INNOVATIONS IN WASHOUT TOOLING TO LOWER COST, SHORTEN LEAD TIMES, AND IMPROVE PROPERTIES

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ABSTRACT

Nevada Composites Inc. has developed *Green-Aero*^{SM} tooling—lightweight ceramic tooling that is stable under high pressure and long-duration cure cycles and can be washed out with water after cures above 315 °C (600 °F). Tools, whether single-sided or washout, have a composite-compatible CTE, provide tight tolerances, are stable to storage under ambient conditions, and are of affordable cost. All steps in the production process are environmentally benign. Tools, particularly washout mandrels, have been provided to several different military and commercial clients for use in processes including hand layup followed by autoclave cure, filament winding, and VARTM. The goal of the current Navy-sponsored research has been to improve both the cost and the delivery time as well as reproducibility for use by Navy repair depots.

The paper describe innovations in non-oven hardening of the mandrels as well as other mandrel-production innovations. The changing role of rapid additive manufacturing in mandrel production is also discussed.

1. INTRODUCTION

Nevada Composites Inc. (NCI) has demonstrated a technology that is capable of meeting the goals of a water-washout composite manufacturing tool at temperatures of 177 ºC (350 °F) and above while using manufacturing processes such as filament-winding and autoclave curing. The United States Department of the Navy (DON) is interested in this technology because, when developed, it will allow faster repair at lowered cost. Current technical efforts are directed at taking this from a shop-scale process to developing materials and manufacturing processes that are repeatable and meet DON customer requirements while working toward cost and lead times that will meet the needs of the Navy repair depots.

The original STTR topic presented the following goals for washout tooling: (1) has a coefficient of thermal expansion (CTE) compatible with carbon-fiber/epoxy composites, (2) is usable in typical composite processes including tape laying and vacuum-assisted resin-transfer molding (VARTM), (3) can be used in autoclave processing at 177 ºC (350 ºF) and 700 MPa (100 psi), (4) is produced by a highly repeatable process, (5) meets tolerances of +0.13 mm (+0.005”) on thickness and +0.26 mm (+0.010”) on everything else, (6) is low cost. i.e., $40-$50 per tool of size 38 mm x 305 mm x 13 mm (1.5” x 12” x 0.5”), (7) requires minimal processing time, (8) requires no oven postcure of the composite after the tool is removed, (9) has thermal shock and impact resistance equal to ceramics, and (10) is environmentally friendly in both material and waste stream.

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In this paper we are reporting the progress to date on those goals. Since this work is in progress some of the findings are preliminary while some others will be definitive but suggest further work to be done. In some cases more definitive results will be reported during the presentation.

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1.1 Background

Manufacturability of any composite structure in which the tool is trapped is always an issue. Tooling options are limited by their ability to maintain required tolerances and to be removed from the cured composite. This is of increasing concern as cure temperatures are increased above 177°C (350°F). If a higher-temperature composite resin is used in a structure designed for 177°C (350°F) cure a new mandrel system may be required, often necessitating design changes.

Most tooling materials have a coefficient of thermal expansion (CTE) larger than the composite by one or two orders of magnitude. If so, as cure temperature increases the mandrel thermal expansion must be compensated by design changes. This becomes more severe as cure temperature increases, particularly when the shape is complex or internal features are required.

Table 1 shows a comparison of physical and thermal properties for various tooling materials and also shows why *Green-Aero*^{SM} tooling from Nevada Composites is of interest.

Table 1. Summary of Comparative Physical and Thermal Properties for Tooling Materials

Tooling Material	**Specific Gravity** g/cc [lb/ft^3]	**Coeff. of Thermal Conductivity** W/mK [Btu/ft^2/hr/°F/in]	**Coefficient of Thermal Expansion (CTE)** 10^{-6}/°K [µin/in/°F]	**Temperature Limit of Tooling** °C (°F)
Carbon/Epoxy	1.5-1.6 [94-100]	4.5 to 6.0 [24.0-42.0]	Average: 2.5 [1.4]	177 [350]
Aluminum	2.70 [168]	201 [1395]	23 [12.8]	~177 (350]
Steel	7.86 [490]	52 [360]	11.3 to 13.1 [6.3-7.3]	<540 [1000]
Invar 36	8.11 [506]	10.5 [73]	1.44 [0.8] (<390°F)	205 [400]
Invar 42	8.13 [508]	15 [106]	5.2 [2.9] (200°C/390° to 345°C/650°F)	About 350 [660]
Monolithic graphite	1.74-2.00 [109-125]	23 to 31 [160-215]	1.8 to 3.6 [1-2]	425 [800]
Carbon foam	0.32-0.40 [20 to 25]	0.25 to 25 [0.18 to 175]	2.0 to 5.0 [1.1 to 2.8]	315 [600]
***Green-Aero*^{SM} tooling**	**0.48 [30.0]**	**0.12 [0.83]**	**5.0 [2.8]**	**Washout: ~400 [~750] Permanent: abt. 650 [1200]**

Green-Aero^{SM} tooling combines ceramic microspheres with a small amount of low-water-content proprietary inorganic binder. [1-5] This unhardened material is not wet-cast but rather molded by packing it around a master or into a mold to capture its shape. Molding first requires physical consolidation to eliminate low-density areas, then vacuum-compaction to achieve a consolidated state. Once consolidated, the microspheres of this "green" tool will remain in a close-packed configuration so long as vacuum is maintained, allowing the green tool to be removed from the master/mold. Hardening by thermal or chemical means is then used to produce the final tool. Hardening produces no measurable changes in volume or shape, insuring very good tolerances for

the tool. The tools are shelf-stable but washout readily. It should be noted that in recent work we have also reformulated our binder to insure that all components will remain available for at least several decades.

2. DEMONSTRATED APPLICATIONS

In this section we will discuss other recent unpublished work and how it relates to the effort supported by the current DON STTR.

Over the last decade NCI has extended and scaled up the applications where we can successfully use our tooling. The various applications have not only demonstrated where our tooling can be used but also shown where more development could lead to extended applications.

2.1 Large mandrels for replacement ducting

For example, one of the issues with *Green-Aero*^{SM} tooling is the fact that the material is a thermal insulator. If we harden the final tool using thermal methods cracking from the thermal differential can occur. This has been seen, or not, in our applications. For example, we produced a set of mandrels to be used in a 121 °C (250 °F) cure of replacement ducting for a legacy rotorcraft. The mandrels were fairly large (up to 0.8 m / 31”), were complex and often convoluted, and had sections of maximum thickness as large as 0.25 m (10 in.). They were hardened at 150 °C (300 °F) but we did not experience more than minimal cracking, and that was repairable.

Figure 1 shows two mandrels: the one on the left is complete and coated while the one on the right shows where the flaws have been repaired but the duct has not yet been coated.

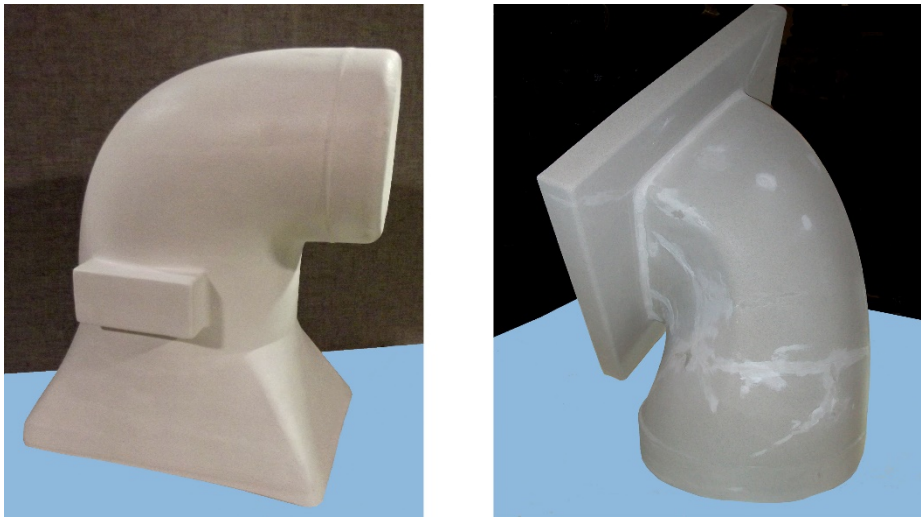


Figure 1. Washout mandrels for ducting for a legacy Army rotorcraft. The mandrel on the right has been patched but not coated while the mandrel on the left has been coated and is ready to use.

However, in more recent work we repeatedly encountered cracking in a 0.15 m (6”) diameter cylindrical section. We had problems with cylindrical sections before, with frequent cracking in sections thicker than about 0.127 m (5”). We concluded that the more complex the mandrel or tool, the more complicated it is to predict the results of thermal stress and also that cylindrical sections

seem to offer a significant challenge. This finding is one of the reasons why we have been looking at out-of-oven approaches to hardening our tooling.

2.2 Caul tools for layup of bismaleimide-matrix (BMI) composite tooling

For another project we produced *Green-Aero*^{SM} tooling/caul plates on which 230 ºC /450 °F-cure BMI composite tools could be laid up. The largest of these caul tools were about 0.3 m (1 ft) by 0.9 m (3 feet), an example of which is shown in Figure 2.



Figure 2. Largest caul tool made for the Navy at FRCSW

The caul tools were nearly flat but had a precise slight curvature and required carefully located scribe lines. For this work we developed a non-washout room-temperature-hardenable tooling material with similar characteristics to our elevated-temperature-hardening *Green-Aero*^{SM} tooling. This material can also be used to take a "splash" of an existing part or structure, such as a component on an aircraft on the tarmac. In addition, since we have shown that the material holds up at temperatures to 177 °C (350 °F) it has also been used as a mold or master for our tooling.

We have continued this effort in developing *Green-Aero*^{SM} tooling formulations and processes that provide non-thermal hardening of our tooling and would allow the capture of a splash for repair purposes.

2.3 Complex ducting mandrels for grounded military aircraft

In work for a commercial customer we produced six complex multi-armed mandrels each of two types to repair the ducting on a grounded legacy military aircraft. For this project we molded sections of the ducts in molds machined from tooling board and then joined these together using our water-soluble ceramic adhesive.

Figure 3 shows three views of the CAD model of one of the ducts along with three similar views of the *Green-Aero*^{SM} mandrels we made to reproduce the ducting.

In our current work we continue to use ceramic bonding as an option to create complex mandrels.

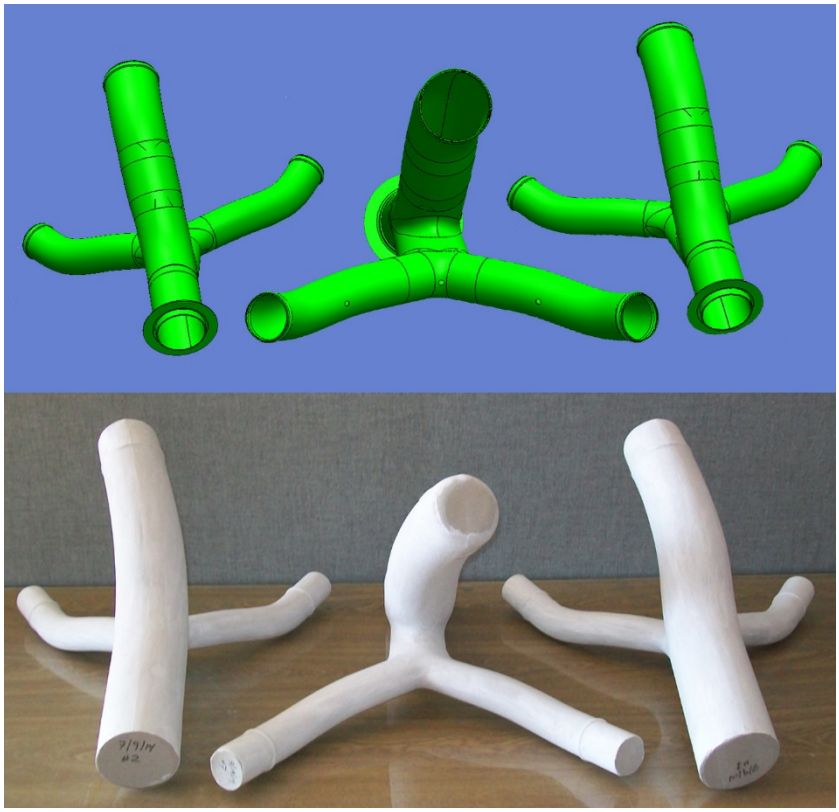


Figure 3. Above, three views of CAD model for replacement ducting for a legacy military aircraft and, below, three coated duct mandrels used to recreate the ducting

2.4 Historic cost data as a guide to reducing the cost of our washout mandrels

It should be noted that to make molds we have used both additive and subtractive methods. For smaller molds we have used fused deposition modeling (FDM), a type of additive manufacturing, and found the molds easy to use and the mandrels we made from them very satisfactory. For production of large numbers of identical tools they are also superior to CNC molds machined from tooling foam since FDM molds are very durable and tooling block edges may dull after multiple uses, depending on the density of tooling foam used. (More dense foam is more durable but it also weighs and costs proportionally more.) Unfortunately, the cost of producing additively manufactured molds increases significantly with mold size and at some point it becomes economically inadvisable to use such molds.

Figure 4 shows our historic cost as a function of mold size for *Green-Aero*^{SM} tooling based upon several years of manufacturing commercial tools/mandrels for customers.

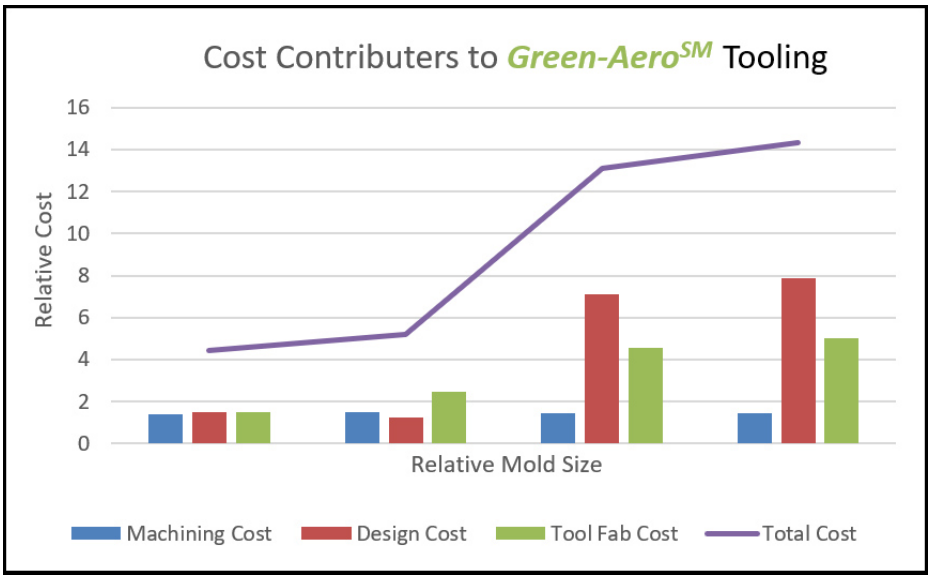


Figure 4. Cost as a function of mold size for *Green-Aero*^{SM} tooling based upon historic company data. (Note that Design and Machining costs are for the mold and thus are NRE, thus amortized over the number of tools made.)

This figure illustrates ways we can reduce final tool cost:

1. Both the cost of designing the mold and the cost of machining/printing it are non-recurring expenses (NRE), meaning that they are not repeated if multiple mandrels/tools are made from the same mold. In addition, taken together this NRE is somewhat to a lot more than the cost of producing the mandrel itself from the mold. Thus a significant cost reduction can be had from making multiple mandrels from the same mold.
2. Except for small tools the machining/printing cost for the mold is more than the cost of making the mandrel/tool itself and for larger molds is significantly greater than the cost of designing the mold. Thus, means of reducing the cost of machining or printing the molds would give an obvious reduction in overall mandrel-production costs.
3. The cost of fabricating the mandrel/tool itself from the mold is almost linear with mold/tool size. Currently this step requires the most touch labor and thus is an obvious area for cost reduction. As we will describe this is another reason why we have pursued non-oven hardening techniques for our mandrels.
4. It would obviously be attractive to completely eliminate the NRE costs of making the mold by directly printing our mandrels. This, however, is no small feat since our *Green-Aero*^{SM} tooling materials are non-polymeric in nature. Nonetheless, direct printing of our mandrels is a high-risk / high-reward effort currently under investigation.

2.5 Guide to reduction in lead time for *Green-Aero*^{SM} tooling

Similar data could be generated covering the time-to-manufacture of our *Green-Aero*^{SM} tooling. If a mold or master is available the uncoated tool can be produced in minutes to overnight. However, the usual rate-limiting step is production of a mold or master, with creation of the mandrel itself

taking hours to a day. Final finishing for special features or adhesively bonding sections together may also require extra time but typically surface finish or coating of the tool is another rate-limiting step and can take minutes to days, depending on requirements.

3. CURRENT NAVY WORK

In the Introduction we described the goals expressed by the Navy in the original STTR topic description. NCI had already met some of these goals in work prior to the Navy STTR. Our CTE is compatible with carbon-fiber/epoxy composites and our thermal shock and impact resistance are those of a ceramic. Several projects had demonstrated compatibility with typical composite processing including filament winding, tape laying, and VARTM. Autoclave curing has been used to temperatures and pressures significantly above 177 ºC (350 ºF) and 700 MPa (100 psi) and this high-temperature capability insures that no postcure of the composite is needed after tool removal. We can meet the required tolerances either as-molded or, for more complex tools, after finish machining. In addition, our material and everything in our process is environmentally friendly.

Nonetheless, our discussions with the Navy repair depots have made it clear that our lead time, particularly for mold production, is not currently acceptable. In addition, while very simple or multiple replicates of small mandrels might cost $40-$50 or less, larger and/or more complex mandrels could cost ten to a hundred times more. Finally, our *Green-Aero*^{SM} material characterization work has shown significant batch-to-batch variations in properties that lead us to be concerned about reproducibility. For this reason our work on the current Navy STTR program has concentrated on lead time, cost, and reproducibility.

3.1 Improvements in lead time and cost

Although lead time and cost do not have a direct relationship in most cases those steps in the washout tooling process that take longer also cost more and vice versa. Thus we will discuss these two factors together.

Steps between having a design for a composite part made that requires a washout mandrel and having a final *Green-Aero*^{SM} mandrel for fabrication of the part:

1. Starting from a CAD file of the part determine how best to make the required mandrel and then design the mold or master needed to create it.
2. Create the master or mold
    a. If it is economically feasible and equipment is available use additive manufacturing.
    b. If additive manufacturing of the mold/master is not feasible create it by subtractive processes such as machining from tooling block.
3. Use the mold/master to create the green tool.
4. Harden the green tool into a free-standing mandrel.
5. Perform any finishing, bonding, etc., needed to create a usable mandrel.
6. As needed, take care of sealing and/or surface finishing the mandrel by tape-wrapping, shrink-wrapping, coating, or other means.

To date on the current Navy contract most of our work has concentrated on Step 4 and on both producibility and reproducibility. We have focused on Step 4 because this is the step we can most readily control and it also has bearing upon producibility.

3.1.1 Microwave hardening of Green-Aero^{SM} tooling

Early on in our DON STTR work we investigated microwave hardening of our tooling. As described in Section 2.1 one of the major issues for our tooling is that the material is a thermal insulator and thus significant thermal stresses can be encountered between a hot exterior and a cool interior during oven hardening of our tools. This led us to consider microwave hardening as a way to reduce the thermal gradient. Figure 5 illustrates the advantages of microwave hardening of our tooling.

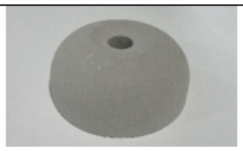
	6" Diameter Dome Time to microwave harden: 7 min
	Small Duct Time to microwave harden: 10 min
	Y Duct Time to microwave harden: 13 min
	Caul Plate / Tooling Master Time to microwave harden: 15 min
	Bellows Duct Time to microwave harden: 21 min
	6" Diameter Cylinder Time to microwave harden: 44 min

Figure 5. Time to microwave harden *Green-Aero^{SM}* mandrels with our existing microwave oven. Each would take 340 minutes to harden in an oven.

Our early experiments were conducted in a modified consumer microwave and quickly led us to identify one problem with such an oven, namely that the emitter is in a fixed location. Nonetheless, initial experiments were encouraging and we have since scaled up to a larger microwave. Again,

the fixed emitter location poses some problems for uniform hardening and the rotating plate used in consumer microwaves is not compatible with our vacuum lines. We are in the process of making modifications to improve the uniformity. Nonetheless, we have succeeded in increasing section size and greatly reducing hardening times with no loss in washout ability.

3.1.2 Gas (chemical) hardening of Green-Aero^{SM} tooling

In order to improve our ability to harden thick sections of *Green-Aero^{SM}* we are also investigating a binder formulation that can be hardened by exposure to a gas. To date this has given us a thick, hard specimens that wash out easily. Stability, humidity resistance, shrinkage, maximum section size, uniformity, and other properties await investigation.

3.1.3 Reduction of lead time by additive manufacturing of molds

As mentioned in Section 2.4 we have previously used FDM to make molds that worked very well in making our mandrels. Typically the lead time for additive manufacturing is less to much less than machining of molds but as the size of the required mold increases the cost also increases. So we find a trade-off. However, the cost of additive manufacturing continues to decrease and the cross-over point in size where it is no longer economical continues to move upward. Producing guidelines for when to use additive and when to use subtractive approaches for molds is part of our current development work.

3.1.4 Direct 3D printing of Green-Aero^{SM} tooling

As mentioned previously, *Green-Aero^{SM}* tooling is not polymeric in nature. It is both formed and dissolved by removal or addition of water. In addition, it requires vacuum compaction to form properly. This makes additive manufacturing challenging. However, our research team has outlined some possible approaches and these are under investigation by UNLV.

3.2 Improvements in reproducibility

Early on in our DON STTR work it was our intention to compare the mechanical properties of *Green-Aero^{SM}* specimens as a function of variables such as binder formulation, mixing method, and hardening method in order to determine if different techniques produced different results and to help us select the best fabrication techniques. We chose four-point-bend flexural testing as a good quality assurance test and compression testing to give a more direct measure of mechanical properties.

The testing and analysis for this work was performed by our research partner UNLV.

In our initial testing we were trying to determine whether microwave-hardened specimens of *Green-Aero^{SM}* gave different mechanicals than did oven-hardened. We also wanted to determine the influence of changes in binder formulation. I present here only a taste of what we found—a taste of what alerted us to a reproducibility problem.

Table 2 shows the results of the first UNLV work comparing different batches of specimens and microwave vs. oven hardening.

Table 2. Flexural Properties of Batches of Oven or Microware Hardened Specimens

Specimen Batch	No. specimens	Flexural Strength (MPa)	Standard Deviation	Flexural Modulus (GPa)	Standard Deviation
MM MW	5	1.76	10.7 %	1.82	4.6 %
OV B1	9	1.57	14.7 %	1.44	15.5 %
MW B2	8	1.80	37.6 %	2.17	13.9 %
OV B3	12	1.56	19.2 %	1.41	18.9 %

As you can see from this data there seem to be some significant differences in both strength and modulus but the standard deviation of the results is frustratingly large for many of the groups.

Table 3 shows a statistical comparison of the flexural strength of various oven-hardened and microwave-hardened batches of two binder formulations.

Table 3. t-Test of Mean Flexural Strengths (95% Confidence Level)

Comparison of Strength (MPa)						
Specimen	**1) OV B1 v 2) OV B3**	**1) MM MW v 2) MW B2**	**1) Combined Oven v 2) MW B2**	**1) SM4-20-5 v 2) MM MW**	**1) SM4-20-5 v 2) MW B2**	**1) SMO-4-20-5 v 2) (OV B1 & B3)**
Mean 1)	**1.57**	**1.76**	**1.56**	**1.98**	**1.98**	**2.22**
St. Dev. 1)	**14.7%**	**10.7%**	**17.0%**	**8.5%**	**8.5%**	**30.4%**
Mean 2)	**1.56**	**1.80**	**1.80**	**1.76**	**1.80**	**1.56**
St. Dev. 2)	**19.2%**	**37.6%**	**37.6%**	**10.7%**	**37.6%**	**17.0%**
df	19	9	8	8	8	7
t critical	2.093	2.262	2.306	2.306	2.306	2.365
t value	0.108	0.156	0.954	2.100	0.271	2.515
Means are different?	No	No	No	No	No	Yes

The table shows that in all but one case there is no discernable difference at the 95% confidence level between the mean strength results for different variables. While this may seem to be good thing we expected some differences. The modulus values showed more differences but in some ways these seemed random and not clearly related to changes in variables. Our conclusion was that our batch-to-batch variation was too large and was overwhelming any opportunity to see effects on properties from variable changes.

We thus embarked upon a major effort to control sources of batch-to-batch variations. Looking for the possible causes we determined there to be two likely sources: either our mixing technique or something in the chemistry.

We had suspected for some time that our mixing technique, especially for the small batches used to make specimens, was at fault and was introducing greater differences “depending on which foot we stood on” than were introduced by the variables we wanted to study. Thus, we set out to study our mixing technique itself. We prepared three different batches for each mixing technique with

at least seven specimens in each batch. We also prepared one "easy to mix" specimen batch as a control. This gave 13 different batches of specimens with seven to eight specimens in each batch.

The results of the testing at UNLV are reported in Table 4. Once again we see frustratingly high standard deviations for some of the batches. The statistical comparison of the means for both strength and modulus gave various results depending on which two batches were compared but the overall conclusion was unavoidable: we still had way too much batch-to-batch variation.

Table 4. Flexural Strength and Modulus for Multiple Batches of *Green-Aero*^{SM} with Various Mixing Techniques

	Average Strength (psi)	Strength St. Dev. (%)		Average Modulus (ksi)	Modulus St. Dev. (%)
E1AMM	110.0	15%		81.1	17%
E1BMM	156.6	7%		127.1	13%
E1CMM	108.4	12%		69.8	32%
E1AHM	126.9	22%		70.5	43%
E1BHM	295.5	8%		232.5	11%
E1CHM	210.0	39%		171.4	50%
E2AMM	198.8	12%		158.9	20%
E2BMM	120.0	6%		59.9	6%
E2CMM	342.9	33%		168.4	22%
E2AHM	133.8	13%		89.6	12%
E2BHM	233.2	28%		180.5	22%
E2CHM	269.3	9%		205.6	8%
4_22_3	297.8	9%		210.3	7%

Thus we next looked at our binder chemistry as a possible cause of the batch-to-batch variation. We realized that one step in our process produced a material that was difficult to mix with other components. After a series of experiments we found a very simple modification that completely eliminated the difficulty in mixing.

At this point we called a halt to UNLV's compression tests on the 13 batches and prepared a series of new flexural specimens for them to test. Those results will begin to be available soon. We are optimistic that we will have significantly reduced our batch-to-batch variability and can return to identifying the effects of variables such as changes in binder formula .

4. CONCLUSIONS

In summary, Nevada Composites Inc. has demonstrated a technology that is capable of meeting the goals of a water-washout composite manufacturing tool at temperatures of 177 ºC (350 °F) and above while using manufacturing processes such as filament-winding and autoclave curing.

Current technical efforts are directed at taking this from a shop-scale process to developing materials and manufacturing processes that are repeatable and meet DON customer requirements while working toward cost and lead times that will meet the needs of the Navy repair depots.

During the current effort we have made several improvements in lead time and cost. We have scaled up our microwave hardening, which gives us a very large reduction in hardening times. We are also beginning on work on a gas-hardenable formulation of our binder. Meanwhile our research partner, UNLV, is investigating options for direct 3D printing of our mandrels.

A major effort has been in understanding batch-to-batch variations in specimens we produced to study other variables. After a lot of mixing, specimen-making, and testing we believe we have eliminated a major contributor to the lack of reproducibility. Testing of the resulting specimens for confirmation is just beginning at UNLV.

Our next effort will be to create design rules for using *Green-Aero*^{SM} for a variety of applications.

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