

The Case for Geopolymer Concrete in Seasteading

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Introduction

Thousands of years ago, the Romans built wooden ships, cheap copies of a Carthaginian design they'd found, steered by oars--they never developed the rudder--and constructed from massive sections of lumber nearly a foot thick. But there's a certain seaworm, *teredo navalis*, that burrows into driftwood, inevitably poking holes in even the thickest piece of timber.

Steel became a favorite building material in modern times, but it is prone to rust even in the best of circumstances, must be kept unfailingly well-painted in marine climates, and can suffer from thermal shock in arctic conditions.

Then along came fiberglass, an inherently water-resistant material, extremely strong and lightweight, but expensive. Sailboats and luxury craft of all manner resulted. But as the cost of fiberglass has risen, manufacturers have used thinner and thinner fiberglass walls, making many boats fragile and vulnerable.

Then came a brief craze for steel-reinforced concrete boats in the 1970's, called *ferrocement*. *Ferrocement* construction techniques were popular due to the low price of concrete, but such boats tended to only last a decade or so before water penetrated to the steel reinforcement, rusted it, leading to concrete failure and a sinking boat. The sailboat world went back to fiberglass and remains there still today.

Two years ago I read about Roman harbors around the Mediterranean made with an ancient concrete that have survived in continual contact with the sea for over 2,000 years now, without any concrete degradation. Which is surprising because our modern concrete breaks down within about 75 - 100 years of contact with the ocean even in the best circumstances. Amazed, I followed up on it and discovered its modern cousin: geopolymers concrete, a material capable of replicating this feat of engineering by the Roman concrete masters. Geopolymer concrete, like Roman concrete, could last for hundreds of years in contact with the sea but is also as strong as modern concrete.

Such a concrete could be an ideal material for long-term ocean structures.

Geopolymer Concrete and the Sea

Most geopolymer concrete research today is driven by applications on land, intended to be a green alternative to Portland cement--not for the material's seawater-resistant properties.

The greatest threat to any concrete structure is water, whether that's fresh water or seawater.

So great is the threat of water boring into concrete and rusting the steel inside that bridge overpasses in every modern city are built with far, far more concrete than they actually need in terms of strength. They make the concrete thick to forestall water seeping in and rusting the rebar skeleton. The rule is that each inch of additional concrete forestalls water reaching the steel reinforcement and rusting it by another 10 years, and most highway project use an extra 7 inches of concrete, if I recall correctly,

giving them an effective lifespan of 70+ years. By contrast, ferrocement boats typically used a mere 2 inches of concrete.

The situation is grim when seawater is considered, since seawater directly attacks the chemistry of Portland concrete itself, causing much more rapid failure. What causes Portland concrete to fail at sea is the large percentage of calcium-compounds that Portland concrete contains, being about 70% calcium. These calcium compounds come under attack by sulphur-compounds in seawater, which rot the concrete, cause it to lose structural coherence and strength, become soft, soggy, and slough off, exposing the steel reinforcement underneath it, leading to rapid failure. This is why those ferrocement boats tended to fail in a decade.

The concrete industry responded with low-calcium Portland variants, but even these might extend the life of a structure to as much as 120 or so years, not hundreds or thousands.

Once raw steel is exposed to water it begins rusting. Rust takes up more volume than iron by itself, meaning the iron begins to *swell*. This swelling pushes out against the surrounding concrete and causes it to spall, or break off, ultimately causing failure of the structure.

Geopolymer concrete foils this typical degradation scenario by minimizing calcium-compounds in its chemical composition. Geopolymer concrete made with type-F low-calcium flyash can have as little as 2% calcium, resulting in incredible chemical resistance. The geopolymer test bricks I made used a local 5% calcium flyash--both figures are well into the safe zone for seawater chemical resistance. Using such a material it should be possible to replicate the feat of the Romans, to create ocean-borne structures that can last for hundreds or thousands of years at sea without significant maintenance or risk of chemical degradation over time. In one series of tests, a block of geopolymer was exposed to a strong acid for a month's time, and at the end of it the block has lost only 2% of its mass. Geopolymer has also been evaluated for locking hazardous waste materials inside it because of its ability to block chemical migration through it.

And such a material is also immune to any and all attacks by plant and animal life that other materials have so much trouble with at sea.

Flyash

How much calcium a finished geopolymer cement has is determined by the composition of the flyash used. There are two types of flyash, type C is more commonly focused on in the literature, and is high in calcium, just like Portland cement. This material could make a fantastic green concrete to replace Portland cement, but it's unsuitable for use at sea.

Type-F, which is what we're interested in for our purpose here, is very low in calcium and can produce a sea-resistant geopolymer concrete.

Flyash comes from burning coal, so the kind of flyash produced is determined by the kind of coal and coal deposits being burned locally. At least in the United States, about 50% of coal burned is low-calcium coal, and I would expect a similar scenario to be found around the world.

Today most flyash is being thrown away in landfills, treated as a waste-product of coal-power production, which means it's exceptionally cheap and widely available. Recently the cement industry has begun adding flyash to regular Portland concrete as an inexpensive filler and water-reducing agent, so a supply-chain for the material already exists as well. However the end product is not a geopolymer at all.

Curing Flyash

Regular Portland concrete will heat up when it is exposed to water, known as the heat of hydration, and this chemical reaction is due to the calcium compounds in Portland concrete reacting exothermically with water. Naturally therefore, type-F low-calcium flyash will not heat up when water is added to it, instead we must cure the resulting mixture by adding heat to it externally. However it doesn't need very much heat, as little as 85°F for 24 hours will completely cure it, or perhaps 200°F for 4 hours, or any range in-between.

This gives us some added flexibility, because the geopolymer concrete will not even begin to cure until we have added heat to it, we don't have to worry about it setting up too quickly, etc. On the other hand, we actually have to add heat to it.

Adding heat can be done by building an insulated tent of sorts over the structure, composed of foam insulation sheets that are readily available at any hardware supply store, or for larger structures it may be possible simply to use a fabric dome and pipe hot air into it to keep it inflated using inexpensive

commercial hot-air blowers. Or if a mold is used, hot water could be poured around it for a time, or submerged in it, water having a high heat capacity .

There's a lot of interest in geopolymers in India and Australia, places which are naturally quite hot, like the equatorial regions, where 85°F is more akin to a cool breeze which would have no trouble at all curing a geopolymer structure of any size.

Lessons learned

Soon after researching geopolymer concrete I obtained materials to make it, and prepared to pour my first batches, excited to get hands-on experience with it and try out a few experiments.

Having worked with concrete professionally for years as part of the contracting company I co-owned, and having done a good deal of tile work as well in those years, I tried to apply my knowledge of regular Portland concrete to working with geopolymer concrete, to get it to do things I wanted it to be able to do.

I quickly learned that this material is its own beast and a lot of the conventional wisdom surrounding Portland concrete has to be thrown out when dealing with it.

For instance, it was natural for me to try to get a thicker or thinner mixture by playing with the water content I gave the material. But with geopolymer concrete this is a bad idea. As it cures it does not off-gas the water the way concrete does--it actually incorporates the water molecules into its chemical matrix, stripping them down into oxygen and hydrogen ions and binding to them into the material. So giving the mixture too much or too little water adversely affected the chemical reaction. I produced a number of failed pours by trying to play with the water ratio too much in this way. But I also produced a number of excellent pours too.

This is somewhat a problem because geopolymer cement is naturally quite loose and wet when being mixed. This makes it quite good for pouring into molds and forms where it will readily take the shape of the mold and not strongly entrain air, but means that it might be difficult to find a formula that could be mortar-sprayed on a vertical form and expected to stick. It simply is not very sticky, and you can't simply add lime as with Portland concrete to get it stickier. I suggest choosing production methods that involve the use of forms and molds rather than plastering.

It may be possible to thicken the material significantly with fiber additives and certain finely powdered sand and rock aggregates, well graded in size, but I have yet to play with mixtures involving those more expensive well-graded aggregates. They may thicken the mixture significantly like adding corn-starch to a soup.

Advantages

Portland concrete must be kept wet as it cures, has to be kept from drying too quickly. Workmen typically cover it with wet towels and keep it sprayed wet for days. In very large concrete structures this can become a problem, if any part of the structure is allowed to dry significantly faster than the rest of it, it can easily shrink and crack.

One of the great boons of geopolymer concrete is that it does not need to be kept wet while it cures, it cures very rapidly, and there is no significant risk of cracking during curing--a major advantage over traditional concrete.

Geopolymer simply does not offgass water and shrinks very little during curing. Instead of shedding water it forms a chemical gel that hardens over time, going through a series of rapid chemical stages, and ultimately forming alumino-silicate polymer chains.

We oven-baked our test bricks at 195°F for 4 hours and produced 90% of final strength within that time, meaning that there is an opportunity for unparalleled efficiency in mold-turn-around time when using geopolymer concrete. Regular concrete would have to be babysat for a good three days typically, kept wet and covered, etc. But with geopolymer you could produce from the same mold nearly six times a day.

Alternately, if one were building in a warm climate such as the tropics, 85°F for 24 hours is just as good as baking it for only a few hours at 200°F. Tropical climates have an innate advantage in using geopolymer, only they have to now worry about the material starting to set up as it is being prepared. The way to avoid premature setting up in this scenario is to mix water, flyash, and stone aggregate together well and then add the chemicals just before pouring. So it's not such a problem after all.

The Geopolymer Formula

Geopolymer cement is made up of four inexpensive and widely-available components:

- Flyash
- Fresh water
- Waterglass (sodium-silicate)
- Lye (sodium-hydroxide)

When I sourced these components, the most expensive by far was the waterglass. Buying it in small quantities, it increased the cost of our test bricks to on par with high-end concrete at ~\$150 a yard.

However, buying in bulk brings the cost down significantly for both lye and waterglass. Lye is extremely cheap, I was able to obtain 10 pounds of it for about \$35, far more than I needed. And waterglass can actually be made from lye, and there are chemical advantages to doing so (waterglass molecules begin crosslinking almost immediately, so there are decent strength gains to be had by immediate use).

So the potential for geopolymer being much cheaper than concrete is there.

Buying flyash proved to be a challenge because the minimum quantity Boral wanted to sell me was *27 tons*, enough to fill the back of a small shipping container, and the price for that quantity was \$810. I realized it would cost me more to ship it to California and store it than to actually buy it.

Handling concerns

One of the big reasons geopolymer concrete hasn't caught on faster amongst concrete builders is that it's not as versatile as Portland. As I'd explained earlier, in terms of adding more or less water to get it to do what you want it to do, geopolymer is more finicky, but also it requires working with and mixing very caustic chemicals, measuring out the chemicals precisely, and careful handling of these materials-- it's dangerous stuff. Essentially lye and waterglass are caustics capable of burning you similar to acid. But worse, the burns they cause do not hurt immediately, so it's possible to be burned without feeling burned until the damage is already done. However, once these chemicals are added into the concrete mix, they're relatively harmless while curing.

Pure lye can dissolve the fat and connective tissues of your skin away instantly. If you rub a bit of lye-solution between your fingers it will feel very slippery--they say that's the feeling of skin cells being stripped from your skin as you do so. We made sure to wear protective gear while making our test batches.

Another risk is lye preparation. Lye must be added to water in measured quantities to produce the proper molar solution, and doing so produces heat. There's a risk of boiling the water and causing it to boil over if you add too much lye too quickly to the water. Our basic rule became that we would add about half the required amount of lye in the first dose and stir it in. This would produce a good deal of heat in the water, enough for there to develop small bubbles of air in the water, the first signs of boiling.

We would then stir until the heat came down, add half of what was left and stir, then finally add in the rest. We never had any problem with overheating water using this procedure. However the quantity of water needed for larger projects calls for more up-front planning. Large projects would have to add lye to water slowly and stir it in, then allow it to cool overnight in order to use the next day at room temperature.

Laminate construction

One possibility I'd thought of is to use geopolymers as an exterior skin to face the sea, a seawater-proof material, about two to three inches of geopolymer should be enough to protect against seawater attack indefinitely I'd think, let that cure overnight, then back it up with many inches more of regular concrete which we're more familiar with. I'm planning to test a laminate structure like this soon in ocean conditions for an extended time and see what results, see if I get delamination or some negative reaction at the boundary-layer.

Basalt rebar

As great as geopolymer concrete is it needs an accompanying revolution in reinforcement. Steel is too risky for a structure that is designed to last hundreds of years potentially.

We've found that in basalt rebar.

Take basalt stone, one of the most plentiful minerals on the planet, and heat it up to a good 1800°F, run it through a micron-size palladium-die and produce micron-sized *threads* of basalt stone, which at this size are actually flexible and soft as silk.

Weave millions of these together into strands and threads, then lay thousands of those parallel and lock them together with some epoxy and you get basalt rebar, a waterproof, chemical-resistant, fireproof material with a tensile strength of about 4 gigapascals, several times stronger than steel rebar, on par with carbon-fiber, but with none of carbon-fiber's problems with chemical reactivity and water-absorption.

My supplier is Sudaglass in Texas, whom provide a range of rebar sizes. The rebar is ribbed just like actual rebar to provide a mechanical grip with the concrete, but there is also indications that geopolymer concrete may be binding to it on a chemical level as well, something that steel and concrete cannot do. A piece of basalt rebar laid on top of a piece of wet geopolymer and allowed to dry will actually chemically bond to the rebar and make it impossible to remove. So there seems to be a superior bond strength produced between these two materials compared to steel rebar and regular concrete which produces only a mechanical bond.

Basalt rebar is a very interesting product. It's extremely light and also fairly flexible compared to steel rebar. It comes in large coils of indefinite length, and for this reason is much easier to place, store, and transport than traditional long and straight cut steel rebar.

One downside is bending shapes. It requires heat to bend permanently, about 500°F, which is about what a hot iron produces. I haven't yet run tests on bending the basalt rebar samples I have. In short sections they're as light and stiff as carbon fiber, but get a 5' section and you can easily bend it like a fishing-pole. This is perfectly fine for reinforcement--rebar doesn't need stiffness, just tensile strength to perform its job, and in that area it excels.

Sudaglass also produces woven sheets of basalt rebar, shaped like chicken-wire, in various sizes and thicknesses, and also cut basalt fiber additives much like the nylon fibers commonly used in concrete, and I would expect to use a quantity of these fibers in any commercial pour for added strength.

Application and Conclusion

For the Seasteading Institute's goal of creating very large block-sized monolithic concrete structures, I see no reason not to use a material such as geopolymer concrete, given that the engineers understand its material properties well enough to design with it.

In terms of compressive strength, geopolymer concrete is on par or better than standard concrete, so there's no issue there. It's also about 5 times more flexible before cracking compared to Portland, which is even more desirable for a floating structure.

While it requires adding heat to cure, it's not much heat, and the material isn't picky about how much heat it gets, and this is a favorable tradeoff to the requirement in time and expense of keeping regular concrete wet for days, all without any risk of cracking due to curing too fast such as regular concrete faces.

The major challenges will be quality control on the chemical proportions as they're mixed for such a large pour, and getting heat to such a large structure. Of course if it's being built in a hot climate, then heat is much less an issue in the first place.

I'd also like to recommend you look into using the [A4 proportions](#) ($1:\sqrt{2} = .70710$) for the shape of the concrete structure you're going to build, the basic idea of which is that two smaller structures with this proportion exactly equal one larger structure, and so on and so-forth, which allows large and small structures to place nicely together and slot in together.

E.g.: Say we have one block-sized rectangular structure that is say 300' x 212', this is an A4 proportion. If we cut the 300' dimension in half we make two structures that are 212' x 150', and this will *also* be the exact same proportion. The advantage is scaling, you can scale up or down and all the parts will continue to play nicely together and slot in with each other perfectly.

Ultimately I'm excited to be a part of this grand and historic effort, and am eagerly awaiting the time when we can realistically move to a seastead and start building the future. Say the word, Randy, and I'm there.

~Michael Eliot