USE OF FILLED POLYMERS FOR STRUCTURAL APPLICATIONS

By

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Members of the construction industry overwhelmingly believe that concrete is the most desirable structural material. This ubiquity is based upon many factors, not least a historical predilection towards that composite. It is trusted due to millennia of regular use, and the ease of locating the ingredients. The material is also very tactile; workable as clay, then hard as steel. Concrete is familiar.

Polymers bring up entirely different associations. They are commonly regarded as flimsy, cheap, and "tacky." The synthetic nature of plastics creates distrust. The perception of chemists in white coats and vats of gelatinous goo comes to mind. The material is distant from direct sensation. Far greater conceptualization must be engaged in when approaching polymers. Previous research has mirrored these assumptions, and appeared almost apologetic when considering plastics for wider applications.

This research has the goal of analysis of polymers without preconception, often expressing findings in layman's terms. In this way, objectives based on true merit, or deficiency, may be discovered by researchers beyond a limited audience. Application of these methods will clarify relative value in the use of concrete and polymers. Identification of the relationship of attitudes is a correlative of that investigation. Evaluation of respective loading capacities will be

performed in the laboratory, testing relative compressive strengths. Compilations of properties, in chart and table format, will further elaborate the materials comparison. Therefore, a combination of actual testing and reliance upon published and unpublished sources will be used.

CHAPTER 1
A FLORIDA EXPERIMENT

In the wake of the development of increasingly light and effective sustainable building materials, the status of traditional modes of construction are being rethought. This is not just a private sector phenomenon. More conservative public entities, such as the Florida Department of Transportation (FDOT), are also utilizing this innovation. During concrete building, for example, the standard has been employment of steel bars, known as "rebar," to distribute tensile forces. However, as structural plastics have increased in status, displacement of steel, and even concrete, has increased. A material formerly thought of as unworthy of structural use, polymers continue to gain greater influence as a fundamental building component.

One polymer, common in the private sector, which strengthens concrete and acts as an independent structural unit, is called Fiber Reinforced Plastic (FRP). This family of Plexiglas may be used in many ways, with flexible modeling potential. The Florida Department of Transportation (FDOT) has taken a keen interest in this malleable material in current state construction projects. The reasons for this are various – corrosion protection, acceleration of construction schedules, simplified procurement with less expense, and use of large and light components, such as plastic bridge piers.

In fact, FRP and concrete share a symbiosis in bridge abutment and pier erection. A prevalent danger in this type of work, using steel rebar, is corrosion. This problem is often viewed in terms of anodic and cathodic relationships, essentially a chemistry problem of managing electronegativity of adjacent metals or materials. Corrosion also takes place when salt water, or vapor, infiltrates concrete. This will directly corrode interior steel rebar. However, if polymers were to be used effectively, there would be no need for any consideration of corrosion. Fiber Reinforced Plastic (FRP) has very low conductivity and a neutral electromagnetic charge.

Using an FRP admixture would simplify concrete preparations for pouring, because no rebar work would need be included in the formwork. In the case of tube encasement, as described below, the form is the FRP structure itself. Therefore, costly and time-consuming procurement and laying of rebar would be absent. Furthermore, scheduling difficulties may be mitigated, with project acceleration as a result.

Fiber Reinforced Plastics may be associated with concrete in dust, fiber, extruded, and pultruded form. The material varies from polymerized products which are manufactured in Portland cement plants, such as fly ash and slag, in that they are not merely collected from furnace refuse. FRP is more sophisticated in its chemical engineering. As a product of Plexiglas, it is derived from an elastomer with laminar properties. Therefore, it may be ground, or shaved, into dust or a fiber concrete mix additive. It may also be extruded and pultruded into virtually any shape.

FRP is used in bridge piers as an assemblage to give the support characteristics of steel rebar. According to researchers, "Results show that external confinement of concrete by FRP tubes can significantly enhance the . . . strength of concrete" (Saafi et al. 1999, p. 500-509). Another structural approach is achieved through the process of pultrusion. This manufacturing process increases density exponentially. The product created is a so-called "profile section," often used in conjunction with a stiff foam or pultruded corrugated interior. Both the tube and profile are modular innovations with quite acceptable Young's moduli and performance, rivaling that of steel and concrete.

Despite these promising developments, there are drawbacks to wide application of these technologies in Florida. Construction using FRP techniques will leave polymer detritus, some of large size and weight, long after the life of associated composites have expired. While steel

reinforcement will corrode and degrade, as would concrete, the thermoplastic or thermoset FRP would have to be collected, or allowed to lay in situ. Collection would presuppose an infrastructural innovation of large scale recycling. Judging by current FDOT department-issued literature on the subject, it seems these hazardous consequences have not yet been fully appreciated in FDOT planning.

Such a recycling effort could include strategies of policing sites and configuring the waste into extruder-ready material for solidification into storable units. The Plexiglas characteristics would be retained, and exploited again when the unit is shaved, crushed, extruded, or pultruded for a new task. Though initially expensive, FDOT has the capacity and regulatory muscle to implement this type of infrastructural innovation over several years. Recycling conditions could even be included in Request for Qualifications parameters in bidder responses for future state work.

It is evident that Fiber Reinforced Plastics have significant potential benefits when applied to FDOT projects. These attributes include structural capabilities comparable with metal rebar and concrete, potential easing of schedule constraints, likely reduction of procurement burdens, and strong stand-alone polymers of light weight. However, these technologies are not a panacea. It could be argued that sensitivity to environmental concerns would mandate future state responsibility to provide an infrastructure of recycling with adoption of FRP-based construction. This could infuse unanticipated costs into Florida's transportation budget for at least a decade.

Conceptualizing the Phenomenon of Change

This experience in Florida, matching the properties of polymers with concrete, indicates human beings are creatures of habit. It is easier to understand new concepts in the context of previous experience. The Florida Department of Transportation has adopted use of a

conceptually flimsy material as a heavy structural component for bridge piers. But has this process been thought through? From the exploration just recounted, it would appear FDOT assumes that FRP has the same life cycle properties as concrete. This is not the case, and any use of FRP must carry the attribute of recycling on a massive scale. An entire future infrastructure is implied, which would include identifying and collecting a huge amount of material that must be treated for reuse. Preparations for such an endeavor are currently lacking.

The central argument of this study is that the Florida example is typical of any proposed use of polymers in relation to concrete. It may be argued that bias toward prior understanding of polymers is the main obstacle in the wide adoption of this material for structural use. The word "bias" has a pejorative connotation. However, any psychologist would assert this condition is necessary for the survival of our species. An ever-changing kaleidoscope of images and sensations would bar formation of any model for the operation of this world, without bias. When does bias become harmful, the status quo insufficient? This thesis is concerned with that phenomenon.

Change occurs in two essential ways, through coercion or consent (O'Rourke 1994). When applied to the topic of environmental sustainability of construction processes and materials, change may be viewed in two basic ways, as either continuous or revolutionary. The point of historical observation will determine application of "the new" to society. For example, the model of a caesura between past and present could be asserted. This type of presentation is given by groups such as the International Council of Local Environmental Initiatives (ICLEI). A political agenda is the primary component of this option. Sustainability concerns are couched in rhetoric describing rights of indigenous populations and responsibilities of industry. The entire question is framed as an abrupt transformation of society, dismissive of the individual.

From the standpoint of this research, such a perspective misses the real significance of the larger issue. The assertion here is that the sustainability conundrum is a continuation of technological developments to aid industry, which began in the early Industrial Revolution. The chronology of this process dates from the eighteenth century onwards. The line of reasoning could trace ever-increasing efficiencies of design and distribution, especially in the growth of a market economy in Britain. Emergence of perceptions of consumer-based notions of "style" are very important to note in this progression. Advancing technological innovation brought correlative restructuring of labor markets. The theme would be continuity in development of more efficient and profitable strategies within the context of economic growth. Thus, two very different models of a sustainable future exist, at odds. The fate of DDT as a pesticide, and the development of digital communication represent the divergent ends of these alternatives.

Employing the Means of Change

Rachel Carson is remembered as one of the early titans of environmental awareness. Carson's book, "Silent Spring," (1962) gave rise to a movement which virtually eradicated DDT. The chemical is an insect repellant that protects plants. An abhorrent practice was identified – children's apples covered by insecticide – and public pressure was subsequently harnessed. The message was simple, DDT was a killer that needed immediate attention. There were unintended ramifications to this line of action. The most significant of these was a massive increase in the third world death rate through insect borne-disease.

The employment of DDT in mechanized, large-scale agribusiness was not the chemical's only attribute. In lower socioeconomic areas, the potent mixture was an effective and affordable means of controlling mosquito populations. Those parasites would otherwise infect people with malaria. The immediate curtailing of DDT manufacture and distribution had tragic consequences. During the popular uproar, this more complex effect was overlooked.

Furthermore, there was a pernicious assumption that DDT could only be understood through its use in a rich country (O'Rourke 1994).

Mathematicians have studied fractals for a very long time. These functional iterations, when graphed, create "geometric monsters" of repetitive streams of equations. Use of analog technology was standard in communications throughout the 19th and 20th-centuries. During the early years of the space program, a problem with wavelengths was identified. Antennae for long-range radio transmissions would have to be huge to pick up signals over vast distances. The situation was resolved by patient examination, using empirical methodology. Instead of an enormous dish-shaped surface, fractal modeling concentrated that area into a tightly corrugated space, a small antenna with a capacity-area of reception approaching infinity.

Both instances described above were portents of epochal change. Ms. Carson's book mobilized mass support to address a troublesome issue, leading to common awareness of sustainability concerns. The Apollo missions went a long way towards ushering in the digital age. Again, there are two types of approaches to change, emotional and empirical. The former is immediately gratifying, but often based on slender analysis. The latter makes use of rational scientific methods. This choice is less exciting and more time-consuming, but it lends itself to progressive examination. That crucial appeal provides the necessary prerequisites to truly ponder altering patterns of behavior.

The current research asserts that sustainability solutions will be found over the course of the next 100 years. That timeframe will become very important as this analysis progresses, because a fundamental change in cultural perception and construction modalities must occur. Therefore, the approach to sustainable building will be made in a bifurcated manner, discussing a relatively straightforward proposition, along with the wider ramifications of its acceptance. The

proposal is that polymers should be utilized to a greater degree as a structural component, versus concrete. A spotlight will be cast upon this hypothesis, which will also treat the societal structure that supports concrete as the traditional choice.

Case Study of Change Utilization

The delivery mechanism employed for this comparison between plastics and concrete, will be capable of dispensing both materials. This method of modeling identical processes, using each alternative, will greatly aid in presentation of clear conclusions. Application of life cycle assessment (LCA) would possibly benefit this analysis. But, as the story at the beginning of the dissertation indicates, logical discontinuities and historical biases greatly influence evaluation of life cycle costs. An example is that of the recycling dilemma of FDOT. So that aspect of the discussion will be omitted.

Contour Crafting had a promising potential as the result of a long-term study by an academic institution. The automated mechanism central to the project was highly technical. It made use of sophisticated software capabilities, 3D printing innovations, and contiguous pattern building. The use of concrete and ceramics as primary structural materials perpetuated traditional expectations. The system operated through the use of Building Information Modeling (BIM). The computer program created an exact virtual fabrication of the building. The structure was visualized, complete with material attributes, details regarding placement of every component, and the ability to monitor actual progress. This was accomplished with a gantry mounted with extruders, nozzles, and electronics, which behaved just as a stylus would with a miniature printer. The gantry travelled a path over parametrically predetermined 3D shapes on a grid. According to the breakout literature, the mechanism was designed to deposit five-inch layers every hour, including piping, wiring and forms. Materials were extruded in a paste, with concrete amalgam as the core, which cured as the machine followed the template. This layer by layer

strata-creation was capable, for example, of completing a 10-foot high dwelling in 24 hours. Integration of the completed product with its surroundings was also an important goal.

The new delivery method was called Contour Crafting. Although it was possible to use the technology to construct individual show-pieces, that was not feasible unless the owner had considerable assets to invest. The complexity of the machinery involved lent itself to mass utilization. It was envisioned that the system would operate on a large plat of land. Development of this process had been very dependent upon research. It followed that corporate support, as opposed to a specifically entrepreneurial enterprise, was the paradigm. Funding came from a concrete conglomerate. A driving force behind the method's broadcast was at once academic, and theoretical.

Theory was exemplified, for example, by literature describing aspirations for the invention. There were many suggested applications, some by their very nature rather utopian. A particularly revealing scenario stressed rediscovery of the ancient method of layered construction within the technology. This certainly was the Contour Crafting manner of creation, layer by layer, via gantry. However, it was envisioned that locally abundant natural materials could be fed into the system to produce culturally sensitive structures. This type of niche application was revealing by its appeal to activist opinion, the first option as described above. It alluded to socio-economic goals associated with ICLEI, the political entity that supports full incorporation of regional economic and cultural conditions as preconditions for sustainable construction.

Absence of accomplishment in localized construction revealed the technology had not lived up to those ideals. The real aim was to align with a powerful ally to tout this theoretical vision, very consistent with academic standards. To continue with the assertion of local materials use, it is worth reiterating that the delivery method was most realistically designed for urban

construction in developing nations. The reasons for failure of this vision were several. For example, any local material used would need to be mixed into a workable, chemically composite paste. It then would have to be distributed to multiple gantries on large projects. An enormous supply would constantly have to be made available. This was hardly something that could be done properly without sophisticated procurement and expensive bureaucracy, capabilities hard to find in the Third World. A consequence would almost certainly result in “creep” of project scope, with lab facilities brought on site.

Even if movement of the apparatus was found to be possible, a rural environment would almost certainly lack the ready support chain, upon which Contour Crafting’s complicated system is dependent. Thus, the discussion turns to a Cornell analysis (Weinstein and Nawara 2015). The study addressed respective probabilities of the process becoming an acceptable building mode in developing nations. Among the conclusions, it was found that developing nations were not in a financial position to choose building these large public projects. The point is that Contour Crafting literature portrayed a comprehensive delivery method. It presupposed many assumptions that have borne little correlation to reality. This fact has also impacted flexibility in considering anything beyond concrete and related composites, local or otherwise. The Cornell article (Weinstein and Nawara 2015) includes an estimation of third world government funding by each nation that employs Contour Crafting. The funding will come from each nation,

The original vision for Contour Crafting consisted of a variety of applications, ranging from inexpensive mass housing to extraterrestrial colonies. This has yet to materialize. The product has yet to be proven in the marketplace. Polymers could readily be used, But they are relegated to subordinate components, usually fibers or pellets diffused within concrete structural

forms. The technology has suffered a distinctive lack of definition in real-world situations. Its marketing has been overly focused on "checking the boxes" of various theories, by default, eschewing a wider market founded on aggressive identification of entrepreneurial possibilities. This strategy presupposed certain truisms about materials, especially those which were considered as naturally deposited.

The ICLEI local model assumed an indigenous composite supply would be utilized by the technology. There appeared to be little thought about ultimate deposition of extruded elements. The use of plastics was only defined in association with modalities defined by concrete building practices, thus exposing an infrastructure weakness reminiscent of FDOT's potential recycling dilemma. So, ironically, the biodegradability issue could be exacerbated by this subordination of polymers to concrete, leaving a widely scattered detritus of mingled cement, polymerized dust and fiber across the landscape.

Allowing for Variety within Change

Still, the concrete amalgam dispensed through Contour Crafting is generally viewed as eco-friendly; plastics are not. That is just the way it is. Thermoplastics are recyclable, but less desirable because they are not a natural alternative. Opinion about thermosets is decisively negative. They are often considered the worst option, neither a natural nor a biodegradable, substance. All this exemplifies a lack of rational investigation, reasoning that denigrates polymers within a framework of conceptualizing change as an immediate imperative.

These patterns of thought and behavior are specific examples. However, they represent ingrained attitudes which constitute repetitive myopic narratives of current environmental doctrine. The message is that everything must be radically realigned. It is little wonder, when discussing sustainability, that near-panic is the next resort. Since the early 1990's, when climate change became a hot-button issue, the intensity of opinion has become progressively galvanized.

All too often, those engaged in this conversation respond to emotional appeal. An ever-present danger is that discussion will turn to simple propaganda, that pesticides taint apples which then harm children. This thesis will attempt to provide an optimistic alternative to such negative sentiments. A skeptical viewpoint will not be adopted. The intention is to present a thoughtful, creative illustration of the future.

While attention will be centered upon an admittedly limited subject, greater reliance upon polymers in the fabrication of structural units, the findings will be extrapolated into a constellation of further possibilities for research. The dual intent will be to define a narrow topic, while alluding to the big picture. It will be the contention of this dissertation that a cultural learning curve must precede any real evaluation of effective sustainability initiatives. Solutions and processes will be developed when varying practices are utilized by millions of people, over an extended period. This dispersed "trial and error" approach will be inevitable, unless restrained by political or bureaucratic measures. The drivers for those type of restrictions would likely be the determination by those in influential positions to apply doctrine. The development of doctrinaire attitudes has been caused by assumptions that the situation to be corrected is well-defined at this point. On the contrary, long-term effects are difficult to foresee.

So, a very large factor affecting the conversation is the assumption that sufficient information now exists to make wholesale conclusions and provide appropriate responses. This is contradicted by the longevity of the climate change argument. The problem has not existed for long in the general consciousness. It is far beyond the scope of this research to study the cause. This is only noted to illustrate that such paucity of experience has created, in some minds, an apparent failure of the mass of people to appreciate its gravity. An unfortunate by-product has been impatience and somewhat shrill political and social coercion, polarizing reception of the

message within public discourse. A related difficulty arises when individual choices are framed as either enlightened, or regressive. This temptation to criticize established modes of building behavior can serve to separate, rather than to unify opinion.

An example may be helpful at this juncture. Suppose a decision were to be made regarding sustainable properties of a primary structural material. The parameters of argument are to be influenced by the mindset described in the previous paragraph. For example, take the construction of a residential building. A home is a statement of personality. If an owner were a trailblazer, they might opt for a fiber reinforced polymer (FRP), or “faux wood” dwelling. A different owner might make a similar statement about their proposed home by selecting construction with a concrete amalgam, applied through an automated process. The former owner would place far greater emphasis on use of a non-traditional structural material; the latter would value a non-traditional building process.

Depending on a given attitude, either of these choices could appear progressive or regressive. The polymer home, due to biodegradability concerns, could be disparaged. Likewise, use of an automated process to build a concrete dwelling could likewise be criticized for the extensive use of a material whose manufacture contributes to approximately 5% of greenhouse gases. The conundrum rests upon whose decision is deemed correct, a relatively small group of experts or each person impacted. The presumption here is that there are myriad paths to achieve sustainability goals. Suggestions that stick will do so because they are empirically convincing, eventually overcoming bias. The dangers in preferential selection by experts is very tangible with greenwashing. In this way, emotional reactions to products and practices have been tamed by pseudo-science in support of their environmental benefits, though the case could be too complicated to render carte blanche approval. This situation is so prevalent that the certification

agency, Leadership in Energy and Environmental Design, (LEED) publishes very specific parameters about the subject. For example, “extended producer responsibility,” which is targeted at fabricators of material, is a mechanism which follows and records the “impact” of those products and practices (Poplar 2014).

The Ultimate Simplicity of Change

Contrary to the argument outlined above, bias is not just historically-based and societal. When a researcher studies various processes and materials, the possibility of individual bias is ever-present. Just because something is interesting, emotive, or novel, does not mean it has inherent value. An internet search returning something at the top of the list does not give that information any more weight or accuracy. In response to such concerns, this paper will use methods elaborating specific conditions indicative of the whole, analogous conceptualization. One such will be comparison and contrast in the evaluation of factors effecting cost of a small generic home, using both polymer and concrete as a central structural material. Methodologically, this means application of comparable subjects, apples to apples. Simplicity will eliminate distractions, as well as nuances of highly complex and conjectural issues. In lieu of entanglement, the focus will be maintained upon limited subjects, with a tactile attraction. This is not a manifesto detailing remedies for complex and intricate problems. Underlying this discussion is a simple plea for better understanding of necessary transitions, defining elements of that huge process using continuities of past development.

The Solution of Functional Learning Curves

It follows that respect will be given to the status quo, in that it is the origin of general perceptions regarding present affairs. That point must be clearly stated, due to difficulties which arise when engaging in abstract analysis. A common mistake is discounting those whose livelihood depends upon current building modes. Those who have invested in such modes should

be given due consideration. Everyone from the miner extracting ore, to the teamster transporting it, and the paver who places it, receives more than just a paycheck. The author of a ground-breaking book about the psychology of project management ,"Human Factors in Project Management," defined internal motivation and team dynamics (Wong 2007). The author recounted historical research enumerating rewards for participating in employment (McClelland, et al 1953). According to Wong, quoting McClelland, a worker has "three basic needs: (1) achievement-attain realistic but challenging goals and gain achievement in the job; (2) power-lead and have their ideas prevail; and (3) affiliation-cooperative relationships with others" (Wong 2007, p. 23). Anyone who has been unemployed can attest to psychological dislocation and loss of self-esteem experienced by the absence of expression through labor. Work is identity, even if those doing it cannot elaborate that concept. The manner in which an employee deals with this – at times subconscious – empowerment defines their identity. Intangible rewards therefore flow from labor. Many go unrecognized until the job is altered, possibly disappearing altogether. Labor practices represent a continuum. Employees understand the progression of modalities. And, by repetition, a style of performing new tasks becomes unique to every individual, but also becomes streamlined.

This learning curve, the way someone completes activities, is a crucial concept. It may be described as a cognitive bridge from current to envisioned practices. If a construction professional were to hear the words, "learning curve," that person would probably visualize a fundamental scheduling technique of construction planning. Everyone in the profession acknowledges its value. That means there is commonality of definition that may be used to persuade the reticent.

Change is Dependent upon Time

Questions opposing human versus environmental benefits are volleyed back and forth. Arguing those questions would be an invitation to unproductive responses to change. It would presume an adversarial relationship exists; one must suffer at the expense of the other. The idea that human beings have become alienated from their surroundings by economic and technological development would further complicate things. This somewhat vague notion has a long lineage, beginning, at least, with the advent of Luddite philosophy. A hazy, romantic version was expressed very well by a Victorian-era academic writing about the decline of traditional English village life. The author said that ancient rural existence had "great compensating advantages. It was neither ugly nor unnatural. It was lived in the country, and whatever man himself added to nature did not detract from the beauty of things" (Treveleyan 1953, p. 219). It is argued here that following this type of reasoning presents endless pitfalls.

One would only need to reflect upon possible conflicts arising from such beliefs, the most obvious being the construction industry's place within that world view. Is any sort of building an affront to nature? Discussion of such a slippery topic could very easily degrade into a stalemate. Again, intricate and subjective ponderings are well beyond the scope of this research. The assumption made in this analysis is that a tectonic shift *must* occur, possibly signaling a change in epoch. This progression will most probably be measured in decades, or centuries. A correlative assumption, that of environmental practices being subsumed by centuries-long development of productivity, answers the counterargument that big decisions must be made immediately. Imminent danger remains unproven; there is time. A model incorporating that constant takes shrill alarmism out of the equation. Such a template of environmental conditions is not without its detractors. For the purposes of this study however, it is the most useful means

of concentrating on well-targeted analysis. In other words, the goal is consensus about sustainable strategies, that will be workable as soon as possible.

So, lack of success in transmission of the message can therefore be improved by respecting the role of time. Studies in transition of technology chart beta curves, adoption increases in pace and then reaches the critical apex. The curve then descends rapidly as a shrinking number of recalcitrant non-adopters succumb to inevitable change. It is a generally accepted fact that automation and new materials can be of great benefit in achieving the goal of sustainable construction. The capabilities of these applications could improve the built environment in startling ways. Given time, and the proper technological means, hardly an aspiration would escape realization, or problem, a solution. With these possibilities in mind, a specific question could be asked about whether concrete should continue in its traditional role as the dominant structural component. Furthermore, considering the implications of automation, would there be a better alternative going forward? The research here will explore whether polymers can become that material.

The linking of computer software with new use of materials has opened many theoretical advances in the field of lean engineering. Such innovation could create patterns of sourcing, supply, and project management radically different from the current paradigm. This change could greatly influence materials processing, component manufacture and traditional labor practices. Taking supply as an example, the “Amazon” phenomena could revolutionize the speed and sequencing of distribution. Anything could be delivered anywhere in the world at competitive cost, in any quantity. This coupling of information technology and economies of scale could greatly ease the expense and time lag of materials’ delivery. If there were a distribution system that could integrate all these features, the effect would be transformational. It

will be asserted that eventual societal commitment could create enormous recycling networks. These infrastructure systems would be further enabled through internet supply chains.

Economies of scale only wait for a spark to conflagrate. Mass production and distribution should be expected to beget efficiencies. Even without large scale support, many companies already have made significant strides in re-sourcing the most feared polymer class. A company, called Northstar Recycling, is one example of this latent capacity for innovation. They have specialized in the repurposing of thermoset plastics, a major environmental concern. It is well beyond the limitations of this discussion to argue for specific policies to achieve such a situation. However, as stated above, an assumption of technological optimism exists. Given time, people will come up with solutions.

As will be seen, the case for optimism is strong. In his 2012 TED talk, an architect named Michael Hansmeyer has some fascinating ideas about means to extrude polymers. These concepts, if allied with Contour Crafting, could generate mass producible polymer buildings made of super-lightweight structural components. This could be done by allying computer software modeling with biomimicry principals. Modeling based on biological structural integrity, on a very small scale, has already been accomplished. Through exploration of polymer combinations, the technique could be perfected over the next several years.

Imagine combining Hansmeyer's vision with supply chain innovation and delivery! Pursuant to the discussion that use of local materials would be complex, polymer mixing would not present concrete's level of incumbrance. A constellation of sources would be available to produce the exact recipe for any project conditions. There are firms such as Sigma-Aldrich, Americhem, and Curbell, who specialize in doing this very thing. But, they lack sufficient infrastructure, so costs remain high. Still, with proper support, any of these companies could take

customer specifications and complete the order online (assuming adequate lead-time) for virtually any proportion of ingredients and mixing techniques. The chemical manufacturer would then test, create, package and send the finished product wherever needed, in whatever bulk. Polymer pellets or sand could easily be emptied into the extrusion hopper. Due to the tunability of polymers, arriving at the exact chemical lattice configuration and then delivering it, extruder-ready, would be relatively unchallenging.

Imagine the future! Automated delivery systems could create fully recyclable structures on a mass scale. These would be like jigsaw puzzle pieces in the box. If they are laid out and matched, potential benefits would include eradication of slums, provisions for vast new employment opportunities, and an effective market-based strategy in response to climate challenges. All that is missing is investment in flexibility.

It must be iterated that the intention of this research was not to provide half-measure solutions. While it is understood that necessary transitions must have intermediate forms, those forms are not the terminus envisioned. Likewise, the notion that polymers must be subjected to apologetics is rejected. There are no excuses needed when arguing for superior material properties and function. The thesis is that plastics should be considered on an equal footing with concrete, and if time is allowed, that piece of the big picture will fall into place.

Figure 1-1. Optimistic blog item regarding thermosets.

http://www.northstarrecycling.com/new-opportunities-to-recycle-thermoset-plastics/

CHAPTER 2
LITERATURE REVIEW

3D Printing of Plastic Structural Components

Michael Hansmeyer had a dream: "Nature has been called the greatest architect of forms. And I'm not saying that we should copy nature … I propose that we can borrow nature's processes" (Hansmeyer 2012). The architect elaborated his point while discussing column design in front of a TED audience. Hansmeyer's proposition was creation of a structure that used successive "folding" to define integrated forms. These forms had the potential to span the micro through the macro sphere. He continued: ". . . they [the column components] have information at very many scales. We can begin to zoom into them. The closer one gets, the more new features one discovers. Some formations are almost at the threshold of human visibility." (Hansmeyer, 2012).

The barrier of scale was overcome in this architect's work by modeling with a 3D printer. This algorithmic approach made use of fractal iterations involving repetitive halving. A theme of Hansmeyer's presentation was that software could do this and provide consistent structural integrity in a very well defined "print." However, the architect acknowledged his process was too cumbersome and limited in scope to be immediately applicable. He was almost certainly using acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), or similar polymers in common use, to perform this modeling. The brittle quality of those media stopped the dreamer in his tracks.

There are recent indications this architect's dilemma is, in fact, soluble. Progress has been made in 3D printing, reducing inflexibility of forms, particularly on a small scale. In their research of polylactic acid/polyolefin elastomer (POE) mixtures, scientists found ". . . the presence of POE in PLA foams has a great influence on their mechanical properties and . . .

toughness" (Forghani, Azizi, Karabi, and Ghasemi 2016). The study centered upon capabilities of foam insulation, but the results were quite applicable to computer modeling processes that employ identical materials properties. That study illustrated characteristics of existing polymers, used in new modalities, leading to discovery of workable structural combinations.

Rejecting Polymer Extrusion in a Process Developed from 3D Polymer Printing

The solution to any given problem will not be contained within just one monomer chain. Whether thermoplastic or thermoset, interoperability is the very principal inherent in the 3D printing concept. That concept has been a parent to Contour Crafting (CC): ". . . a gantry system carrying extrusion nozzle(s) mov[ing] on two parallel tracks installed at the construction site. Trowels smooth the surface of the layers as the concrete is extruded. The cement does not require forms, each layer extruded can keep its form as each successive layer is added" (Weinstein and Nawara 2015). Contour Crafting is not new. The effective filing date for the U.S. patent was October 26, 2006. This sustainable construction method could be most useful in developing countries in need of reliable, inexpensive, and safe mass housing. The economic feasibility of that research virtually guaranteed assembly-line building techniques. The Cornell study authored by Weinstein and Nawara, analyzed the respective probabilities of Contour Crafting becoming a viable building mode in developing nations within these parameters.

Subordination of Polymer Alternatives to Concrete Practices

That technology is a conduit to future applications envisioned in this review. Building information modeling (BIM) software was used to direct construction of CC projects. Materials selection could be changed in a heartbeat. This presented a natural opportunity for deployment of polymers, with their tunable properties and flexible use. A range of plastics were already being utilized in this manner, as noted again by the Cornell study. For example, reinforcement of the extruded concrete amalgam is often provided by fibers or pellets. These reinforcing elements

need only be loaded into the gantry nozzle to be mixed with the amalgam as it is layered. That is a contributing factor (along with the narrow width of concrete layers) to the self-supporting quality of the fast-curing amalgam.

A pivotal issue concerns concrete amalgam. There have been no concerted efforts in the past decade to explore new materials. Only concrete has been deemed acceptable. Conversely, Hansmeyer's dream would most certainly entail using a chain polymer-like iteration, thus eliminating concrete as an option. The material is strong and possesses a high Young's Modulus, but would be too brittle to perform such exquisite modeling. A likely motive for the decision to use only concrete was explained by a USC College of Engineering press release touting CC, ". . . instead of plastic, Contour Crafting will use concrete,' said Khoshnevis; actually, it's a special concrete formulation provided by USG, the multi-national construction materials company that has been contributing to Khoshnevis' research for some years as a member of an industry coalition backing . . . the initiative" (Viterbi 2008). A major factor for the persistence of concrete use is its mass application, which could expect to provide a profitable market for expanding CC projects.

Cementitious Materials as Polymer-centric Transition

Support given by the United States Gypsum Corporation, (USG) has been a constant since the technology's inception. Caterpillar also got on board the development program in 2008 (Viterbi 2008). It could be argued that both these conglomerates had a vested interest in keeping concrete as a central ingredient of the Contour Crafting process. There was a study examining the use of silicon dioxide-based mixtures which could give an opening to employment of organically-based, polymer-like compounds. This development would potentially be consistent with strategies preferred by the sponsors of CC. (Nazari and Riahi 2011) indicated: "Strength and water permeability of the specimens have been improved by adding SiO_2 nanoparticles in the

cement paste." It also must be noted that there were several competitors using CC technology, possibly beyond control of patent restrictions. This may lead to the supposition that research and development of extrusion plastics (or even organic equivalents) to supplant (or modify) concrete amalgam, may come from abroad. Still the question persists whether plastics could subsume concrete's role in Contour Crafting.

Another agent which had success in preventing concrete shearing was Fiber Reinforced Plastics (FRP), which used a filler of polymerized waste produced by the manufacturer of Portland Cement. This family of Plexiglas has also provided, in dust form, an integral component of tensile resistance in concrete. Yamada and Mihashi (1995) discussed these properties during a conference of construction materials experts. The two Japanese researchers found: "…. grain size of FRP powder is similar to . . . silica sand. These [findings] suggest FRP powder . . . use as a substitute of . . . silica sand [in] an extrudable (sic) composite." True, this is still a componential relationship, but the change from mere additive to integral component is intriguing.

The material properties touted in that research describe a polymer. If there were such a substitution, an important feature of CC could be obsolete. This would be the "method that combines an extrusion process for forming the object surfaces and a filling process (pouring or injection) to build the object core" (Khoshnevis 2004). The core need not necessarily be enclosed. The product extruded could be in molten form. Less troweling would be possible because it would be stand-alone material. Another intriguing idea that expresses the scope of change inherent with a shift of core processes which previously revolved around concrete amalgam.

CHAPTER 3
PROBLEM STATEMENT

The Current Situation

Much discussion has been expended, thus far, upon possibilities for new polymer applications. That vision could be quite a long time in the making. The predominance of concrete in the building industry is questioned only on occasion. The main effort toward development of sustainable building materials is going into design of increasingly efficient cement-based products, using polymerized ingredients. Government transportation agencies now often consider those types of mixtures satisfactory substitutions for concrete. It has already been shown how FDOT planned to use structural polymers for bridge piers in place of metal and concrete packages. This paper has argued this ultimately an unsustainable practice, not least, because recycling strategies are not in concert. For example, polymerization of dust ingredients for cementitious materials, for recycle, is dependent upon furnaces manufacturing Portland cement. So, there is no clamor for change to a totally different material, a true transformation. The tipping of the balance so evident in the climate change debate has not been replicated regarding concrete dependency of the construction field. The polymer debate awaits the advent of champions to argue its cause. A mass advocacy is needed, a critical number of proponents to make the case. The following apologetic is very specific in its delineation between objective and subjective factors of material properties. This type of argument is effective because it invites comparison, convincing and audience with contrasts using topical subjects. A balance is found by using science to highlight misconceptions about points familiar to the listener. People must be convinced using understandable persuasion. The average person tends to believe they grasp the substance of the mundane, things encountered every day. This arrangement of objective

evidence, revealing the mundane, exposes unconscious perceptions that are suspect. In this manner, transformation of thought can be achieved.

Advocating for a Polymer Bench

Examination of common objects could, therefore, provide analogies to more complex matters. The following discussion could be truncated at any point, or given detailed elaboration for any audience so inclined. It could begin with a simple proposition. For example, a listener would be asked to imagine a generic structure, say, a bench in the front yard of their home. It will be built with an elongated seat. The superstructure will be supported at either end, possibly with separate pieces to aid in portability. This bench would also represent a loaded beam. The case to be made is that of polymer use as a structural component. Therefore, the task would be to select the best construction material. Excluding natural polymers (wood), there would be four common alternatives from which to choose: metals, ceramics, composites, and non-organic polymers. There would be many factors affecting each choice, the object should appear reasonably comfortable and stable, or at least give the impression of functionality to casual inspection. In other words, it should possess constructability, satisfaction of the end-user's subjective vision of a bench.

It is axiomatic that any selection would depend upon individual taste and priorities. But, appearance will not guarantee constructability. This bench must possess objective properties which insure durability, and it must function properly. This dichotomy between actual material content and performance, contrasted against a consumer's desire for an attractive product, lay at the heart of this example. The goal will be to expose the complexities of apparently straightforward decisions. Therefore, would be helpful to take each choice and examine both its physical properties and psychological effect. The most obvious concern for most people would involve cost. A metal design of a strong, supple, and lightweight aluminum product would

certainly present an attractive and functional option. It would be easily movable and look durable. Aluminum could also be twisted and crafted in interesting ways. Speaking of malleability, copper would be better, due to features like the classic green patina it would acquire through weathering. Both these options would be expensive. A customer would most probably look to obtain equivalent performance with less cost. A cheaper metal would be more than adequate, such as that of steel, or iron. With approprate coating, each could display copper's patina finish, or the shine of aluminium. When employing lower cost metals for seating, there would be at least two major concerns, conductivity and weight. Discussion of bench selection for an outside restaurant, or park, would include these important properties. Customer seating would encourage turn-over. A material that is a conductor of heat and cold would be desirable. A heavy, formidable-looking bench would also discourage vandalism in a public place. If the proposed outdoor furniture were to be in placed at a residence, exuding a welcoming environment, the parameters would change drastically. Conductivity would be a drawback; sweating or chilly visitors, perched at the edge of their seats, would not do at all. And, a totally immobile bench which could not be moved under a tree, or next to a backyard pool, would further exclude this choice. The argument is working its way towards a polymer structure.

A ceramic bench would mitigate, though not remove, the conductivity issue. Weight would be lessened. The shape could be sculpted to fit any taste. These properties would generally meet the evolving criteria. Because they are essentially kiln-made, ceramics are by their nature brittle. A bench composed of the material would be prone to cracking over a large surface, under its own weight. It would need to be constructed in sections. A solution for this would involve expensive options, such as "doping" the ceramic with polymerized sand, resulting in greater

tensile resistance. This would most probably eliminate a ceramic choice, while suggesting plastics.

The option of polymerization would bring the choice of a composite material to the fore. The traditional composite used in construction is concrete. This cement-based material has very high resistance to compressive forces. It also is strikingly formidable by inspection, due to expectations fostered by historical use from time immemorial. Concrete would possess similar conductive properties to ceramics, due to the insulator absorbency of Portland cement and sand ingredients. The weight of concrete would always be a problem because, even when the composite can support itself, it is restricted in area without reinforcement. If the material covers too much area it will crack from the effect of gravity. Even with reinforcement, cracking often occurs at the edges, while brittleness persists on the margins. An aspect of the nation's crumbling infrastructure could be mentioned at this point, attributable to this condition.

Plastic fibers introduced into the mix would greatly insure stability. At this stage in the discussion, the listener would be brought full circle. If using polymers were an option, it would make sense to go all the way by selecting a completely plastic bench. Extent of the materials suitable properties for the job could be elaborated. Polymers are composed of molecular chains. Although there are exceptions, the propagation of such latticework would distinguish them from the other materials through tunability of the molecular composition. The listener could learn more about tunability at this juncture. That property would enable chemical adjustment to imbue a plastic structure with virtually any desired qualities. The nature of this lattice creation could induce permanence, creating a product that would not necessarily promote bio-degradability. But, that situation need not become axiomatic because modulation of crystalline formation is also tunable. Other selling points of plastics include great flexibility and strength. The material

can easily be made in colors; it would take little effort to chemically add metals or halogens to give color attributes. This would just entail direct mixture: manganese could render pink; sulfur and chlorine, yellow; bromine, red; gold and copper, gold and copper. The elements would merely link to whatever chain is present in the vat solution. When discussing these features as a priority, it would be important not to confuse the structural material with another plastic, elastomers. This type of plastic produces rubber and glass.

These elastomers lack the stiffness necessary for a structural unit. It could be stressed to the audience that physical strength of polymers lies in their density, most often achieved by cooling of the molten material. Plastics are also noteworthy among the group of proposed materials because they are amenable to melting and recasting into infinite and complex shapes. They can be formed through an extrusion process to exhibit a wide variety of properties. One such is high density to behave as a structural unit, a loaded beam. A typical extruder operates somewhat like a conveyer belt, heating plastics from various states when put into a hopper. An interior auger distributes the gel with uniformity. Heated to a molten state, the plastic could be either directly deposited into a form, or applied through a trowel, to create the desired object or continuous shape.

This is not the only type of extrusion. Pressurization could also act as catalyst to molecular chain propagation. In this procedure, a polymer gel would be extruded to dry when exposed to oxygen. The process has been incorporated into mainstream construction practices. techniques utilized include spraying of foam insulation into wall cores, or into a dome-like configuration as support for a subgrade shotcrete roof. The rate of drying, dependent upon ambient temperature, would determine the exact properties of the plastic. This would most likely

fail to produce a true load bearing element. Issues surrounding control of environmental variables would make the effort prohibitive.

Constructability and Perception of Concrete Versus Plastic

At this point in the discussion, it would be prudent to remind the listener that the basic intent of the entire supposition is to demonstrate the capacity of structural plastics. In this situation that would involve fabrication of a uniform component with concrete or ceramics-level resistance, adequate to handle compressive forces. Tensile reinforcement would be unnecessary because Young's Modulus could be tuned through monomer and repeating molecular unit propagation. In Along this line of reasoning, the audience would be invited to conclude that, absent subjective factors, plastic could very well become the ideal choice. It could also be pondered that a favorable view of this selection would depend upon perceptions of constructability, regardless of objective evidence. This concern could become paramount. Subjective standards of functionality, stability and attractiveness may become determinate. The goal would be to highlight to the listener that the alternatives of a concrete or polymer bench could be evaluated, independent of constructability prejudice, in an empirical manner. It would probably become clear that the main barrier to polymer use would involve the general subjective preference for concrete.

Attention could then shift to further objective evidence in support of a polymer, why an objective decision would be so important for the sake of structural safety. The proponent of the case for a plastic bench could thus posit a scenario altering the load, adding an equal length backing at a 45° angle. This would favor selection of concrete if only conductivity were to be considered. A plastic would be largely heat-neutral. Concrete would retain warmth and cold in moderate amounts. People would enjoy a cool surface shaded by the seat-back in hot weather, or in the cold from warmth generated by sun. But these features would be negated by structural

factors. Even with careful reinforcement to manage tensile load, the weight of this composite could very well generate diagonal cracks along orthogonal surfaces. The concrete would almost certainly fail. A counterargument could discuss the solution found in the amalgam arrangement discussed regarding ceramics. Polymer fibers could be introduced to strengthen the concrete as it cured. That, in fact, is representative of current practice. The material is regularly cast in molded shape, only supportable with rebar or introduction of polymerized additives. The stability of the concrete is at times tenuous in these situations. But, constructability perceptions dictate the subservience of polymers. The audience could then be reminded of the FDOT example of bridge piers with plastic profile sections supporting a concrete column.

Properties of a Corner Wall Section and Faux Wood

Speaking of columnar shapes, there would be less force (tensile or compressive) for which to account if the bench were analyzed as a loaded beam. However, if the bench were to be tipped up endwise and secured at the base, each material may be more definitively examined as a corner column compressed from above. Contradictions in this matter of choice could then be illustrated in greater relief. A reasonable loading in the column scenario could be visualized as a wall corner supporting the side of a building. If the area of each side (seat and back) were extended, say threefold laterally, the altered picture would be complete. A fundamental flaw would become evident. Even with reinforcement, concrete at a 45° angle would gain exponential tensile strain Under that force, each side of the concrete wall would compress and acquire an upward thrust, countering internal displacement. Common damage to concrete resulting from this type of orientation would be cracking along a 45° plane, as internal strain would add shear stress from support connections. Another danger of this configuration, if steel rebar were used, could be crevice corrosion. The porous nature of concrete could allow metal reinforcement to oxidize and compromise the component's integrity. This quality would be magnified by stresses

to the interior. The flexible quality of a polymer column would tend to disperse the weight, though with some sacrifice of stiffness, and possible deflection. These drawbacks need not become threatening, assuming the material would have been heat treated to retain a high crystallinity. If placed in appropriate conditions, thermoplastic constructability effects could be managed.

Departing from the discussion between advocate and audience, the supposition has been incongruities of perception. Materials are often represented in guises confirming the viewer's subjective definition of constructability. For instance, concrete is often shaped to mimic stonework. Plastics could also be used as an underlay to a veneer, giving the same impression; take faux wood molded into plank form. Such an arrangement can be found in the deck of a footbridge at the University of Florida student union. It is very convincing and is only given away by the small Phillips screws securing each plank. Walking on it gives the sense of moment without bending, a sturdy wood floor. Furthermore, the sound of each foot tread is almost absent. So, really, the only sensations are those based on preconceptions of what a good bridge ought to be. It is left to the individual imagination.

When context is considered, the importance of atmosphere is very noticeable. This emphasizes the contextual nature in any process of changing attitudes. Reitz Union has been recently renovated, and this arrangement is indicative of a well-thought-out effect. Any student who regularly uses the building (it is almost impossible to avoid) must follow a learning curve to navigate the facility. That same student is confronted by subtle and direct choices These choices, such as the bridge, are intended to educate that person regarding qualities of a sustainable building. Each student is habituated to certain practices when encountering the central feature of this university.

Much the same point can be made about the use of polymer. Attitudes may change when educated about the material's possibilities. If plastic is coddled in the mind, it may be imaged with much the same building capabilities as concrete. There need only be the willingness to engage in the exercise, to open one's mind. From this perspective, decorative single planks of the faux wood could be central to an automated delivery construction method or traditional uses. So, quite mundane paths are possible to acclimatize the mass consciousness to new possibilities. Such a transition could involve pondering whether up-ended polymer planks could be combined as structural columns in traditional homes. This would challenge convention because decorative faux wood is often applied to concrete and steel columns to give the impression of a wood beam.

The planks need not be subjected to a mold for effect, disguised as accessories. They could be fed into an extruder on the Contour Crafting gantry. The molten product could then be shaped by trowel while layered by the nozzle to cool as the gantry moved along, faux planks, in different state, stacked upon one another. In this orientation, they would need less brittleness (due to dimensional support in the vertical) and could be engineered with ease by chemists as thermoplastics, with less density. An advantage could be ready recycling at completion of their functional-life. The learning curve in this entire process would encourage variegated and expanding pathways towards recycling, by generalized application and repetition. Such a process would require many individuals' experimentation. A hypothesis of this paper is the crucial factor of single decisions, summed in critical mass to create technological and productive change.

Education through a Shifted Paradigm

Within this paradigm, the audience considering bench material could better grasp possibilities of polymer use in applications far exceeding lawn furniture. The person would, through familiarity, contemplate much more adventurous applications. To back up this possibility, a stress-strain graph comparing concrete and polymer structural qualities could be

judged with a more critical eye. The two graphs below illustrate effects of maximum levels of force on an experimental concrete beam (left), and a that of a thermoplastic (right). The bench is essentially a loaded beam. The left side depicts the response to an applied force as an initial linear relationship between stress and strain, then, with a sustained parabolic curve. This represents initial loading and then sustained compressive stress on the top of the beam, with a correlated elongation caused by tension stress on the bottom. The apex of acceptable compressive force is just before the curve tangent becomes negative. From then on, the beam experiences a reduction of compressive force capability and tensile forces become determinant. As the curve grows increasingly negative, the composite can be seen to crack (if pinned-in the diagonal) and to crumble. There is an instance on the curve where the beam will catastrophically fail. It will not snap (as would a thermoset brittle plastic) but deteriorate as the parabolic line tends toward the asymptotic limit of zero.

The failure will be demonstrated by concrete dissolving under the weight. The composite breaks apart because there is not enough consistent allowance for the growing strain, or internal displacement, caused by tensile elongation. The remedy for this decay would be steel or polymer reinforcement. The plastic has a built-in response to such elongation. When looking at the righthand graph there are three lines. The plastics shown have very little common molecular structure. The one labelled as brittle is thermoset, or hard. The middle is a thermoplastic; the bottom is a polymer demonstrating almost-elastomer flexibility. This discussion is focused on the middle curve. As with the concrete, the initial loading produces a linear relationship between stress and strain. What happens afterward indicates the true misconception regarding respective strengths. The bump just beyond the end of the line shows the proportional limit of the plastic. In other words, this is the instance where initial loading ends and tensile forces become significant.

It is important that the curve does not bend downward, but beyond the bump, exhibits a convexity.

Remembering the concavity of the other graph, a key property of a thermoplastic is revealed. It carries within its own form great tensile resistance. The graph indicates this by the attenuated curve. The material can take a great deal of internal displacement. On the molecular level, the polymer has created crystals with long tails. To visualize this activity, imagine opening a package containing a plastic rain poncho. It is folded in long horizonal alternating layers in an accordion-like fashion; a fold on this side, a fold on the opposite. It is done in this manner to allow air to escape, avoiding entrapment that would increase package bulk. This same concept is observed at work in the crystal, tight alternating folds which decrease density, while providing essential strength. Crystals initially attract high energy until the lattice regains equilibrium. The resulting molecular texture discourages chain layers from sliding. This allows flexibility, while maintaining an acceptable stiffness. Of course, there is an instance on the graph when the polymer will snap, indicated by the small “x” at the terminus of each curve. But the load resistance factor could be determined well before that eventuality would occur.

Another way to view the situation would be to reflect if concrete seats were to have concrete backs. The structural integrity of such an object would be unsound, without a great deal of accommodation. If the back were at an obtuse angle it would need a prohibitive amount of reinforcement. And, if it were at a right angle, the distinct possibility of the occurrence of diagonal fissures (a danger at any orientation) would make this option equally prohibitive. The solution is very revealing, often to satisfy a prejudice toward stability with the more amenable plastic using subterfuge. An example would entail extrusion of a plastic bench, with a marble patterned overcoat of paint, added superficially.

The need to develop sustainable building materials and techniques has accentuated the deleterious effect of current presumptions. Disruption of this mindset is already underway. The tendency has involved a top-down approach to employing renewable strategies. Due to their high profile, the most likely adherents to this philosophy are managers of massive private, and public projects. Large private enterprises possess detailed organization and cohesion, with sophisticated procurement streams. Government controlled schemes are mandated by evolving regulation.

What sort of persuasion might be effective to communicate benefits recognized by the government and large contractors? An Ashby chart (CES/Granta 2010) would very informative to the technically-minded. This cartological evidence indicates material qualities on a continuum between two axes. These axes can be defined by any number of interactive properties, including cost, strength, and conductivity. Suppose a building project were taking place in California. There definitely would be legitimate seismic issues involved with any kind of construction in this region, especially if residential housing were involved. For the purposes of this comparison, between concrete and polymer use, fracture toughness would be a beneficial property, even at the expense of some loss in Young's Modulus (E).

Looking at the chart more closely it may be observed that the y-axis indicates resistance to cracking, with the x-axis measuring stiffness. Polymers are denoted by blue, concrete by yellow. The general disposition indicates polymers are exponentially less susceptible to damage from earthquake, through fracture, than concrete. In terms of actual field conditions, this finding would argue that a lighter structure made of plastic would probably be more suitable than one of heavier concrete. A conventional concrete foundation home built in this area could only hope to equal flexural performance of the polymer through utilization of an expensive rocker/jack system.

Marketing Plastic Homes

So much for technical analysis regarding the benefits provided by plastics. The appearance of a house constructed from the material could really arouse interest. A polymer residence would be feasible, though a great deal of development in technique may be necessary. There are certainly situations where the polymer option has been seriously explored. The market will bear other possibilities than those driven by concrete. Entrepreneurially motivated attempts to establish the idea of structural plastics are gaining in momentum in the public conscience. One heavily advertised option is called Green Magic. The units are priced between $14,900 for a single bedroom, to $119,000 to construct a four-bedroom structure. The marketing emphasizes a complete "do-it-yourself" assembly from a pre-fabricated kit (Green Magic Homes, 2018). This presentation unfortunately plays to expectations of flimsiness and cheapness often associated with construction in plastics, because the core components are made of fiberglass. The home is designed to be insulated by the earth and thus characterized as an ecological statement. It is also designed to sit on a plot of land. A picture is created of autonomous villages of these dwellings far away from crowded cities. The idyllic nature of that narrative is interesting when contrasted with the current trend in environmentalism favoring a density building model. In recent years sustainable planning has developed a strong tendency toward concentration of new building within existing metropolitan entities. This Green Magic Homes option can be viewed as a specialty item.

Another promising possibility was written up in Forbes magazine (Winkless, 2016). The story described a businessman with an idea to build polymer homes from waste plastics. Prospective homeowners were slum-dwellers in Latin America. The hopeful candidates collected useable polymer trash, with the positive effect of cleaning up their neighborhood, and gave it to the entrepreneur. The builder then used extruders to fabricate relatively quickly assembled

components for new modular housing. The cost of each home was approximately $5,200. The mood of the written piece was highly optimistic, private sector solutions to environmental problems. When reading the column more closely one may detect an undercurrent of guilt. The initiative appears to be more philanthropy than the result of hard-boiled business decisions. Capitalists were using their wits to deal with situations for which they may have been largely responsible. The company constructed the dwellings by winning a $300,000 prize in a New York City competition, called “The Venture,” The award has enabled this business to complete 42 “temporary shelters,” with another 20 slated to follow.

Sustainable construction is such a ubiquitous topic, and even a polymer discussion so wide-ranging (in fact a lifelong field of study), that scope must be strictly controlled. The options just discussed, are revealing in their perfunctory qualities. When the specifics of earth-insulated and temporary urban polymer structures are considered, long-term solutions disappear. Both are indeed small private ventures to a niche market which use of thermoset prefabrication, though the similarity ends there. One option is urban-based and intended as itinerant shelter, the other marketed to utopian suburbanites with somewhat bohemian sensibilities. Neither option is designed to supply a broad market. The cases above have been included to represent an utter paucity of real alternatives to concrete, a crucial factor when holding transformative expectations. Any adoption of sustainable polymers would depend upon fundamental cultural change. Anything less than this would be ineffectual in dealing, for example, with the effects of climate change.

Operating on the assumption that cost has a rough equivalence with materials use and construction processes, a United States Census Bureau graph (below) shows current building trends. The first two columns of the index indicate a large preponderance of private, residential,

and nonresidential categories that remain untouched by sustainable imperatives. In other words, this is that would be the audience to convince. The graphic makes one thing very clear, a wide deficit in adoption of sustainable strategies exists. Furthermore, this represents a chasm of perception. It acts a barrier between those who perceive the need for change, and motivated to seriously consider alternatives, and those unwilling to concede that investigation is necessary.

The construction industry is a cultural expression. Through the centuries, this culture has developed building styles and associated material choices with the aim of satisfying pretensions of fashion and functionality, resulting in deeply ingrained societal traits. Post-modernism in architecture has only served to reinforce this gilding tendency. There will be very difficult challenges ahead when confronting those inherited values. Potential effects of climate change could offer a sufficiently pressing case to warrant the effort. Study of that question is well outside the scope of this paper. But, it can reasonably be inferred, as has been stated previously, that change will be accomplished through the actions of many, within a kaleidoscope of situations. The goal here is to further that process by focusing upon the fundamental underestimation of potentialities for plastics use, hypothesizing limited issues that contain significant elements of the central problem.

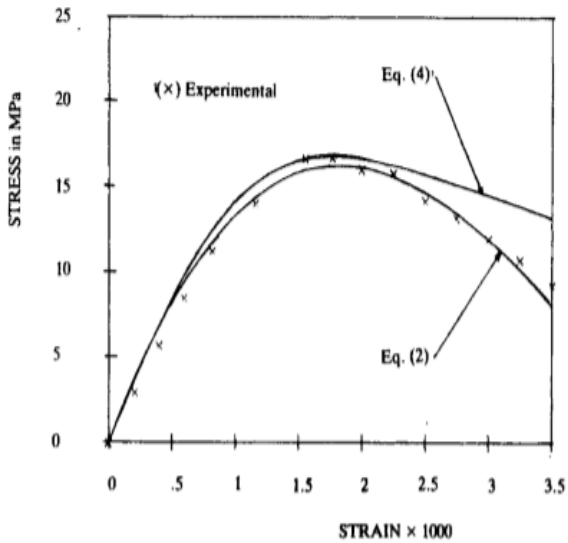

Figure 3-1. Concrete stress-strain graph.

Anis, Mohamed Ali, Stress-Strain Relationship for Concrete-
file:///C:/Users/Wolfgang%20Ryor/Desktop/StressStrainConcrete.pdf

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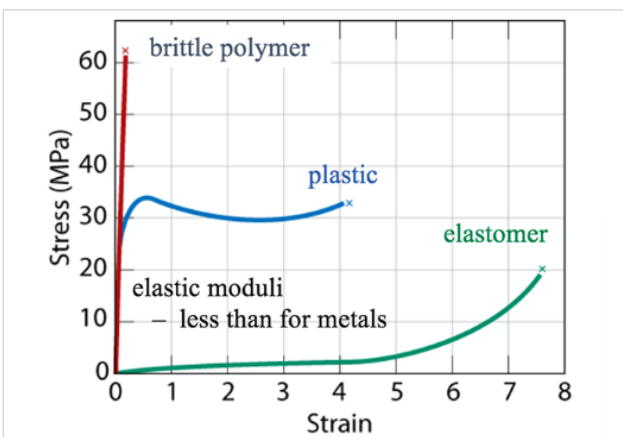


Figure 3-2. Polymer stress-strain graph. https://www.e-education.psu.edu/matse81/node/2109 By permission of Pennsylvania State University College of Earth and Mineral Sciences Open Educational Resource license/Creative Commons Attribution-noncommercial ShareAlike 4.0 international license.

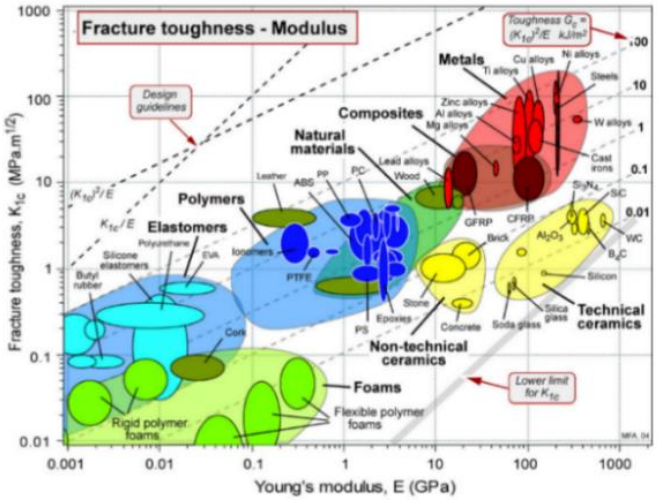


Figure 3-3. Fracture toughness and Young's Modulus Ashby graph. Granta CES Textbook-Granta CES Textboofile:///C:/Users/Wolfgang%20Ryor/Desktop/2-Materials-Charts-2010.pdf

Figure 3-4. Author's photo of walking bridge at the University of Florida student union.

Value of Construction Put in Place at a Glance

April 2018

	Seasonally Adjusted Annual Rate				Not Seasonally Adjusted		
	(millions of dollars)				(millions of dollars)		
Total	1,310,404	XLS (11k)	PDF (31k)		106,736	XLS (11k)	PDF (31k)
Private	1,014,282	XLS (15k)	PDF (36k)		84,035	XLS (15k)	PDF (36k)
Residential	556,294	XLS (8k)	PDF (16k)		46,609	XLS (8k)	PDF (16k)
Nonresidential	457,988	XLS (8k)	PDF (18k)		37,426	XLS (8k)	PDF (18k)
Public	296,122	XLS (11k)	PDF (24k)		22,701	XLS (11k)	PDF (24k)
State and Local	268,738	XLS (11k)	PDF (31k)		20,597	XLS (11k)	PDF (31k)
Federal	27,385	XLS (8k)	PDF (18k)		2,104	XLS (8k)	PDF (18k)

Figure 3-5. USCB information of proportion of private to public construction.

Permission: Press Release of United States Government; United States Census Bureau, April, 2018

CHAPTER 4
OBJECTIVES

Interrelated Hypotheses

The discussion has thus far concerned a variety of issues surrounding mass adoption of sustainable practices, highlighting the situation of polymers. Inherent problems have already been discussed regarding the perception of materials, within a broad context of current attitudes. The main hypothesis this paper will seek to address is unproveable in this brief examination of a vast topic. It will be necessary to elaborate upon such a proposition to some degree, that prejudice favoring concrete suppresses consideration of other, possibly more efficient, alternatives. It has been argued that the concrete issue is representative of general attitudes which may hamper adoption of broader sustainability policies. Interrelated, and much more manageable, hypotheses will be advanced, necessary to frame some of those persistent beliefs. Consequently, the chapter addressing suggestions for further research and limitations of methods will assume a pivotal role. The intent is to propose, define, and prove understandable hypotheses, exposing misconceptions which could invite more incisive examination of sustainable alternatives.

A Limited Hypothesis using Contour Crafting

Among those more limited questions are polymer and concrete use within an automated process, touted as a significant development in sustainable construction. The delivery method of Contour Crafting will be explored. Front-end material costs for a proposed structure will be estimated. The unit cost of the exact concrete amalgam dispensed in the Contour Crafting process cannot be accomplished, due to its proprietary nature. However, a reasonable facsimile can be determined for comparison purposes. The situation concerning polymer estimation uses similar modeling. The manufacture of this material depends upon propagation of the desired

molecular matrices. It would be preferable, though not essential, to design a thermoplastic with a high crystalline percentage. This would greatly increase resistance to applied stress through heat treatment. The hypothesis to be proven will demonstrate that molten polymer fabrication would produce structural properties, when utilized within an automated process, that are equivalent to concrete amalgam. Examination of unit cost and infrastructure will also be addressed as factors. The next hypothesis will involve the nexus between perception and marketing decisions, to be reiterated with testing.

The Marketing of Faux Wood

Another subsidiary hypothesis will assert that faux wood is, in common practice, a decorative item. Manifold examples of structural applications for this material could be cited. It is, after all, plastic, a chemistry known for tunability. This argument will be advanced through research and testing. Focus will fall particularly upon cultural attitudes. Expectations of the utility of faux wood in the public consciousness will be presented within an advertising matrix. Laboratory work will emphasize these points.

Concrete Versus Cementitious Material

A hypothesis closely connected to that of faux wood will address qualities of cementitious materials, alongside those of concrete. The intention will be to draw out, and analyze, similarities and distinctions between the two. The assertion will be that similarities far outweigh differences.

An Aside into Competing Life Cycle Claims

Polymers are made of hydrocarbon chains, generically called petroleum, or crude oil. That fact would tend to raise competing claims surrounding life cycle costs. Although this discussion will fall within suggestions for further research, it will now be dealt with in a cursory manner. These are to be contentious points and may only be introduced as subtexts of the main

hypothesis. Yet, it would be prudent to at least mention the argument. There are many facets to the life cycle and sustainability calculus. Manufacturing and transportation figure prominently. The raw crude is usually trapped within the earth's crust while under high pressure.

There are three primary stages of supplying the commodity. First it must be drawn to the surface. The familiar geyser analogy would not present an accurate picture. Derricks have become very sophisticated due to possible leaching. The British Petroleum disaster off the coast of Louisiana in 2010 need only be remembered to explain that danger. After extraction, the resource is taken, usually by conventional bulk transport, to the refinery. This is accomplished by myriad steps of addition and purification, depending upon end use. It is noteworthy that many plastics are the last remnants of the process and readily available for recycling, due to the refining infrastructure. The fluid is then distributed across regions and continents.

Life Cycle of Concrete

It could be argued that concrete is relatively less renewable than polymer, owing to supply demands associated with mixture sourcing. Its composite form can require prodigious quantities of Portland cement, sand, and aggregate rock, not to mention additives. All these components must be independently obtained. A common perception is the composite's ingredients are natural. Cement, for example, is viewed by most as environmentally friendly. A closer look from an embodied energy perspective renders quite a different verdict. Polymers are ever-increasing in the mix, as fibers and polymerized sands. That would mean those items could only be recovered for recycle at end-of-life use, digging through tons of concrete and complicating any recycling pattern. This was discussed in the introductory chapter when analysis was made of FDOT strategies.

Portland Cement

Portland cement alone travels a variegated path to combine in recipe with other ingredients. The Portland Cement Association (PCA) described their product as a ". . . closely controlled chemical combination of calcium, silicon, aluminum, iron. . . limestone, shells, chalk. . . marl combined with shale, clay, slate, blast furnace slag, silica sand, iron ore. . ." (PCA 2016). The PCA also commented upon the trade association's environmental policy. Highlighting employment of polymerized refuse, the group "fosters continuous improvement in cement manufacturing and distribution…" (PCA 2016) It was also asserted that the group had become an adherent to life cycle assessment. To count the procurement streams described, a total of 14 would be rendered, assuming they were all independently sourced and not part of a further level of manufacturing and collection. At least three levels of manufacture would be suggested by their description: 1) processing of iron and steel ore, which would incidentally supply polymerized recyclables; 2) the manufacture of concrete itself; and 3) manufacturing within the Portland cement factories.

Consideration of Figure 4-1 could also bolster the argument for plastic (Granta/CES 2010). This graph displays flexural strength against relative cost. It seems to greatly favor concrete (narrow yellow ellipse, lower left corner), showing its lower cost. However, lack of tensile resistance without reinforcement demoted the composite farther down the strength axis. When compiling the distortion, the fact is that unit cost, at purchase, provided the basis for cartological reference.

More Accurate Assessment of Materials Costs

"The single most important feature in reducing the impact of embodied energy is to design long life, durable and adaptable buildings" (CSIRO, 2015). This statement, from an Australian government manual, addressed the somewhat slippery question of embodied energy's

definition. It made clear the fact that a full and accurate life cycle assessment must be taken into consideration. This is reflected by the “Plastic” and “Concrete” bars’ relationship in the graph. That diagram in Figure 4-2 indicates true relative value, with weight given to disposal costs after useful life. Consequently, the Ashby inaccurately represented the given material’s life cycle. In that graphic, front-end unit cost per volume constituted the baseline.

A significant challenge to the prospect of proper assessment of the life cycle are constructability concerns, and a chauvinistic attitude about materials. Examination of a regular complaint used to reject plastics, their non-biodegradability, gives further insight into weaknesses in consensus opinion. Thermoplastics are currently recycled on a mass scale. Functional barriers to inclusion of structural plastics only consist of logistics. The will to establish correlative integration of structural plastics into the mainstream presents the real obstacle. If polymer buildings and residences were a regular feature in the construction industry, then infrastructure to re-purpose expired components would surely follow. This would, in turn, spur evolution of substantial efficiencies in a moribund recycling dynamic. Resultant synergy would be crucial for evaluation of back-end costs. Present efforts to quantify this expense can be highly inaccurate, or absent altogether.

Recycling infrastructure must not only prove efficient, but ultimately sustainable, in practical terms. Current problems with recycling are attributable in significant measure to this lack of coordination and ingenuity. Using extrusion of concrete amalgam in Contour Crafting as an example, the paste could include polymer fibers in support of tensile resistance. It has already been argued that creation of efficiencies in retrieval and recycling mechanisms of these polymer elements is more difficult because the material is encased by concrete. It is generally assumed that concrete will eventually decompose to its natural composite components while plastics will

not. The contradiction of this perception is self-evident; polymers are set up to to be nonrenewable in that scenario. Circular logic is employed as proof.

This anti-recycling tendency is exacerbated by the production of Portland cement. The central concrete component can only be manufactured with copious amounts of alkaline and non-alkaline metals, combined with metalloids and pure metals. This is often the problem with accurate life cycle assessments – i.e., inaccurate metrics. Portland cement manufacture has a limited capacity to reduce its carbon footprint. Furthermore, the attitude supporting this effort axiomatically discourages retrieval of polymer additives. Despite pronouncements to the contrary, there is no escaping a profound level of waste within this inherently cumbersome process.

With all this said, the economy is structured to support these labor-intensive and inefficient practices. Concrete is not a bad option, particularly in the short-to-medium term due to our society's reliance upon it. This dependence does not just include building methods, but also labor and business relationships. A smooth transition away from this dependence is possible through positive use of technology. A tactic towards this "soft-landing" would be application of modalities like environmentally lean concrete. A periodical article (Plastics News Europe 2014) described that emergent technology. The European Union recognized the industry's socio-economic role and made made efforts to promote the combination of detritus (discarded plastics, for instance) into the mix. This would lessen the environmental impact of the composite, while maintaining the current ubiquity of use.

The logic of these actions is akin to the Latin American example discussed earlier; the assumption is that polymers are junk and concrete is perfectible. This twist of reasoning has been discussed at length already. But, people's livelihoods are invested in that perception. Merely

criticizing the concrete industry as a wasteful enterprise in need of overhaul is therefore insufficient. While the cement manufacturers raising LCA as a standard worthy of praise is somewhat disingenuous, it is probably essential to the transitional process. The concrete industry makes a fundamental contribution to society. Given time and education, opinion could begin to understand that digging giant holes in the earth is not sustainable. Developers may then perceive that mining numerous elements for the sake of creating a historically preferred material is a damaging proposition. Then, if society persists along this line, even the most recalcitrant may sense investment in a costly industry, which annually emits five percent of the planet's greenhouse gases (Plastic News Europe 2014), has acceptable alternatives.

The purpose of this research is to give ammunition to that educational process. The goal is to oppose myopic tendencies and the correlative polarization of opinion. A common error when attempting to explain partisan positions on the topic is a retreat to diametrically opposed viewpoints. Inertia surrounding adoption of incremental environmental policies is often a result of simple bickering. Yet, beyond this type of conjecture, a way forward can be found. Mechanisms which determine acceptability of emerging technologies and new uses of materials can play a significant role in adoption of sustainable processes. The pressure of climate change, shifting demographic concentration, and disrupted patterns of productivity, are powerful drivers of change. Their operation, over decades, could create an ever-increasing momentum toward adoption of these strategies. Therefore, the time horizon is critical to the hypotheses advanced.

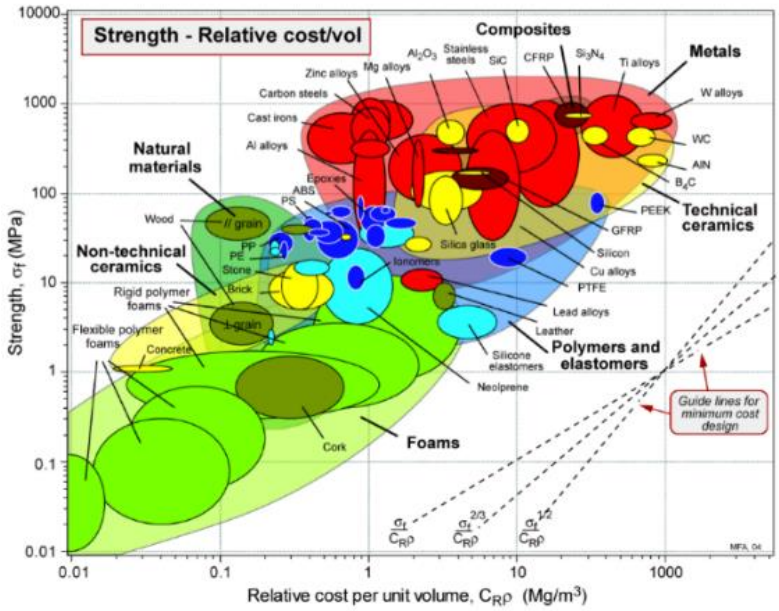
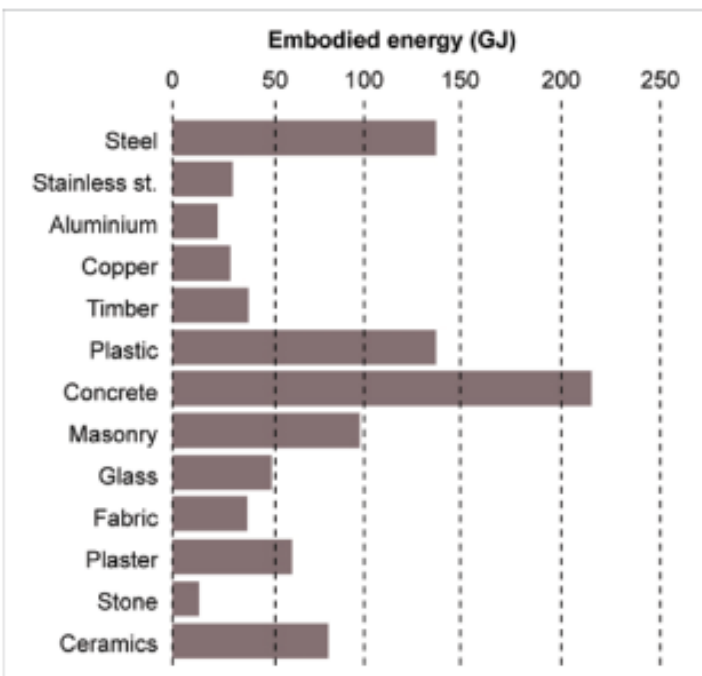


Figure 4-1. Flexural Strength against Relative Cost



Source: CSIRO

Figure 4-2. Back-end energy costs of materials.

CHAPTER 5
RESEARCH METHODOLOGY

Lab work consisted of compressive and flexural testing of concrete, cementitious material, and faux wood. A cementitious mix makes ample use of polymerized, or burned, products of cement manufacturing. Examination of faux wood involved two primary morphologies, structural and decorative. The purpose of these selections was to test the limited hypothesis that, although structural faux wood could be delivered as a single component, cultural attitudes demote it to an accessory covering for concrete.

The first morphology was molded, in shape and texture, as a plank in the deck of a walking bridge at the University of Florida. The material was not tested by this researcher, but was representative of a structural component with expected results. This was based on results, cited in the Results chapter, of composite faux lumber testing by the Colorado DOT in 2000 (Janowiak 2000). The planks of the bridge were most likely composed of a block copolymer of two macromolecules in chain, closed cell, alternating configuration. This property would have provided strength through density, but may possess a brittle quality. The exact chemical composition was proprietary, though the material was quite possibly a high percentage, semi-crystalline thermoplastic. To support this view, the other faux wood option was decorative, mimicking a beam. It was composed of regular polyurethane foam. This material was subjected to compressive analysis. The goal was to determine the structural properties of a commercially-purchased channel, or hollow section product, and then extrapolate those data into the hypothesis described above.

Concrete

The concrete was obtained through a specific mixture, making use of FDOT #89 coarse aggregate, due to a limited size yield of 0.1 cu ft. to create specimens to fit an Instron 5969

Universal Testing Machine. Procedures of ASTM C192-16a (ASTM 2016) were followed to insure proper mix control quantities and curing: 3.00 lbs. of Portland cement; 1.47 lbs. of water; 5.73 lbs. of #89 coarse aggregate; 3.63 lbs. of fine aggregate; 1.20 mL, Darex AEA; 2.70 mL, WRDA-60. The ingredients were placed in a standard mixer. First all coarse aggregate and half the water were added, with 20 seconds allowed to mix. All the fine aggregate was added next, with another 20 seconds allowed to mix. Then all Portland Cement and the other half of the water were added last. All ingredients were then allowed to mix for three minutes; the mixture was then set in ten miniature molds, secured within plastic and let stand in the lab for 24 hours. After that time had elapsed, the ten molds were submerged in an aqueous solution of 2.67 L, including 0.020 lbs. of $Ca(OH)_2$; the solution was sealed in an airtight container for thirteen days for adequate curing.

Mead's resource equation was employed to determine the proper sample number and group distribution for the concrete. Originally, it was intended that 10 specimens would be used to calculate standard deviation (s) and tolerance (r=2.8 x s), providing the representative sample. The resource equation for that scenario read; N - T = E; 10 – 0 = 10. The decision was made to test one group of ten specimens, providing standard deviation and tolerance. Because the material was mixed composite concrete, given to greater variance than a manufactured product, one group of ten specimens was tested. The specimens were subjected to a single modality, flexural measurement using third-point loading. All laboratory activities were performed according to ASTM C78-18 (ASTM 2018) procedures. The same Instron5969 Universal Testing Machine was used.

After thirteen days of curing, the specimens were removed from the solution and allowed to dry for 20 hours. Preparation of the specimens for the extensometer was accomplished through

progressive sanding, and each was measured for its planar area cross-section. The roughness of the surface caused by the nature of the material, regardless of careful preparation, was anticipated to involve possibly extensive lag-inertia values.

The actual test was performed by this researcher, supervised by an expert, at 115 Rhines Hall, in the Lattice Lab, on the University of Florida campus in Gainesville. The date wasJuly 2, 2018; the time, 10:00 a.m. to 6:30 p.m. EDT. The room temperature was 72-73°F with a Relative Humidity of 34-37%. Ten specimens were measured for thickness and width with a digital caliper, across each cross-sectional area, and for length. The compressive, three-point bending technique (TPBT) parameters and method were entered and calibrated through Bluehill3 software into the Instron5969. Appropriate dimensions were entered into the computer, following ASTM D695-15 (ASTM 2015), for each. Compression rate was set at 0.050 in./min. for each; stress and strain were recorded graphically and quantitatively. The compressometer was set at 23.0 mm (0.9062 in.) between two fixed points, and was judged visually, to minimize lag-inertia when specimens were aligned with the compression tool plunger. The Instron5969 provided applied force and displacement measurements for each specimen. All those data were stored in a computer file for each specimen. Values for stress, strain, and Young's Modulus were manually calculated through insertion into equations: $\sigma = P/A$; $\varepsilon = \delta/L$; $E = \sigma/\varepsilon$. Deflection was also calculated for concentrated and uniform loading.

Cementitious Material

The cementitious material was prepared (Tackey-Otoo 2018), following FDOT Section 346 (FDOT 2005) and ASTM C78-18 (ASTM 2018) standards. Slag and Pozzolans (fly ash) compliant with Section 929 requirements was prepared as a cement replacement as specified in Section 346-2.3. (FDOT 2005) The mixtures, whose results are enumerated in the following chapter, were composed of the following proportions:

- Binary A mixture, consisting of 80% Portland cement and 20% fly ash; Binary B mix was also cast, with proportions of 50% Portland cement and 50% slag.
- Another mix, called Ternary A, was cast containing 50% fly ash, 30% Portland cement, and 20% slag.
- The last was the only sample with cement as the admixture. Among the materials tested, it most accurately represented the lowest allowable flexural strength capabilities of FDOT sanctioned cementitious material. This was due to the extent to which polymerized sands were included in the mix.

These values were manually calculated using stress, strain, Young's Modulus, equations: $\sigma = P/A$; $\varepsilon = \delta/L$; $E = \sigma/\varepsilon$. Deflection was also determined in this manner using those data recorded by that researcher. This researcher extrapolated those deflection data into concentrated and uniform loading figures.

Faux Wood

The faux wood was commercially purchased from Home Depot for a price of $109.00, excluding tax, with cross-section dimensions, in channel form, of 2.50 in. X 3.50 in., and a thickness of 0.50 in. X 0.75 in. respectively. The length of the beam was 9.00 ft.-10.00 in. The decorative faux wood beam supplied seven specimens, extracted from a localized area of approximately 2.50 in. X 7.00 in. X 5.00 in. The general dimensions of that area, approximately 1/18 of beam length, were selected to minimize any differences within the polyurethane lattice material.

Mead's resource equation was employed to determine the proper sample number and group distribution for the faux wood. Originally, it was intended that 10 specimens would be used to calculate standard deviation (s) and tolerance (r=2.8 x s); providing the representative sample. The resource equation for that scenario read: N - T = E; 10 – 0 = 10. The decision was that one group of seven specimens was to be used, providing standard deviation and tolerance. The determination was made that this number would be sufficient due to utilization of only a

singular modality, compressive measurement (T), on the Instron5969 Universal Testing Machine. The specimens were cut with an Exacto knife and close quarters hacksaw, and then dimensioned through progressive sanding. Each was measured for its planar area cross-section. These values were manually calculated using stress, strain, Young's Modulus, equations: $\sigma = P/A$; $\varepsilon = \delta/L$; $E = \sigma/\varepsilon$. Deflection was also determined.

The actual test was performed by this researcher, supervised by an expert, at 115 Rhines Hall, in the Lattice Lab, on June 8, 2018 from 9:00 am to 10:00 am EDT. The room temperature was 72-73°F with a Relative Humidity of 34-37%. Seven specimens were caliper-measured for thickness and width, across each cross-sectional area, and for length. The compressive, three-point parameters and method were entered and calibrated through the Bluehill3 software on the Universal Testing Machine. Appropriate dimensions were entered into the computer, following ASTM D695-15 (ASTM 2015), for each. The Instron machine provided applied force and displacement measurements for each specimen. The compressometer was set at 23.0 mm (0.906 in.), between two fixed points, judged visually, to minimize lag-inertia when specimens were aligned with the compression tool plunger. Compression rate was set at 0.050 in./min. for each, with stress and strain recorded graphically and quantitatively. All those data were stored in a computer file for each specimen.

Contour Crafting

The Contour Crafting process was utilized to generate cost information, in general terms, because specifics were proprietary. Still, sufficient textual sources did exist to provide accurate background to simulate volumetric values needed to construct a simple structure. This process would entail a Contour Crafting gantry depositing amalgam or molten polymer to create walls in three layers: 1) interior face 2) the core and 3) exterior face. It is important to note that a polymer extruded from the gantry would possess properties roughly equivalent, if not superior, to

concrete amalgam; dispensed from identical equipment. If weight were added to the list, the ideal properties would closely resemble autoclaved concrete blocks. However, the delivery method for autoclaved cellular construction wouldn't easily fit the gantry model. It would involve a specialty material with its own complicated processing (Kosmatka et al. 2008).

The interior wall was used in this example for the dimensions of 5.00 in. X 10.0 ft. X 10.0 ft. Material takeoffs were included to value the 45° zig-zag core, and the exterior face as well. The illustration below gives an accurate picture of the density generated in the construction process. This Revit structure, created by the author, is not exactly to scale (wall thickness), and excludes depiction of the roof, which is merely another exterior face covering the cube. This was intentional, to graphically illustrate the simplicity of the model, for purposes of comparison. It followed that fenestrations within any surface were omitted.

The scenario by which different extruders for wall construction were set upon the Contour Crafting gantry production reduced the mechanism of delivery to a single variance. The polymer extrusion for the envelope was presumed to have been performed through a machine which had sufficient protection for molten gel tolerance through selection of properly protected trowel material, while the concrete amalgam would have exited the nozzle as a paste. It was further presumed that equipment to place the systems linkages into the wall core would employ the same process in both cases, negating consideration of that minutiae.

CHAPTER 6
RESULTS

Findings were divided into three parts from compressive testing employing a three-point bending technique (TPBT). Stress and strain were measured for concrete, cementitious mixtures, and faux wood. The cementitious sample was tested by a colleague who provided unpublished information (Tackey-Otoo 2018). Concrete and faux wood were subjected to three-point compression, utilizing an Instron5969 Universal Testing Machine. Both tests followed ASTM-appropriate C and D procedures.

Faux Wood Compressive Strength Testing Results per Specimen

Specimen 1 ruptured while secured within the compression tool. This was probably due to operator manipulation of crosshead movement. Initial measurements were being provided by the machinery. It was ascertained that contact force had skewed any values derived from the software and the specimen test was terminated.

Specimen 2 did not settle immediately. This was exhibited through a consistent 0.124 in. displacement from test inception. This figure was subtracted from strain measurements around the yield point. It is important to note that this did not represent an offset; described in ASTM D695-15 (3.2.11). Rather, it was attributed to load inertia-lag, described in ASTM D695-15 (5.1.2). The inflection point was demonstrated, as with all the specimens, quantitatively. Offsets, determined through ASTM procedures graphically chart yield point on a stress-strain curve. Inflection, or yield point, occurred at 205seconds. The force level indicated 12.1 lbs. Displacement indicated was 0.295 in. The inertia-lag was subtracted from that of the yield point figure. The result was 0.171 in. displacement.

Specimen 3 was placed incorrectly upon the compression tool base. The consequent imbalance, caused when the plunger descended, ruptured the specimen.

Specimen 4 was loaded according to procedure. Inertia-lag was virtually nonexistent at minus-0.006 in. Inflection occurred at 270seconds, with 22.1 lbs. of force, and 0.2190 in. displacement. Inertia-lag was subtracted. The result was 0.217 in. displacement.

Specimen 5 loaded with the most substantial amount of 0.435 in. inertia-lag, and spoiled. The operator had not adjusted the parameter setting in Bluehill3. This feature of the software determined the level of each measurement, depending upon the desired information from the test. The operator also had not checked the parameter of loading speed. Thus, the rate of loading was accelerated by default. If any parameters for any specimen were not set, they would default to a preset value. The default displacement had been set to terminate the crosshead movement at 0.50 in. Therefore, the attempt to complete testing this specimen ended when displacement quickly reached 0.50 in.

Specimen 6 loaded with the substantial amount of 0.455 in. inertia-lag. The error that had occurred with the prior specimen had yet to be discovered. In this instance as well, the operator had not adjusted the parameter setting in Bluehill3. The rate of loading was accelerated by default. The default displacement was set to terminate the crosshead movement at 0.50 in. However, the crosshead fell too quickly. This was the cause of the rupture that terminated the test.

Specimen 7 loaded with a very satisfactory lag-inertia of zero. Inflection occurred at 212 seconds, with 0.176 in. displacement, and 13.2 lbs. of force. The specimen ruptured at this maximum loading. Inertia-lag was subtracted. The result was 0.176 in. displacement. Analysis showed there had undoubtedly been problems with setting of the compressometer, and the technique of accurately placing the specimens. Furthermore, constant repetition in resetting parameters through Bluehill3 was also lacking. The discrepancy in findings, especially of

Young's Modulus values, were almost certainly due to a combination of these factors. The values derived from compressive testing are listed in tabular form below.

Concrete Compressive Strength Testing Results per Specimen

- Specimen 1 loaded with substantial lag-inertia of 0.232 in. Displacement at rupture was 0.253 in. at 102.5 lbs. of applied force.
- Specimen 2 loaded well. It experienced lag-inertia of 0.009 in. Displacement at rupture was 0.026 in. at 170lbs.
- Specimen 3 was loaded improperly and experienced lag-inertia of -0.036 in. This was due to the coarseness of the specimen. The resultant slippage within the compressor tool caused continued negative displacement, causing rupture at -0.011 in. at 54.0 lbs.
- Specimen 4 loaded with a reasonable lag-inertia of 0.122 in. Displacement at rupture was 0.148 at 1083lbs.
- Specimen 5 experienced a large lag-inertia of 0.441 in. Displacement at rupture was 0.453 in. at 812lbs.
- Specimen 6 loaded slowly with lag-inertia of 0.128 in. Displacement at rupture was 0.138 in. at 67.4 lbs.
- Specimen 7 experienced a similarity in lag-inertia to Specimen 5, at 0.437 in. Displacement at rupture was 0.453 in. at 528lbs.
- Specimen 8 was unable to load into the compression tool properly due to unacceptable coarseness. Therefore, the stress-strain curve was too inaccurate.
- Specimen 9 loaded promptly at 0.010 in. Displacement at rupture was 0.319 at 139lbs.
- Specimen 10 results were inaccurate because the right end of the specimen had crumbled, causing deformation that excluded placement into the compression tool.

These measurements, summarized in Table 6-1, clearly demonstrate the axiom that concrete's stiffness will resist application of a uniform force more effectively than concentrated loading. This is because concrete possesses a substantial Young's Modulus but limited flexural properties. Cementitious material also exhibits this trait. The polymer, on the other hand, will possess a more limited modulus of elasticity, so uniform loading resistance will be less than that

of concentrated loading. More discussion of these features will follow in the Conclusions chapter.

[(5”) X (10’) X (10’) X (4 walls)] + [(5”) X (10’) X (2’ sin (45°)) X (28 panels)] + [(5”) X (10’) X (11.42’) X (5 walls)] > [(0.4167’) X (10’) X (10’) X (4)] + [(0.4167’) X (1.4141’) X (28)] + [(0.4167’) X (10’) X (11.420’) X (5)] > [166.68 ft^3] + [164.98 ft^3] + [237.94 ft^3] = **<u>569.60 ft^3</u>**

Figure 6-1. Calculations for polymer gel and concrete amalgam volumes.

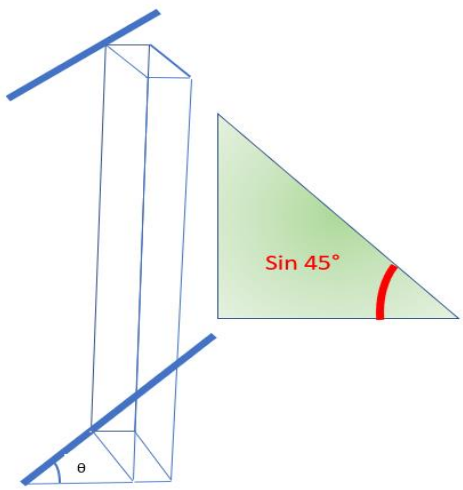


Figure 6-2. Core wall unit construction.

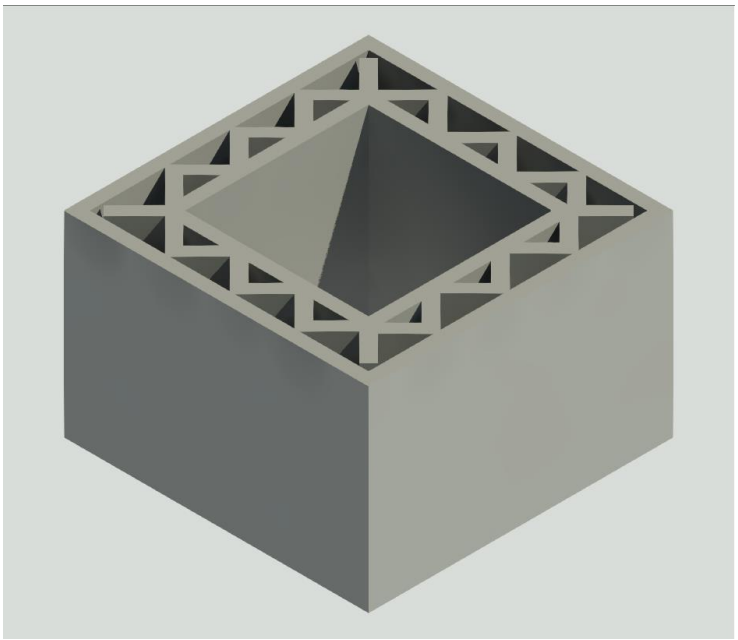


Figure 6-3. Revit image created by author.

	Faux Wood*	Concrete	Comparative Ratio
Young's Modulus (E)	2,280,000psi*	2,500,000psi**	Polymer (10:11)
Tensile Strength (F_b)	7860psi*	300psi**	Polymer (26:1)

* *structural composite lumber (Janowiak et al. 2000)*
** *commonly accepted properties*

Figure 6-4. Expected physical properties of structural faux wood and concrete.

	Unit Cost	Quantity	COST
Concrete Amalgam (ft^3)	$30.00	569.6	$17,088
Plastic Gel (ft^3) *	$67.00	569.6	$38,163

* Polymer-Sigma Aldrich

Figure 6-5. Unit cost comparison between generic concrete amalgam and a given structural polymer, ordered from Sigma-Aldrich. This was purposely done to highlight the costs and benefits of infrastructural support.

Table 6-1. Summary of materials properties.

Concrete Specimen #/Area (sq. in.)	w=P=V (lbs.)	Flexural Strength (3V)(d)/(2A)(t_{avg}^2) Modulus of Rupture (σ_s) (lbs./sq. in.)	Young's Modulus σ/ε (lbs./sq.in.)	Deflection $\frac{5wL^4}{384EI}$ (in.) *	Deflection $\frac{PL^3}{48EI}$ (in.) **	L (in.)	Strain ε = δ/L (in./in.)	W @ Fx (in.)	(t) (in.)
1/1.99	102	77.6 SQ	408NCD	0.36	0.28	2.03	0.13	1.97	0.98
2/1.99	171	114 SQ	6614NCD	0.03	0.03	2.00	0.01	1.94	1.00
3/1.63	54.0	-	-	-	-	2.00	-	1.94	0.82
4/1.39	1084	2273 SQ	10,371NCD	0.43	0.31	2.00	0.08	1.94	0.70
5/1.07	813	3935 SQ	11,843NCD	0.81	0.56	2.10	0.06	2.03	0.52
6/0.46	67.4	658 ***	2407NCD	0.79	0.56	2.26	0.06	0.78	0.57
7/0.54	528	5856	7369NCD	1.65	1.16	2.05	0.22	1.06	0.50
8/0.50	-	-	-	-	-	-	0.10	-	-
9/0.37	139	2709	23,740NCD	0.21	0.17	1.99	0.02	0.69	0.46
10/0.56	229	1566	7498NCD	-	-	-	0.06	-	0.64
Binary (A/28)/16.0	3728	723	2,716,000 (cylinder data)	0.023	0.017	12.0	0.002	4.00	4.00
Binary (B/3)/16.0	2830	549	-	-	-	12.0	NSD	4.00	4.00
Ternary (A/28)16.0	1668	323	-	-	-	12.0	NSD	4.00	4.00
FW2/ 0.21	12.0	1335	677NCD	1.16	1.25	1.35	0.08	0.56	0.25
FW4/ 0.20	22.0	1276	770NCD	0.96	1.02	1.50	0.15	0.55	0.35
FW7/ 0.18	13.1	847	590NCD	0.63	0.67	1.44	0.12	0.51	0.36

*Uniform Load Presumed **Third-Point Load Tested NCD=Non- Cylinder Data NSD=No Strain Data FW=Faux Wood SQ=Square and Planar ***Most Uniform Beam (No Ridge)

CHAPTER 7
LIMITATIONS AND SUGGESTED FURTHER RESEARCH

In this analysis, many topics have been excluded, or simplified. Pursuing them would serve no important function. Avoidance of complexity has been the rule regarding materials and structural issues. The methodology has been to examine a large complex topic through hypotheses of more limited nature. The intention has been to break the main hypothesis into smaller pieces to aid in analysis. This has been achieved through utilization of elements that promote clarity in multifaceted situations, culminating in illumination of specific context by extrapolation into broader themes. It has also been necessary to curtail addressing peripheral components that detract from essentials. An attempt to define political players was necessary, though minimization of such commentary was exercised as much as possible. The intent was not to ignore such a pivotal influence. Instead, a stance against obfuscation has been assumed. Scenarios depicting tectonics between striving brokers of opinion were avoided, while an effort was made to accurately portray the goals of those actors.

Returning to the main question, large-scale replacement of structural concrete with polymers would be somewhat paradoxical. The progression would first entail a relatively straightforward chemistry problem. There is little doubt that, in relative terms, obtaining those properties would be employed via the simple recourse of ordering the material from manufacturing and distribution giants. Sigma-Aldrich has been used, in that role, for comparison of unit costs. Furthermore, it was determined that intricate laboratory testing of the exact compounds was extraneous, if not impossible.

Far more mysterious would be the means and ways in which consensus in the construction industry, and society, could embrace such a solution. It has been asserted that cultural attachment to traditional building habits are very specifically marked, having

institutionalized social and economic relationships over the past few hundred years. Change of supply and transportation infrastructure, contractual provisions, and labor organization will be just a few of the targets of innovation. Specific transitional achievements will provide a fertile field for potential study.

A cultural learning curve would entail familiarity with these types of issues in people's daily lives. That process is in its infancy, as evidenced by the impatience of advocates. Solutions and processes will evolve as variations are adopted, often through singular experimentation. Individual choices will be judged according to effectiveness. Opinions of enlightened or regressive behavior should evolve from this experimentation. Therefore, examination of progressive development of current building trends in polymer housing over the long-term could be very useful in identification of emerging societal attitudes. Monitoring of public discourse will also be important, to evaluate the relative proportion of plans based on political, rather than empirical, information.

It would be valuable to monitor correlative labor aspects of structural plastics. Will resources and personnel be committed to creation of large scale recycling? Will there be measurable indications of synergy between producers, constructors and recyclers? Could extensive use of repetitive, and streamlined re-sourcing processes be identified? Is there a growing shift of emphasis in labor deployment towards recycled deliverables, and, if so, at what rate? Are transitional paradigms in allocation of personnel and resources present at all? At any given time, where could the current situation be placed within the beta curve of technological innovation? In short, study of the multifarious progression of polymer use as a structural material will prove a very potent tool for monitoring transition.

Creation and extension of recycling infrastructure is already on the drawing board. Institutional support for these projects has been given by many governmental organizations and private parties. Re-sourcing parameters are becoming integrated into the text of standards and certification organizations, such as LEED, ANSI and the ISO. Protocols and documentation aimed at regularizing embodied energy feedback, Environmental and Health Product Declarations, Chemical Abstract Service Registration, extended producer responsibility programs, and many others, are continuously being fine-tuned.

Another topic marginally dealt with in this study was Contour Crafting. By necessity, only a few points about this exciting delivery method were highlighted. Propriety restrictions upon operational specifics also accounted for the limited treatment. Still, there will be ample research possibilities as automation technology expands, such as exploration of the extruded polymer gel's character. A case for use of semi-crystalline block thermoplastic in the Contour Crafting process would depend upon heat transfer properties.

The material envisioned by this paper would have to be strong enough to support its own weight, but malleable enough to combine with prior layers. This problem is common to 3D printing – plastic (ABS) extrusion consistency is dependent upon control of temperature variation from the hot base of the model to the progressively cooler layers above. Such research is now pursued by a proliferation of companies. A firm called Celanese has experimented with injection of Boron Nitrate into polymers (Celanese 2018). This strategy would be less than ideal in terms of recycling. Considerable benefit could be derived from ascertaining whether the cooling gel could hold adequate compressive force, without doping.

CHAPTER 8
CONCLUSIONS

The author of this thesis has chosen to present the main hypothesis, a general prejudice against plastics in favor of concrete as a structural material, through the spectrum of limited proofs. The properties of widely marketed faux wood beams has been shown to confirm, to whatever degree, that polymer stability is widely dismissed. An argument with many limitations could be made that this quality determines infrastructure of its supply. The proposition may be asserted that this is a self-fulfilling prophecy. Plastics are flimsy because most of its manufacture is driven by decorative or accessory purposes. Demand must be satisfied because consumers value facile, throw-away items. This situation closely resembles the kind depicted by Peter Norton (2008) in his book "Fighting Traffic." One of Norton's objectives was to explore initial reasoning and influences behind paving decisions for constructing America's road system. The emergence of cement was the result of similar, cyclical, logic.

Testing a sample of repeating unit polyurethane exhibited the representative lack of structural capabilities attributed to plastics. The Young's Modulus of the faux wood sample hovered around 0.676×10^4 lbs./sq. in. Although that test made use of a beam shape, instead of a cylinder, the modulus of elasticity for that material would not significantly improve. Exaggerated deflection would only be replaced by excessive bowing off the centerline. Polymer lumber guardrails, that were not selected for decorative qualities, were likewise examined using test figures generated by a Colorado DOT study (Janowiak 2000). Young's Modulus was regularly recorded around 2.8×10^6 lbs./sq.in. Cementitious binary material was proven more than adequate to be used within the FDOT bridge pier pultrusion profile sections. The mixture of 20% fly ash and 80% Portland cement with a Young's Modulus of 2.7×10^6 lbs./sq.in. could just as easily have been a 50%-50% mix between slag and Portland cement. In fact, FDOT Section 346-

2.3 allowed for such a mix, with 62% slag in drilled holes. This indicated the agency considered highly polymerized mixtures equivalent. It was shown that the public sector often used structural plastics, and would increasingly do so, in place of metal and concrete. The intention of hypothesizing and studying the results of these limited questions was to demonstrate that they were not random or isolated, but constituted progressive usage of structural plastics in the public sector. Private sector choices vastly deviated from the pattern. This dichotomy was further emphasized by compressive testing which demonstrated that polyurethane was conceivable to most casual observers, as only a covering for concrete or steel members. In fact, it often goes unnoticed that bowling balls are composed of highly semi-crystalline polyurethane and smash into pins and alleys. Still, though bowling balls are ubiquitious, these structural properties are not generally valued.

Connection of Uniform Loading with Deformation

While analyzing polyurethane faux wood , cementitious materials and #89 aggregate concrete, certain facts emerged. At first glance, the deflection of the decorative faux wood seemed to totally dismiss consideration of any structural value. However, a recurrent theme of this research has been to encourage imaginative thinking for conventional materials. This polyurethane covering exposed the property of deflection, a factor worthy of a second look. In discovering the true meaning of marked lateral displacement exhibited by decorative faux wood, Contour Crafting could be pondered. This automated, sustainability-oriented, building method has been extensively utilized in this study as a tool of comparison. The central feature of delivery is extrusion of a structural paste or gel, from its computer-guided gantry. This process has the effect of creating an exterior envelope composed of layer after layer of uniformly loaded beams. Furthermore, that dynamic increases pressure on the lower layers of product, exacerbated by the

relative weight of the extrusion material chosen. As may be recalled from the Literature Review this was an issue in Michael Hansmeyer's vision of his plastic, 3D printed column. The architect believed a light material was necessary to provide essential malleability, while maintaining sufficient stiffness. Hansmeyer applied the logic of 3D printing, where lower levels of extruded plastic are subjected to increased forces. In printing, the resulting material stresses arise from thermal properties, the heat of dispensed gel collecting at the base of the model. In gantry extrusion, stresses result from cumulative resistance to application of uniform weight. In both cases, a means should be developed to avoid such deflection, pulling at each corner of the wall structure. This situation could create severe structural problems for a home extruded by Contour Crafting. It will be recalled from the revit model that 45° corners abound in that case, with zig-zag cores enclosed by interior and exterior walls. The bench scenario from the Problem Statement described the same reinforcement situation. The question was whether bench material possessed sufficient deflection and associated internal displacement. If not, what measures would be necessary to achieve that support?

There is an equation which joins all these elements, $\delta = \frac{5wL^4}{384EI}$. The tables at the end of the Results Chapter contained a similar expression, $\frac{PL^3}{48EI}$. Beams will experience various loading factors. A dead load of constant force along the entire length would be represented by the w in the first equation; a point load, on a spot, would be indicated by P, in the latter. So, deflection presents the key to understanding qualities of performance of polymer , cementitious materials and concrete extruded by Contour Crafting nozzles.

It would be advantageous at this point to put two concepts together. It has been established that requisite stiffness is present in semi-crystalline lattices, with application of proper heat treatment. Propagation can be controlled by the rate of introduction of the catalyst,

insuring sufficient amorphous chains form to acquire the deflection properties possessed by decorative polyurethane. Concrete and cementitious materials composite does not exhibit nearly enough deflection, without failing, as performances of the test specimens confirmed. This was further demonstrated by the axiomatic inverse relationship between the reaction of the respective materials to concentrated and uniform loading. Essentially, the concrete and cementitious materials can counter applied force with accumulation of uniform stress because they are much more rigid. Therefore, they also exhibited weaker resistance to deflection under these loading conditions, caused by the increased rigidity when confronted with uniform force. Lack of deflection along the entire beam, due to this uniform resistance, will eventually cause stresses at the corners, cracking and failure. Polymers greater flexural qualities in response to this type of force application indicates a superior ability of walls constructed of that material to deflect, instead of crack, in a Contour Crafting home.

Therefore, concrete amalgam must assume a largely cementitious mix proportion in the Contour Crafting process to approach those polyurethane flexural capabilities. The figures obtained from the binary mixture established this fact by demonstrating the same characteristics, vis-à-vis uniform loading stiffness and concentrated flexural capacity, as concrete. Thus, the limited hypothesis that cementitious material is nothing more than a compromise that perpetuates concrete's dominance was proven in this detailed circumstance.

Regarding polyurethane, the brief stable linear relationship of stress and strain in compression, as demonstrated in this research, could be extended with a different proportion of crystallization within the same material. Such a foam would increase in density, as with bowling balls, without a prohibitive rise in overall weight. The actual constitution of that material would depend upon the scope of construction. Certainly, in a structural sense, this material would

substantially resemble the faux lumber of the Colorado guardrails, or the bridge planks at the University of Florida. The exact chemistry would need further research than was possible in this investigation. The result, though, would also be axiomatic due to properties so often discussed in this study. Once gel composition was determined, information detailing the specific rate of molten extrusion could be programmed into the computer, controlling the dispensing nozzle on the Contour Crafting gantry. The software will already have modeled the condition of extrusion to guarantee positive results. Thus, the limited hypothesis that molten polymer gel used in a structural role is at least as efficient as concrete amalgam and cementitious material, when dispensed through a sustainable automated delivery process, is likewise proven.

It may be reasonably extrapolated from those data that the decision to use concrete amalgam doped with cementitious elements as the central feature in Contour Crafting was influenced by something other than the scientific method. This further extrapolation would necessarily pass into the realm of the unprovable hypothesis in this research, the specific nature of multifaceted and complex societal decisions.

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BIOGRAPHICAL SKETCH

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