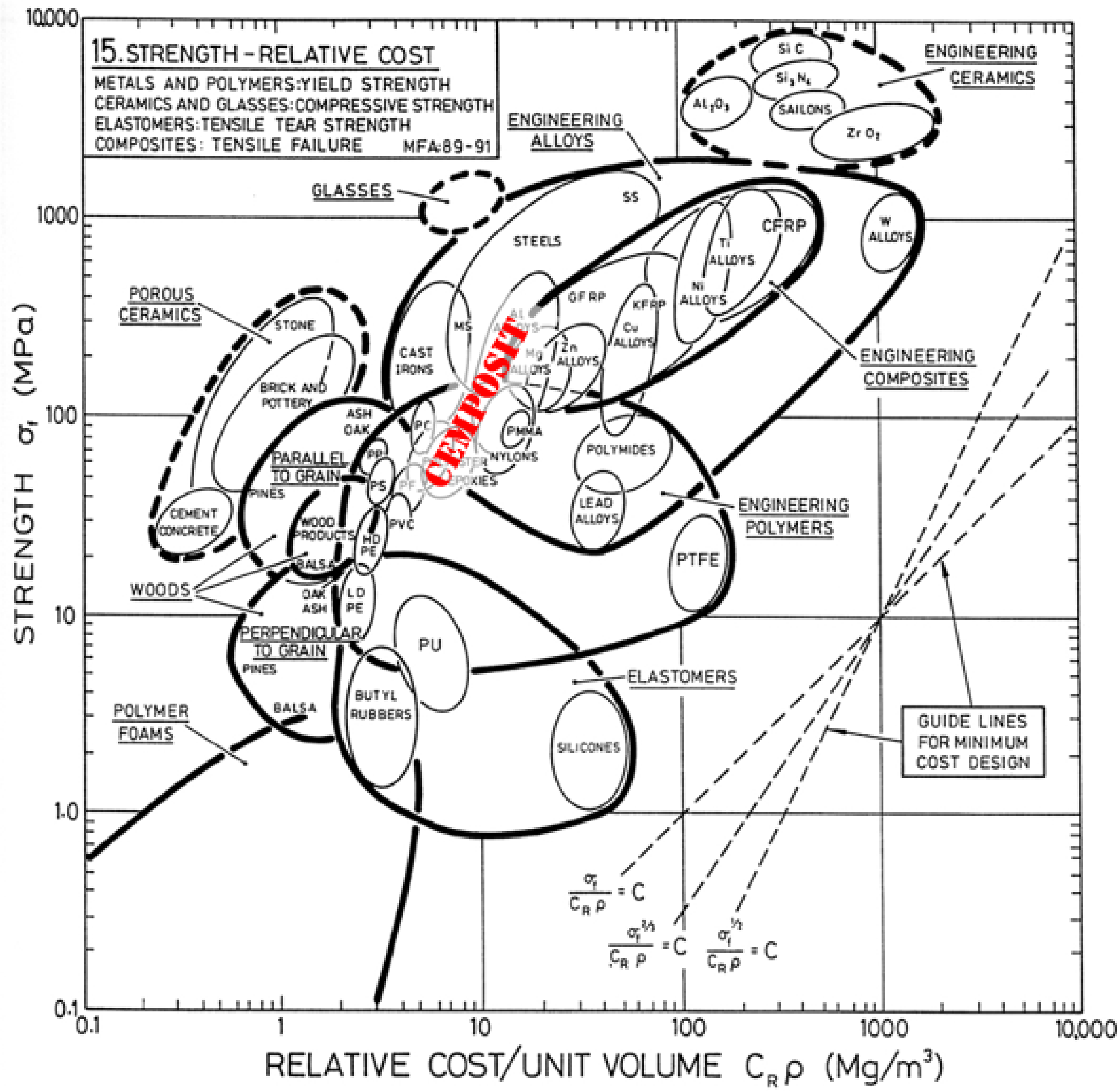


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Figure 17. Strength versus relative cost for representative materials

As can be seen from this figure, and as was previously shown from laboratory results, the strength of CEMPOSIT is greater than that of cement concrete, but the cost is also greater.

While these high strengths are attractive, and higher costs can thus be justified, other material properties must also be considered. The brittle failure mechanism seen during material property tests can be seen more clearly in Figure 18.

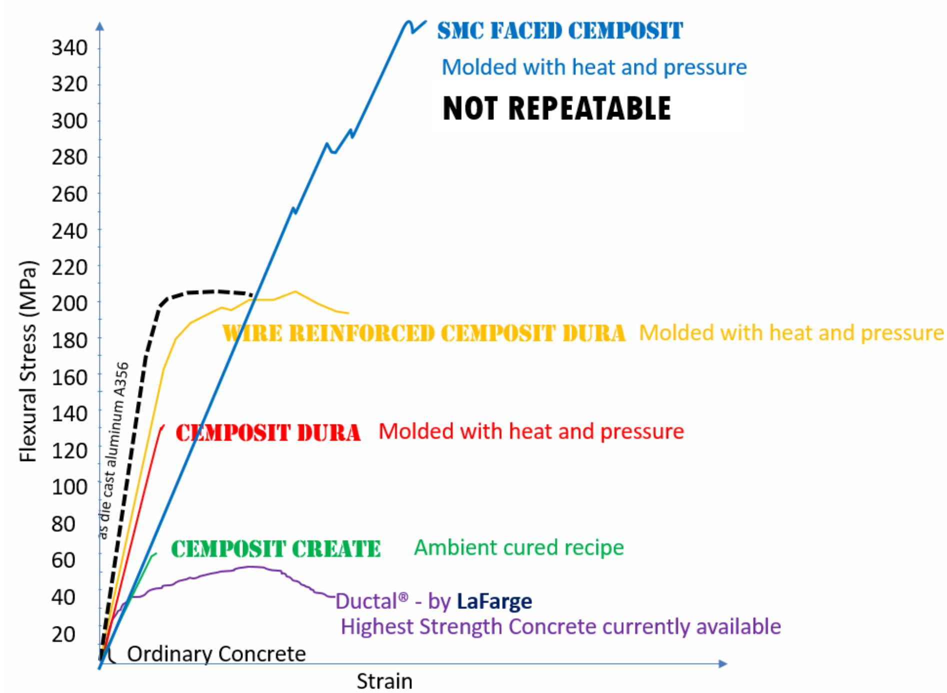

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Figure 18. Stress versus strain for representative materials

This figure shows the stress vs. strain for a number of materials. Toughness is the ability of a material to absorb energy prior to failure at high strengths, and can be visually displayed on a stress-strain plot as the plateau after peak stress is achieved. As can be seen, the wire-reinforced CEMPOSIT exhibited greater toughness than the other lines of CEMPOSIT. The CEMPOSIT Dura and CEMPOSIT Create lines show the high, but brittle, strength of the material. A brittle failure mechanism is not ideal for bridges, as advanced warning of failure is not given.

The excellent air permeability performance of the material indicates that gases and liquids would not easily penetrate the material's matrix. However, once permeation has occurred, the poor freeze-thaw resistance of CEMPOSIT, as indicated by the low durability factor, would allow for relatively rapid degradation of the material to occur. This level of degradation resistance is worse than that of traditional concrete. As such, the material would not be ideal in climates that experience cyclic temperature changes—as much of the US does—unless protective measures (e.g., waterproof coatings, etc.) could be shown to provide sufficient life extension.

CONCLUSIONS

A suite of material tests was performed on an iteration of CEMPOSIT mix, using samples provided by the manufacturer. The samples were created using varying types of forms and layer orientations to determine if these variations had any effect on material properties. These tests included split tensile, compression, air permeability, and freeze-thaw. The laboratory test results showed that CEMPOSIT had:

- Very high compressive strength: Average of 21.8 ksi
- High tensile strength: 1.0 to 1.9 ksi, depending on layer orientation (however, there was significant variability in the results)
- Excellent air permeability characteristics: API >10.0
- Poor freeze-thaw resistance: DF of 54 after 300 cycles

In addition, the strength of the material was brittle in nature and resulted in volatile failures. Based on examination of the collective material properties of CEMPOSIT, at this time there are no apparent viable applications for accelerated bridge construction elements. This is based on the fabrication and fiscal limitations, brittle failure mechanisms, and poor freeze-thaw resistance of the material. However, future iterations or innovations of the material that improve these characteristics may have a place in ABC projects. It is worth noting that the material has several beneficial characteristics and could be implemented for use in other fields.

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