

Paradigm for Design of Biomimetic Adaptive Structures **Carolyn Dry, Ph.D., President, Natural Process Design, Inc.**

Nature builds by 1) using local, available materials which 2) self-ordering or growing by attributes shared between material and environment; 3) repairing themselves, 4) sensing and adapting to changes in environment; 5) disintegrating, recycling back into the material sink; and 6) sometimes enhancing the shared environment. The intent is to improve the environment and to take up effluents from a fossil fuel economy while building as if you are part of nature.

The author has invented and developed materials for all parts of the paradigm either individually or in tandem. Application of these rules in funded research projects briefly described herein are:

- 1) in-situ adaptive ports in ocean made from chemicals in seawater based on bio-mimicking the human body. The formation of which takes up CO₂ and gives off oxygen.
- 2) self-repairing, self-sensing concrete because making cement produces some 6-10 % of the world's CO₂
- 3) self-repairing polymer composites because these are made of oil and use heat to process
- 4) bone-mimicry material self-formation to achieve a cement/polymer composite
- 5) flyash building materials sequestering heavy metals and an effluent from coal fired furnaces.

Natural Process Design, is a biological mimicking system in which the beauty of natural integrated systems are studied and then implemented for human use. It integrates all of the separate functions such as self formation, sensing, repair, self recycling. This integration relies on using the same chemicals which undergo different forces from nature and use various natural processes.

Design with natural process is drawing from the “experience” of evolution and integrating those principles into technology. It is an examination of properties of entire systems and elements, their effects on each other and their performances based on interactions of a complex system. Ultimately their capacity to organize materials in a complex way and reorganize depends upon the interrelationships among elements, not upon the number of elements added.

1. Design of Ports Using the Chemistry of Seawater

The first research project expressed all aspects of this complex biological paradigm over time of self-growth and positioning, adaptation, and recycling. The biomimetic models were corrals and animal bodies. The US Office of Naval Research sponsored a project making in-situ building materials in the ocean from the chemicals in seawater.

The most integrated project is a self building port that uses the chemistry of seawater. The attempt to emulate this model of nature is a project of making in-situ building materials in the ocean from the chemicals in seawater. 1) Calcium carbonate in seawater was to be electrochemically deposited onto a framework following the work of Wolf Hilbertz. This was to be accomplished by charging the seawater (the environment) with electricity which attracts the charged ions (calcium carbonate) to a framework; this is called accretion. 2) When the pier is no longer in use, the absence of pressure allows the charged ions in the structure to lose their electrical attraction and dissolve back into the seawater to be recycled

In the ocean port work, one basic chemistry system delivers many different functions. The fact that the seawater is the same as your lymph allows us to do many body like functions in building in seawater such as forming a structure that is bonelike. Ions are charged particles in seawater and the seawater can carry an electrical charge i.e. it is an electrolyte. That means that these ions can be moved to form somewhere as a structure by electricity. In this project the one basic chemical system of seawater can support the various functions required.

The electrolytic sea water can carry an electrical charge and move calcium ions onto the charged structure. This forms a coral or bone like material. Based on the fact that we evolved from seawater, our lymph is exactly like seawater in chemical composition, so I looked to the human body for inspiration.

The chemicals and process used to accomplish those functions are:

- 1) the cheap materials are chemicals in seawater
- 2) these ocean chemicals can be put into physical organization by the movement of them as charged ions in an electrolyte (capable of carrying a charge), the seawater, by an electrical charge
- 3) reversible, recyclable materials are the very structural material if you turn off the electricity or charge producing capacity the structural chemicals will eventually dissolve back into the seawater from which they came.
- 4) improving the environment consists of taking up CO₂ from seawater as the accretion forms and giving off hydrogen and oxygen are given off. **The overall system functions like a tree in exchanging CO₂ and H₂O for O₂ and H₂.**

1,2) Self Forming Mineral Accretion Structures (based on seashells, coral and bones)

The material can be put into physical form organization by a process integral to the material and the environment and the material to be put into physical form organization by a process integral to the material and the environment

The ability of seawater to dissolve and corrode many substances in it and also to cover them with encrustations of minerals and organic matter can be harnessed. These natural accretions have been found to have the bearing strength of concrete. Sea mollusks make their shells by accreting minerals through use of an electric potential.

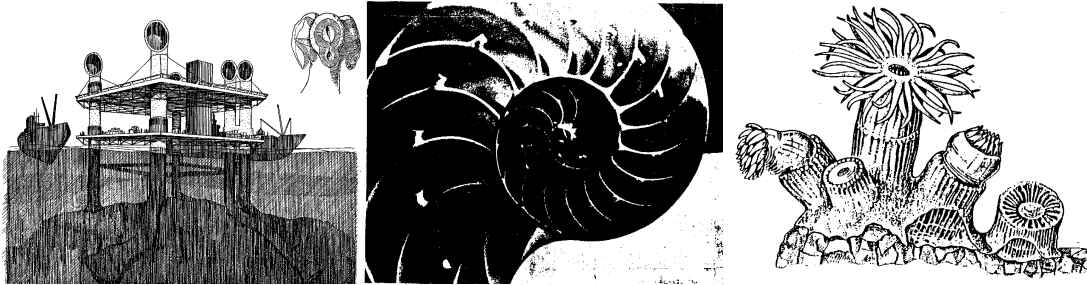


Figure 1) Left, design of ports with natural processes of the chemistry of seawater, Next, the chambered nautilus seashell Right, the corral inspiration

Ions in seawater are subject to such electrolytic processes and these ions can be precipitated onto surfaces. In the system designed by Wolf Hilbertz a metal armature is hooked to external electrodes with a charge and submerged in seawater, the electrical current produces an electrolytic deposition of minerals onto the armature framework. CO₂ from seawater is taken up. The cathode gives off hydrogen; the anode, oxygen. A power supply from a battery charge of about 4.8U at 200mA to hardware cloth, anode of carbon about 10cm x 2cm in an aquarium 3 x 1½ x 2 for a period of 500 hours produces an accretion of 10mm.

2) Self repairing concrete

Nature self repairs and concrete in the built world is the ideal candidate for a self repairing material because **cement production, which is the main ingredient in concrete, produced some 5-8% of the world's CO₂ yearly.** It is the largest single point source for greenhouse gas production. It is an ideal target for self-repair to prolong the life cycle of concrete structures and prevent excessive replacements that utilize cement and give off CO₂ in the calcining.

The usual approaches for repair of structural concrete are: polymer injection, prestressing, geomembranes, and polymer wraps. These techniques seek a ductile, less brittle failure. All of them are based on addition of a repair material to concrete from the outside in; we add the materials inside the concrete. The approach consists of embedding repair material in hollow fibers in the repair matrix, before it is subjected to damage. Therefore, when cracking occurs, this repair material is released from inside the fibers and enters the matrix, where it penetrates into cracks and bonds to the mother material of the structure being repaired. The

cracking and damage, associated with the low tensile strain capacity, triggers the release of the repair material. This is important because in this way, the material acts in an extensible manner. We repair the problem, where it occurs, and just in time, automatically, without any manual intervention.

The ability to fill in for dimensional gaps has been shown to work with self-repairing adhesives that foam. Even with internally released stiff non-foaming adhesives, self-repaired matrices are less brittle, more ductile, and yet stronger in tension than controls without adhesives.

The question of whether we could replace the tensile strength given by steel rebar was also explored. The research results showed that in the first loading, concrete samples with adhesives and a small amount of metal that provides additional tensile strength were stronger in tension than control samples reinforced with more metal wires, metal mesh or even rebars.

In self-repair of cracks, different types of structural failure require different approaches. For instance, in full scale bridge applications, we addressed surface drying cracks by creating in-situ control joints. We placed scored brittle fibers, which broke at the centerline upon matrix shrinkage, releasing a sealant/adhesive. Furthermore, we repaired shear cracks by chemicals released from fibers buried in the depth of the bridges. We observed that when these broke, the entire bridge performed better than the control one without the embedded adhesive filled fibers. Our approach provided a self-repairing technique that transformed the entire structure into a ductile material, where energy was dissipated all over as cracks formed, and consequently, catastrophic failure due to the enlargement of any one crack, was prevented.

Furthermore, we made frames to represent bridges and structures subjected to dynamic loads. We demonstrated that, as a result of self-repair with different types and locations of adhesives, there was less permanent deflection, more stiffness in specific locations, where desired by adding stiff adhesives or more damping by adding damping chemicals. Also, we are researching the self-repairing approach to improve the performance of prestressed members by re-bonding the tendons to the concrete, should any become debonded. These approaches are discussed in references 1-7

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Self-Repairing Concrete Frames Which Represent Buildings and Bridges

The self repairing method investigated for this project utilized the timed release of adhesive into the member at the time of cracking. We constructed concrete frames that simulated buildings and bridges. Chemically inert tubing was cast within the cross section of the member and then was filled with adhesive. At the onset of cracking, the tube wall was fractured, allowing adhesive to exit the tubing and penetrate the developing crack. Two sets of static loading were applied, in which failure modes were checked for each sample to determine either the frame failed at crack sites sealed by the flexible adhesives, or crack sites sealed by adhesive. Then the frames were subjected to cyclic loading (repetitive static loading, not dynamic), immediately after the third test in order to examine whether or not each experimental adhesive was able to exhibit elastic or inelastic behavior in the frame [4].

It was seen that in self-repairing frames, high modulus of elasticity adhesives (stiff adhesives), released at the structural points, repaired the initial damage in critical regions. These stiff adhesives allowed damaged points to regain stiffness, preventing future damage at the joints, while transferring forces to other portions of the structure, preventing catastrophic failure. However, the control frames with no internal adhesive were catastrophically damaged.

The self-repairing frames deflected more than the control ones, while resisting larger loads, see figure 8. The self-repairing frames had fewer reopened old cracks than controls, and the self-repairing frames with stiff adhesives were stiffer than the controls, the ones without adhesives, see figures. Furthermore, testing

on the hysteresis effects showed that the frames with repair chemical more nearly returned to their original configuration than those without repair chemicals.



Figure 2) Photo of frame containing internal self-repairing adhesives, cracking in the third static test, which shows cracking all over, but no catastrophic failure [4]

It was successfully demonstrated how to control structural damage by strategic release of appropriate internal repair adhesives in critical locations of the frame. There was less permanent deflection and more stiffness in locations where stiff adhesives were used and more damping where damping chemicals were added to the matrix. It was proved that structural damage, namely cracking, can be directed to the members themselves, where cracks can be repaired by flexible adhesives which allow some flexibility in the members for energy dissipation, necessary for resisting dynamic loading failure and recovery from deformation. The most interesting result of these experiments was the visual assessment that the adhesive was being pumped further with each crack opening and closing due to reloading, see figure.

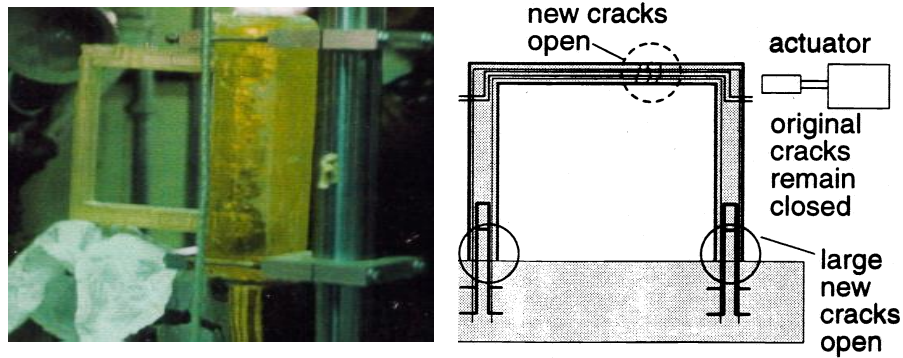


Figure 3) Test frames containing glass pipette fibers filled with adhesive. Not only do such frames repair cracks all over the matrix, but also it was observed that crack opening and closing (caused by load application and removal) drove the adhesive deeper into the matrix with each action, like a bellows.

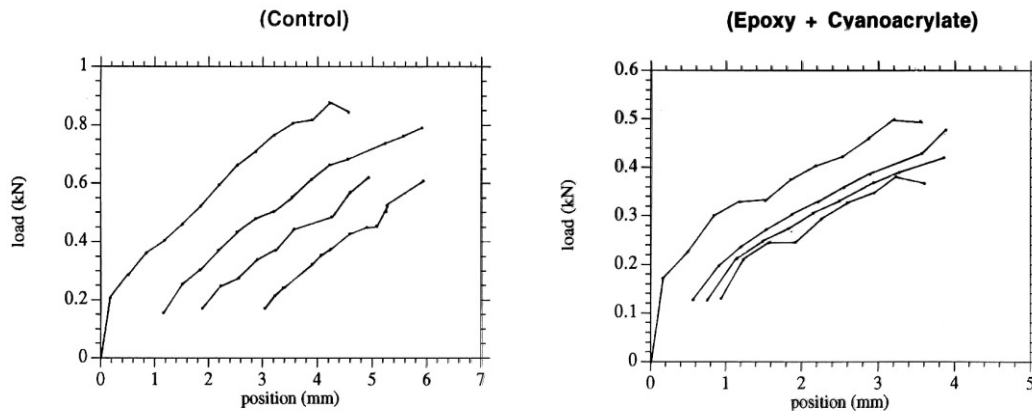


Figure 4. Hysteresis results of test on self-repairing frames on the right, versus frames without repair chemical on the left [4]

Self-Repair of Cracks in Full-Scale Concrete Bridge Decks

Different types of cracking require different approaches. This research, sponsored by NCHRP of the Transportation Research Board and Natural Process Design, and done at the University of Illinois, focused on the repairing of drying shrinkage cracks and on repair of structural load-induced cracks in four full-scale bridge decks. Fibers were thrown into the cement mixer to prove that they could survive the mixing intact.



Figure 5) Fibers being thrown into the cement mixer at the site, on the left, and they survive after mixing in the bridge concrete, on the right.

Surface drying cracks were addressed by creating in-situ control joints. Scored brittle fibers were placed in a row which broke at the centerline upon matrix shrinkage, releasing a sealant/adhesive. In these large bridges, interior shear cracks were repaired by chemicals released from fibers buried in the depth of the bridges [5]. Furthermore, long capsules containing strong, high modulus adhesives were placed below the surface in areas of tension caused by bending, for example the top of the section over the supports. When these broke, the entire bridge performed better than the control one without embedded adhesive filled fibers. The release of an adhesive after testing is shown in the figure. Structural cracks, induced by loading, were successfully repaired. This was evidenced by the higher strength of the bridge decks that contained adhesives, when compared to the control deck. Also, we observed that new cracks formed in certain locations, and consequently, this prevented reopening of any of the previously repaired cracks [6].



Figure 6) Left, photo of fabrication of bridge decks. Right, photo of released repair adhesive [6].

Regarding these results, it is seen that our approach provided a self-repairing technique that transformed the entire structure into a ductile material, where energy was dissipated all over as cracks formed, and consequently, catastrophic failure, due to the enlargement of any crack, was prevented. Cracks were repaired as they formed, so that further crack damage in those locations, intrusion of water or chemicals were prevented at that site

Testing revealed that internal release of adhesives in the three tests increased the modulus of elasticity, the stiffness, and reduced the strain of the three decks, as compared to the control deck, see figure 13.

	Mod. of Elasticity (ksi) Test 1 Load 1-2	Mod. of Elasticity (ksi) Test 2 Load 1-2	Mod. of Elasticity (ksi) Test 3 Load 1-2		Stiffness (kip/in) Test 1 Load 1	Stiffness (kip/in) Test 2 Load 1	Stiffness (kip/in) Test 3 Load 1		Strain Test 1 Load 1	Strain Test 2 Load 1	Strain Test 3 Load 1
Deck 1	2133	853	2276	Deck 1	4.712	4.400	1.257	Deck 1	.000039	.000039	.000137
Deck 2	4267	1707		Deck 2	3.141	1.100	1.675	Deck 2	.000059	.000156	.000117
Deck 3	1067	569	3413	Deck 3	0.785	5.656	4.400	Deck 3	.000313	.000039	.000039
Deck 4	1067	5120	3413	Deck 4	0.785	3.144	3.140	Deck 4	.000313	.000039	.000078
	% Change Between Test 1 Load 1-2 and Test 2 Load 1-2	% Change Between Test 2 Load 1-2 and Test 3 Load 1-2	% Change Between Test 1 Load 1-2 and Test 3 Load 1-2		% Change Between Test 1 Load 1 and Test 2 Load 1	% Change Between Test 2 Load 1 and Test 3 Load 1	% Change Between Test 1 Load 1 and Test 3 Load 1		% Change Between Test 1 Load 1 and Test 2 Load 1	% Change Between Test 2 Load 1 and Test 3 Load 1	% Change Between Test 1 Load 1 and Test 3 Load 1
Deck 1	-60	167	7	Deck 1	-7	-71	-73	Deck 1	0	251	251
Deck 2	-60			Deck 2	-65	52	-47	Deck 2	164	-25	98
Deck 3	-47	500	220	Deck 3	621	-22	461	Deck 3	-88	0	-88
Deck 4	380	-33	220	Deck 4	301	0	300	Deck 4	-88	100	-75

Figure 7. Chart indicating the changes in modulus of elasticity, stiffness and strain of the four decks, that were tested three times. Deck # 1 is the control.

Prevention and Delay of Corrosion

The time of corrosion onset and severity can be improved by the release of anticorrosion chemicals from hollow porous polypropylene or fiberglass fibers. These fibers are coated with a chemical which dissolves in saltwater, polyol. The encapsulated chemical is released onto the metal rebar when the salt water dissolves the coating. ASTM tests for corrosion were used to demonstrate this. The release of the corrosion inhibitor chemical is at the portion of the reinforcing bar in danger of corrosion when conditions would allow corrosion to initiate. In a series of tests with concrete samples containing either no protection or the conventional freely mixed calcium nitrite, this system of internal release form fibers performed well. It delayed the onset of corrosion by at least three weeks, in the laboratory specimens, and reduced the amount of total corrosion by more than half. Figure 12 left shows the data before conversion to times and severity

in real time and space, and figure 12 right shows the visual inspection and assessment of the corrosion samples [7].

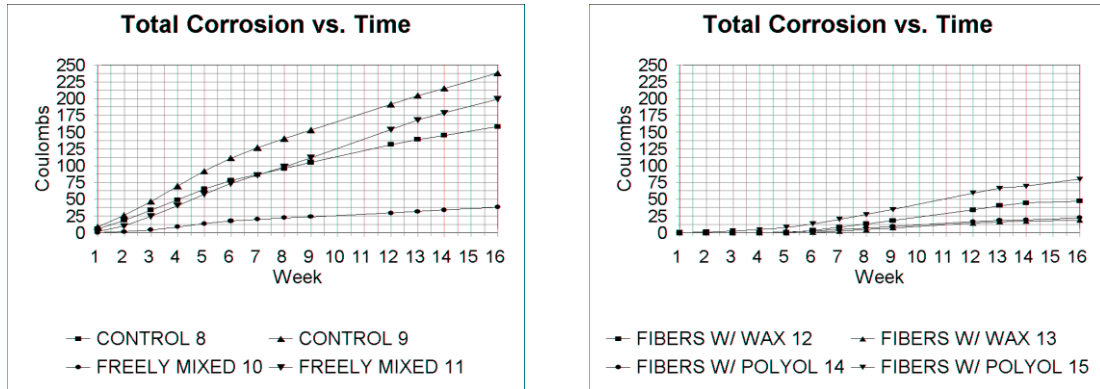


Figure 8) Comparison of onset and severity of corrosion, for fibers containing anticorrosion chemical, on the right, versus those without, on the left [7].

3) Self repairing polymer composites Self repairing composites for air vehicles.

This U.S. Air Force SBIR Phase I and II included: repair of barely visible damage in airplane components using various types of encapsulators, development of repair chemicals that can be processed under typical composite cure temperature/time profiles (250°F and 350°F and pressure), validation of repair durability under a range of loading conditions and self sensing. The goal is to **prevent catastrophic damage to the composite thus allowing use of a thinner lighter component such as wing or fuselage so the vehicle can use less fuel.** The figures which follow summarize key findings:

1. Repair chemicals survive processing heat in graphite laminates
2. Repairs can be completed in less than one minute
3. The system can re-repair
4. The repair chemical can flow into adjacent layers of the laminate
5. Impact damage is repaired and original strength is restored (flexure testing: compression after impact testing: in-plane shear testing)
6. The repair chemical can repair ballistics damage



Figure 9) Left, repair chemicals survive heating in graphite laminates at 350F for two hours after one hour at 250°F. Middle, cut glass repair fibers after processing in the autoclave exhibiting liquid inside and Right, a cut through sample showing that the repair chemical filled an area of delamination.

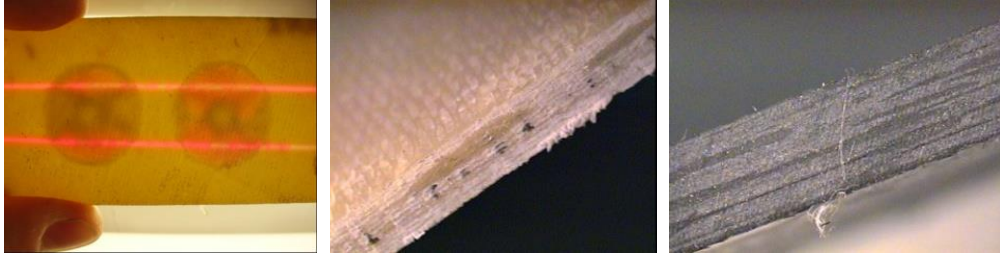


Figure 10) Left, the system can re-repair the laminate in different places or at the same impact site or Center, areas of solid yellow adhesive can be seen in the areas of delamination, Right side view of repaired graphite epoxy shows repair in many layers of the composite.

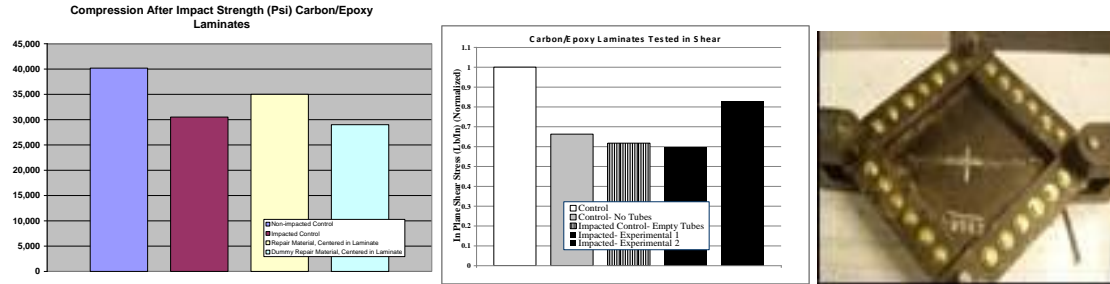


Figure 11) Left, Compression after Impact (CAI) tests were done on graphite samples to assess the repair of the matrix resin. Three types of controls were made: non-impacted samples no fibers, blue, impacted samples no fibers, red, impacted samples dummy repair chemical in fibers, blue. The repaired samples, yellow bar, restored 87% of non impacted controls, blue bar. Center, In-plane Shear BMS 4-23 was applied. In the chart, the repair sample, black bar, had a peak stress that is 82 % restoration of peak shear stress strength when compared to the non-impacted control, white bar. It is a 36 % improvement over sample with tubes only, striped bar; that is the contribution of the repair chemical. Right, a typical sample for shear testing.

4) A ceramic/polymer composite following the rules of bone growth

Most ceramics components are carefully sized, mixed and then fired or otherwise processed. Composite materials structures often have weaknesses at the location where the materials join, where different materials are mixed, placed in proximity or even bonded. These weaknesses, flaws or defects control the ultimate strength of the materials. Coupling agents are used to bond disparate materials into one coherent composite. Usually fibers are added to the matrix after it is mixed and flaws surround the fibers.

The goal was to develop composites with unique toughness and strength by the templating of the ceramic through the polymer organization with intimate bonding, between the two matrix materials. This occurs not by the usual methods of mixing, heating and pouring in the lab but through careful growth sequences over time within the composite itself. Hollow structural fibers are placed first, in a mix of two powders and chemicals are released through the fibers to react with each other in a predetermined order and place. Templating occurs because one component reacts and forms first and the second chemically reacts with it and follows its form. One reaction drives the other by taking up the effluent and giving off heat. No mixing or heat are required because the reactants are physically placed next to each other, in the position where they need to be to react. Superior performance is achieved by the nature of the bonded interface formed between materials, due to careful growth sequences.

Applying Rules of Natural Ceramics to Designed Materials

Controlling composition and structure, the process of formation, its adaptive processes by using the rules of formation is the first step to mimicking bone to obtain superior properties in the various ceramic composite materials. Following the rules of bone growth, according to Arnold Caplan, in the self-growing structure rule 1) porous walled hollow polymer fibers would release organic polymer chemicals into an inorganic matrix. The fibers would act as the organic template of fibrils onto which forms the strong structural bone-

like composite, from the matrix, rules 2 & 3) The chemicals released from the fibers are designed to form a linked organic/inorganic matrix. The chemicals are monomers, which release a chemical when polymerizing. The released chemical sets up the ceramic. The polymer tubes or fibers concentrate the polymer and bone-like inorganic substances on their surface. The proposal is to understand and to choose the polymer reactions in which the chemical released reacts with the ceramic, rule 4) Ongoing self-healing over the life of the structure would be accomplished by reuse of the original void porous walled fibers or separate ones to deliver repair chemicals if and when damage such as cracking in the matrix occurs. In other research we have shown this type of repair improves strength, toughness and ductility therefore there is no focus on it in this research activity.

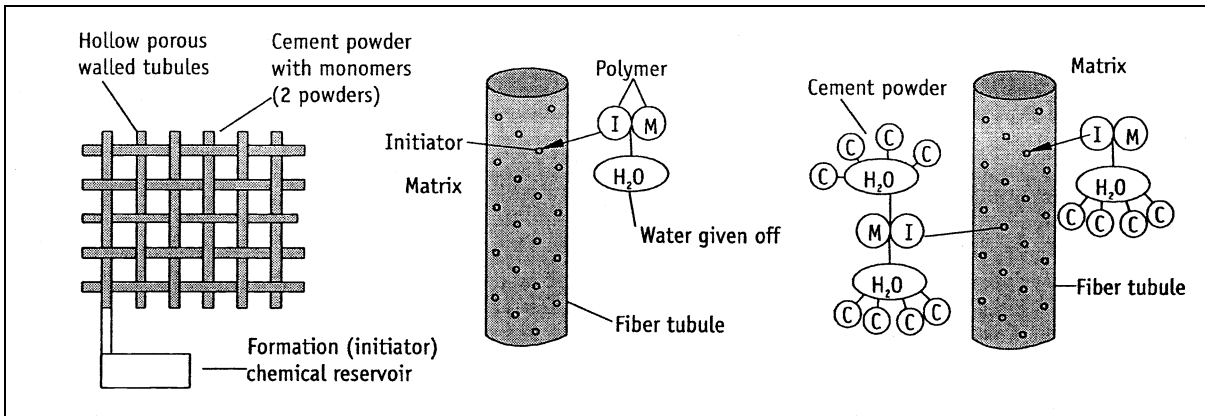
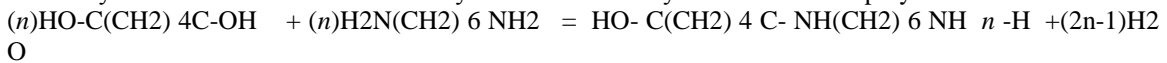


Figure 12) Diagram of the sequence of the processing to create the composite.

Adipic acid nylon/cement cement composite

First we developed a polymer cement combination in which there was some chemical bonding but mainly mechanical bonding. This composite material was relatively weak in tension and compression but tougher than either nylon or cement alone. A nylon polymer and cement were selected because of the variety of bonds and percentage of constituents possible for each individual application. Specifically, the condensation polymerization reaction to produce a mechanical bond was hexamethylene diamine and adipic acid, which produced Nylon-6,6. This selection was based initially on the fact that this polymerization could take place with little addition of heat, the reactants were inexpensive, they were less noxious than many other polymerization reactants, and that nylon-6,6 was a cross-linked non-water soluble polymer. Furthermore, this condensation reaction gave off the water necessary to hydrate the cement. The chemistry based on DuPont's method of nylon formation or nylon condensation polymerization is:



<i>Adipic Acid</i> 146 grams/mol	<i>Hexamethylenediamine</i> 116 grams/mol	<i>Nylon- 6,6</i> 226 grams/mol	<i>Water</i> 36 g/mol
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Cement Hydration (assume water/cement ration of 0.5)

Samples were made to study the basic properties of the nylon composite in comparison with nylon-6,6 and with cement. Butter stick samples (1"x1"x8") and compression cubes (2"x2"x2") were made of each material (nylon-6,6, cement, and composite) to compare the bending and compressive strengths and behaviors of the materials, see figure 3 for bending test results.

Figure shows two scanning electron microscope photographs. At 250X enlargement, it can be seen that the composite material is indeed a combination of the nylon and cement materials, therefore the process of polymerization and cement hydration was successful. At 2500X enlargement, this is further confirmed, while it becomes apparent that the two materials seem to be primarily linked due to proximity in space.

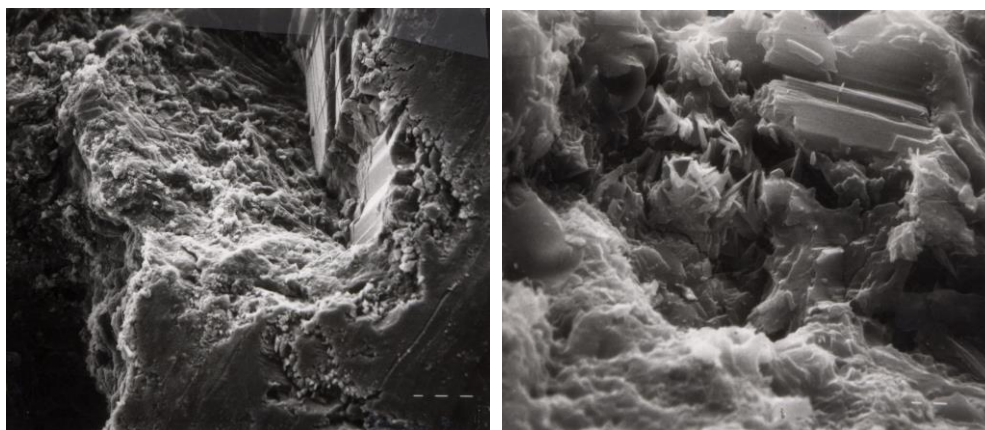


Figure 13) At left is a scanning electron microscope photo of adipic acid nylon/ cement composite sample. Nylon is the block like material. At right is a sem photo at one tenth enlargement of photo at left. There is the appearance in the SEMs of the cement taking on the form of the polymer as a template

A NSF funded project focused on steps one and two of the paradigm: to develop a material which self-forms and self-repairs. A material was developed which mimics bone material formation in order to achieve a cement/polymer composite with greatly improved performance parameters. First, porous-walled hollow fibers are placed in a cement matrix in which one part of a polymer is located. This liquid crosslinking monomer is released through the fiber's walls into the matrix containing the other part of the polymer, as a powder. A condensation polymerization reaction releases water which in turn hydrates the nearby cement material. The advantages of this material are 1) it has the uniquely superior properties of bone, namely chemical bonding between material components; and 2) the composite of fibers and matrix will perform in unison. A polymer/ceramic composite will mimic bone by controlling the 1) structure and form of the material, 2) chemical makeup and sequencing of fabrication, 3) ability to adapt to environmental changes during fabrication, and 4) the ability to later adapt and repair itself. The ceramic polymer composite system and processing rely on templating and bonding between the material phases to yield improved interfaces, due to careful growth sequences. The efforts have concentrated on the chemical makeup, and basic sequencing of fabrication. Like bone, this composite material must be able to adapt to changes in external forces.

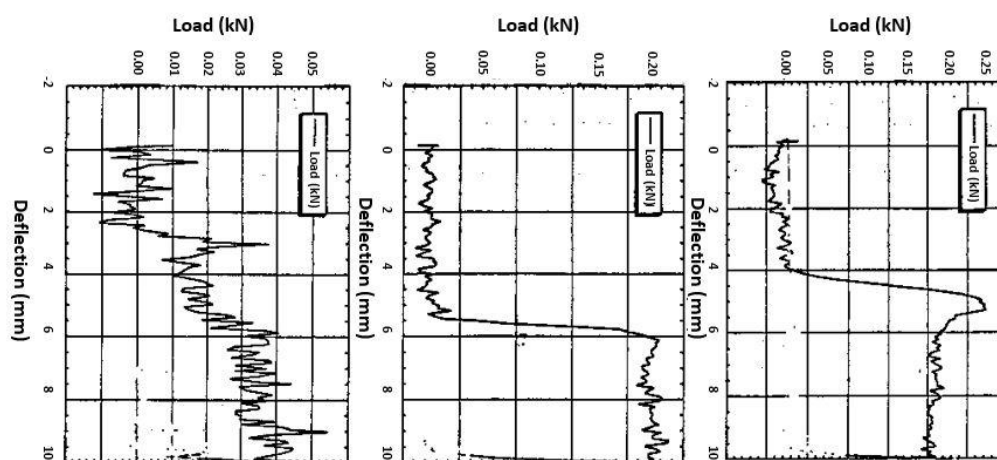


Figure 14) Load diagrams from bending tests on (l to r) polymer/ceramic composite, polymer control and ceramic control.

The delivery systems were required to evenly distribute the liquid monomer to all portions of the powder matrix. Some of the ones tried are shown in figure 5. A series of straight tubules delivered chemical from the ends. Next a system was tried in which porous walled tubules delivered the chemicals and then a spiral formation of tubules was tried. Also a series of porous walled fibers was designed. The spiral and porous

walled tubules were most successful. As the liquid reaches the powder, the liquid monomer and the monomer in the matrix polymerized and give off the chemical, which sets up the ceramic.

Systems Design and Related Technologies

There are three aspects of the particular system as researched to date, namely the epitaxial templating chemistries, the formal time sequencing process given by the release through fiber along the length of chemicals so one material crystalizes so the other can follow the pattern, and the synergistic reactions of the system so that one reaction drives the other and provides the heat for the other's reaction as well. The system is a series of porous membranous fibers or tubules which release chemicals along their length so that the first reaction and byproduct are made and the reaction byproduct is removed along the length of the tube by the second reaction product. The formation of the first product, the polymer, acts as a template and generates an intimate bond for the ceramic, which is the second product. The uptake of the reaction product shifts the equilibrium so that the reactant use is increased as well as the production of both of the desired materials in the composite matrices. Most importantly one desired product is produced first and can act as a scaffolding or template for the second desired material. This whole process was inspired by following the rules of bone growth.

5) Building with fly ash- rule one use waste materials and help the environment get rid of an effluent of a fossil fuel economy

Fly ash is one of the major pollutants of the burning of coal. It has lots of toxic metals and normally finds its way into landfills of piles of ash. Yet it can be sequestered into useful building products. As such it is an example of using waste materials from the fossil fuel economy to make products while using the principles of designing with natural processes to sequester toxic metals and ash from the environment.

During the combustion process of burning coal for the production of energy, electrical utility companies produce large amounts of waste products. Fly ash, because of its low density and small particle size, is collected off of screens above the incinerator from the combustion exhaust. This industrial by-product is recognized as an environmental pollutant, and therefore an alternative to discarding or depositing the ash in landfills or ponds is desired. Fly ash can be used as a primary constituent of large-scale building panels. This ash contains heavy metals, which makes it a difficult ash to dispose. Therefore, an outlet for this waste product is needed.

The top priority concern for use of this ash is leaching of heavy metals into the environment by water seepage. Standard leaching and nuclear resonance tests analyzing for some 30 chemicals were performed on all the sample types. The results showed that heavy metals were well sequestered, particularly when sintered (Dry et al. 2002). This proves to be an environmentally friendly way to dispose of fly ash.

Unlike all of the other uses of fly ash in which it is an additive to other structural material systems often concrete, this use is nearly 100% fly ash, mixed with only a small amount of chemical. The panels are formed in molds and then baked into blocks. Based upon our lab results, the optimal panel composition consists of fly ash, acid, straw, ADVA Flow (a superplasticizer), and water. The ash is 99% of all the materials. The acid acts as a flux, increases compressive strength, and reduces drying shrinkage and cracking. Straw can be used as inexpensive and easily attainable natural fiber that reduces drying shrinkage and cracking. ADVA Flow was shown to somewhat reduce water requirements. Compressive strength increases and water permeability decreases with increases in sintering temperature and duration. The optimal temperature range for the ash compositions appears to be 800°C - 900°C.

Laboratory studies tested the compressive strength, thermal value, water absorption, leaching, and loss on ignition characteristics of the material. Small scale samples of bricks, cubes, and blocks composed entirely of fly ash mixed with some water were made to optimize sintering behavior, reduce shrinkage cracking, and enhance insulative properties, and mechanical properties, particularly compressive strength.

These investigations found that calcining ash increased the compressive strength, provided the lowest water absorption, and allowed for the lowest water/solids ratios necessary for casting. The presence of the acid in the composition resulted in stronger samples than glass powder compositions. However, the presence of

glass increased in the quality of cast samples, including smoother surfaces, sharper edges, and less difficulty in removal from molds. Compacted samples with clay as a binder showed that high strength can be achieved through compaction. Increasing the sintering duration and temperature increased compressive strength and decreased the water absorption (although 800°C appears to be the upper limit before strengths begin to decrease with increasing temperature). Tests also showed calcining the raw ash prior to making the sample results not only in uniform interior cross-sectional sintering, but also results in a sample with considerably higher strength and little water absorption. The calcined ash performed best but calcining is very expensive as is the firing. Various amounts of carbon in ash makes the strength parameters variable.



Figure 15) Left two, manufacturing fly ash panels at a company, Right, Testing fly ash bricks

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