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Perspectives in architected infrastructure materials

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Abstract

This paper presents perspectives and progress in the emerging field of architected infrastructure materials. Recent developments in advanced and additive manufacturing with construction materials have led to new capabilities to define, design, and shape the internal arrangement and overall morphology of materials. In contrast to conventional casting techniques used in the construction of civil engineering materials, such advancements have allowed for purposeful designs of materials into specific morphologies across scales, referred to as architected infrastructure materials. Contrary to monolithic construction materials, architected materials present new opportunities to engineer enhanced mechanical properties and unique performance characteristics in civil infrastructure components through design. Here, we present an overview of the field and the research gaps in design, manufacturing, and materials mechanics. An overview of a few design opportunities, including bio-inspired strategies is discussed. Current advancements in the field are presented focusing on cement-based, non-hydraulic, and cementitious composite architected materials. The existing studies on bouligand, cellular, lattice, auxetic, tabulated, and gradient architected construction materials and their mechanically advantageous characteristics are reviewed. The future directions and perspectives for the field are outlined with respect to the current research gaps and upcoming opportunities.

Keywords: Architected materials; Design; Fracture; Additive manufacturing; Bio-inspired; Concrete 3D-printing

1 Introduction

In the face of climate change [1–3], growing world population [4,5], and decaying infrastructure [6], there is a need to develop or restore stronger, tougher, more resilient, and more ecologically efficient infrastructure materials. In this context, developing construction materials with enhanced mechanical performance and damage-resistant characteristics for applications in civil infrastructure components can play a key role where consideration of resilience in designs is becoming more necessary [7].

Recent progress in Additive Manufacturing (AM) has led to new capabilities to define, design, and shape the internal arrangement of materials [8] or topological formation [9,10]. Such advancements have allowed for purposeful design of materials into specific morphologies across scales, henceforth referred to as architected infrastructure materials [8]. Contrary to monolithic construction materials and structures, architected materials present new opportunities to imbue enhanced mechanical properties into civil infrastructure components by design [11,12].

From a material science perspective, the ways in which a material is processed influence its microstructure, which then determines the resulting properties and performances (Fig. 1a). On the other hand, advanced manufacturing capabilities can help actively engineer a desired design feature into a material at a scale larger than the microstructural scale (Fig. 1a). Thus, a new degree of freedom can be defined to achieve certain structures and control the associated mechanical properties and performances (Fig. 1a).

As such, an integrated manufacturing–design–mechanics approach may be necessary to engineer mechanical response of conventionally brittle and quasi-brittle construction materials (such as paste, mortar, and concrete) with attributes including enhanced ductility, greater energy absorption, and higher fracture toughness (resistance to cracking) (Fig. 1b). This can introduce (a scalable) structural resiliency at the material level that cannot be readily obtained with current design and manufacturing methods.

As demonstrated in Fig.1b, conventional construction materials such as cementitious paste, mortar, and concrete represent a brittle or quasi-brittle response under tension [13]. However, such a response can fundamentally be altered into a quasi-brittle or ductile one by exploiting the design of materials architecture at the meso (mm-cm) scale. At a larger structural (m) scale, enhanced load-bearing capacity and resistance to damage under tension and bending can promote longer service life and reduce the need for reinforcement while allowing for new structural design of concrete besides the common reliance on compression.

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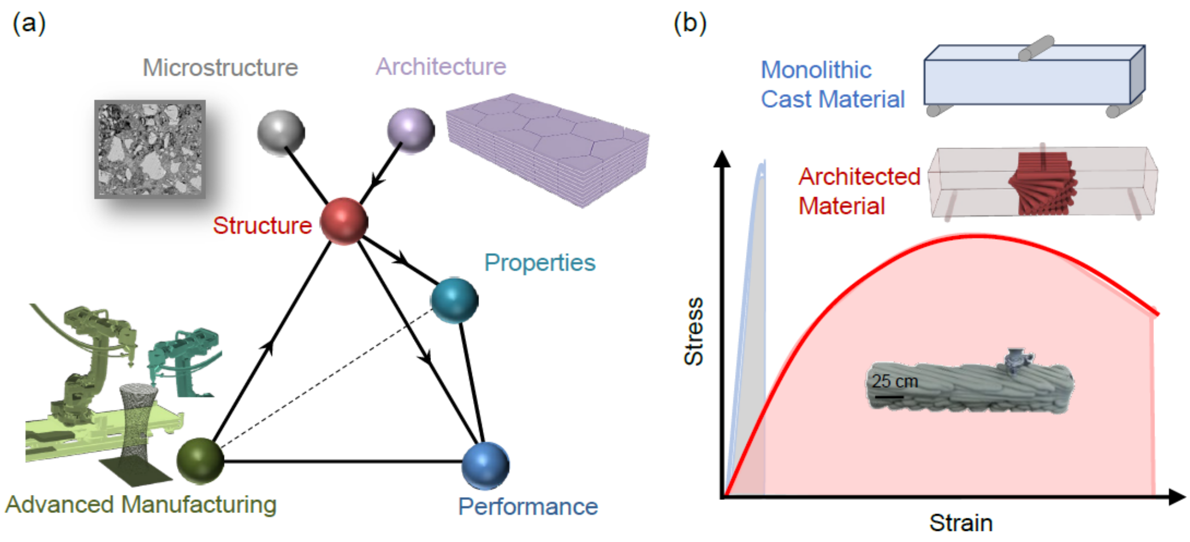


Fig. 1. (a) Material science tetrahedron whereby advanced manufacturing processes can help purposefully control the materials' architecture through the design of internal arrangements and improve mechanical properties and performance, where (b) Architected materials can help engineer unique mechanical responses, compared to the typical responses of brittle construction materials.

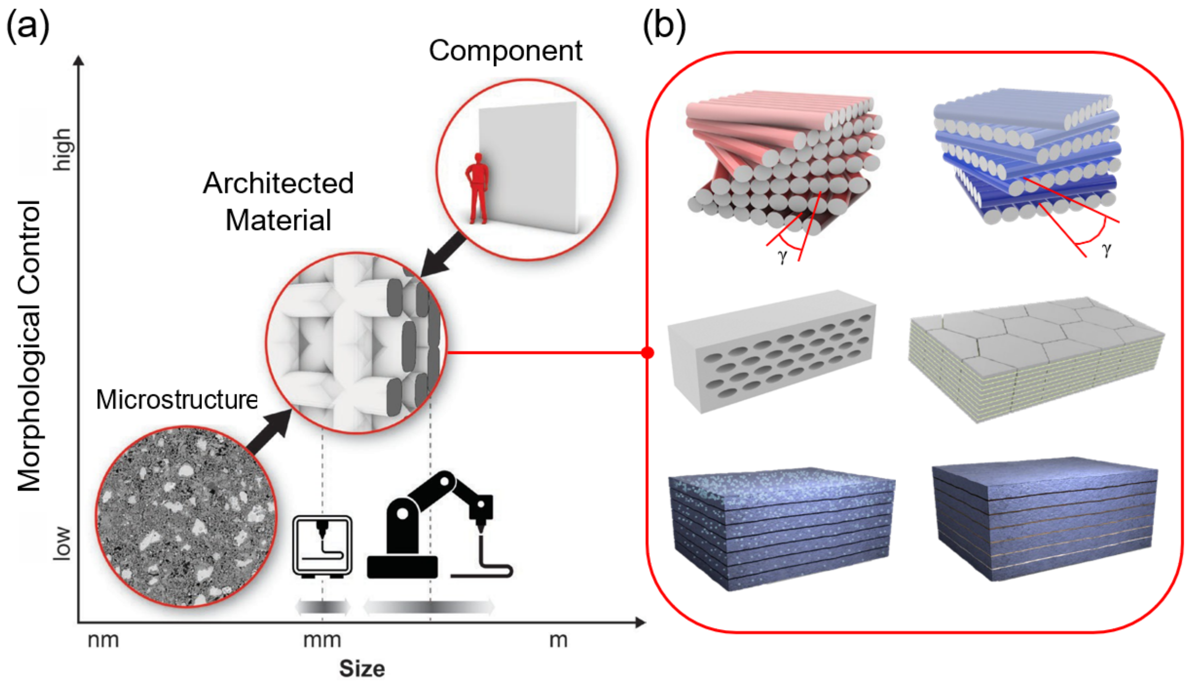


Fig. 2. (a) Morphological control vs. size in the microstructure, architected materials, and infrastructure component level (modified from [16]) and (b) conceptual examples of architected materials including helical and double-helical (top), tubular and brick-and-mortar (middle), and functionally graded materials with compositional control over materials and interface (bottom).

2 Research gap

Design, manufacturing, and fracture mechanics are three related main components of the field of architected construction material that must be considered in assessing the current and future states.

First, the design of civil engineering concrete materials has been constrained by limitations in the material properties and the construction methods. From a materials perspective, little morphological or spatial control exists [14,15] in the microstructural nm-μm scale (Fig. 2a). From a structural perspective, rather high morphological or spatial control can be possible using casting methods, though only at large (m) scale and over bulk topology of the components at the cost of bespoke formwork (Fig. 2a). As a result, the casting construction technologies, mainly due to formwork cost, are constrained in designing bespoke topologies. On the other hand, control of the morphological and spatial arrangement of materials at a meso scale (mm-cm) between the microstructural and structural scale, has only recently been made possible due to advancements in additive manufacturing with construction materials (Fig. 2a). This enabled defining architected materials at a meso scale using digitally automated techniques with a lower barrier to adoption, where a variety of features can be introduced in design and manufacturing process. As a result, numerous opportunities present themselves for designing and deploying architected materials at the meso scale, each with unique performance characteristics (Fig. 2b). For example, by controlling the local arrangement of the materials composition in three dimensions such as in helical, double-helical, tubular, brick-and-mortar, and functionally graded materials and interfaces (Fig. 2b), control of bulk mechanical properties can be enabled in infrastructure components.

Second, the current trend in the growing field of AM with concrete and other brittle and quasi-brittle construction materials has mainly focused on producing potentially low-cost walls for single or multi-story housing, huts, shelters, tanks, and other rectilinear shapes in meter scale, relying mostly on the compression-only design for gravity load, an approach that is similar to cast concrete or masonry walls [17,18]. To date, cost-saving measures and reduced labor expenses are claimed to be the drivers in concrete AM [19,20]. However, from a research and development perspective, the innovation in concrete AM has, to some extent, disregarded harnessing purposeful designs of the internal arrangement of materials in three dimensions. For example, very few works have been recently initiated to take advantage of the design freedom provided by AM that facilitates the deliberate generation of mechanically desirable assemblies of materials at the architecture level [21–28]. Although AM technology can be disruptive, its opportunities have been rather underutilized in research and infrastructure development to date.

Third, unreinforced cementitious (paste, mortar, and concrete) materials, similar to other construction materials counterparts, commonly fail under tension in a brittle and quasi-brittle fashion. Failure under tension in unreinforced concrete material can become the root of the structural collapse [29] or driver of using fiber- and steel-reinforced concrete. Yet, even in monolithic structures where principal stresses are generally compressive, the local tensile stresses can result in cracking and potential failure [13]. In the design of conventional (i.e., non-fiber/steel-reinforced) cementitious materials and structures, the tensile strength is often neglected, which has prevented the efficient use of materials for many years [13].

Improvements in the inherent low fracture toughness (resistance to cracking) of brittle and quasi-brittle construction materials, such as concrete, and transition to more ductile and crack-resistance ones, have been of keen fundamental interest to some researchers [13]. This can be of significant interest to both concrete and additive manufacturing communities, especially as we find new ways to manufacture, design, and engineer the internal arrangement of construction materials.

Besides steel reinforcement, the development of tough and ductile conventional concrete materials has mostly been achieved through altering materials composition and microstructure (e.g., the addition of fibers) [30]. The mechanical response of conventional concrete under tension represents a strain-softening behavior due to the lack of significant toughening mechanisms beyond the commonly known phenomena, including aggregate bridging, microcracking, localization of smaller cracks into larger ones (ahead of the crack tip), and aggregate interlocking (behind the crack tip) [29,31,32]. This lack of other significant toughening mechanisms takes away from tensile load-bearing capacities and imposes the conventional reliance on compressive properties of concrete and sub-optimal designs where tensile capacities are considered minimal [13]. This ultimately limits the overall structural design possibilities and efficient use of materials in structural unreinforced or reinforced concrete [13]. There is a great potential for revisiting brittle and quasi-brittle failure of cementitious construction material – e.g., commonly seen in diagonal shear, punching failure of concrete [33], pullout, and concrete pipes where failure is dominated by tensile strength [13]. To alter the material response from brittle to quasi-brittle or from quasi-brittle to ductile, significant plastic response and stable crack propagation (beyond crack initiation) must be built into the design to allow for reliance on tensile capacities. This challenging task demands a great deal of innovation within the materials' architecture domain. It can steer us toward expanding the creative landscape for the overall structural design.

Nevertheless, developing a purposeful arrangement of architected materials requires specific design principles. Nature offers abundant solutions from which certain rules can be drawn and specific mechanisms can be utilized for the design process.

3 A bio-inspired strategy towards design of architected materials

Synthetic engineering materials, such as cement-based construction materials typically suffer from mutually exclusive mechanical properties, such as strength and toughness (Fig. 3a). The mutual exclusivity arises from the challenges in simultaneously enhancing two material properties due to the underlying microstructural mechanisms that govern them. On the other hand, nature offers abundant inspirations and design motifs for overcoming the trade-off in mutually exclusive properties and for the challenges of engineering resilient infrastructure materials and structures [34–37] (Fig. 3b). Evolved biological materials, in particular, exhibit elegant combinations of competing mechanical properties, such as strength, toughness, and stiffness [38]. In most cases, these combinations of mechanical properties are achieved in nature using a fairly limited selection of materials, but with geometrically unique purposeful design motifs at the micro and nano scales (Fig. 3b). These architected materials in nature represent biological motifs that are purposeful arrangement of one material and space or combinations of multiple materials [16,39] and give rise to unique combinations of mechanical properties [40].

It must be noted that besides biological functions, design motifs in natural materials can serve a specific mechanical function. The relationship between certain design motifs and corresponding mechanical characteristics is exemplified and depicted in Fig. 3b. For example, the shell of abalone mollusks consists of a specific arrangement of mainly hard and partly soft materials in a layered brick-and-mortar type of architecture, resulting in superior fracture toughness and ductility compared to the hard constituent [38]. Biological materials, therefore, manifest a great outside-the-box approach for rethinking the design of human-made materials, including (quasi)brittle civil infrastructure materials.

Engineering bio-inspired designs have been rapidly pursued and implemented across several engineering materials. For instance, relevant nature-inspired mechanisms have been engineered to improve damage resistance in composites [42,43], enhance energy absorption and damage tolerance in metals [44,45], generate shape-morphing and crashworthiness in polymers [46,47], and improve ductility and impact-resistance in brittle glass [48,49] and brittle ceramics [50,51], all mainly in meso scale architecture level. However, realizing such bio-inspired architected schemes in brittle infrastructure materials is more nascent and requires a foundational understanding of the design rules in each specific architecture and the underlying mechanisms that enable the specific mechanical attribute. As such, it is critical in the bio-inspired design approach to not only mimic the architecture but to aim at engineering the mechanisms (e.g., toughening mechanism) that enable a desired performance characteristic (e.g., high fracture toughness attribute). In other words, merely mimicking natural schemes can lead to the ability to produce enhanced and unique mechanical properties. However, in order to develop high-level design rules and frameworks for engineering synthetic counterparts, attempts in bio-inspired design can concentrate on unraveling the underlying mechanisms that better enable the natural schemes to yield unique mechanical properties. This approach may offer a more insightful direction for future developments.

Numerous cases can be regarded in engineering architected materials using such an approach. For example, one of the underlying mechanisms to enhance damage resilience in natural materials such as tough cortical bone (Fig. 3a) is harnessing weak interfaces that surround the tube-like osteons [52]. Due to the weaker tensile strength, these interfaces provide microstructurally preferred pathways for interaction with a propagating crack, enhancing fracture toughness and preventing brittle failure. Such underlying mechanisms can inspire new mechanically favorable designs into brittle construction materials by engineering tubular geometries or interfaces in the otherwise bulk materials (Fig. 2b). These types of strategies require a fundamental understanding of the fracture mechanics of the newly architected materials. Similarly, abundant examples of layered and gradient materials prevail in biological materials in which weak interfaces are harnessed and play a crucial role in improving crack-resistance and overall mechanical behavior. A linear elastic fracture mechanics (LEFM) approach [53] can be extended to understand fracture in synthetic counterparts inspired by these natural architectures. Researchers have explored the use of LEFM as a basis to understand the role of weak interfaces in the design of brittle cement paste with enhanced fracture toughness [54]. Using LEFM, the condition for interfacial crack propagation vs. penetration into bulk in layered materials can be stated in terms of energy release rate as [55]:

$$\frac{G^{(i)}}{G^{(f)}} > \frac{G^{(i)}{}_{IC}}{G^{(f)}{}_{IC}} \tag{1}$$

where, $G^{(i)}$ and $G^{(f)}$ are energy release rate of interface and bulk and $G^{(i)}{}_{IC}$ and $G^{(f)}{}_{IC}$ are the critical energy release rates for the interface and filament. Depending on the fracture toughness of the interface vs. the material in the case of layered materials, as well as the presence of the elastic mismatch in the case of gradient layered materials, a weak interface can promote crack deflection that may lead to a desirable spread of damage in brittle and quasi-brittle materials.

Nevertheless, in comparison to the growing bio-inspired and bio-mediated theme in engineering infrastructure materials, such as the use of biomolecules and micro-organisms [56,57], a mechanics-based approach to bio-inspired design can guid improvements in the fundamental mechanical properties of the construction material (Fig. 3a) by exploiting advancements in the emerging manufacturing paradigms.

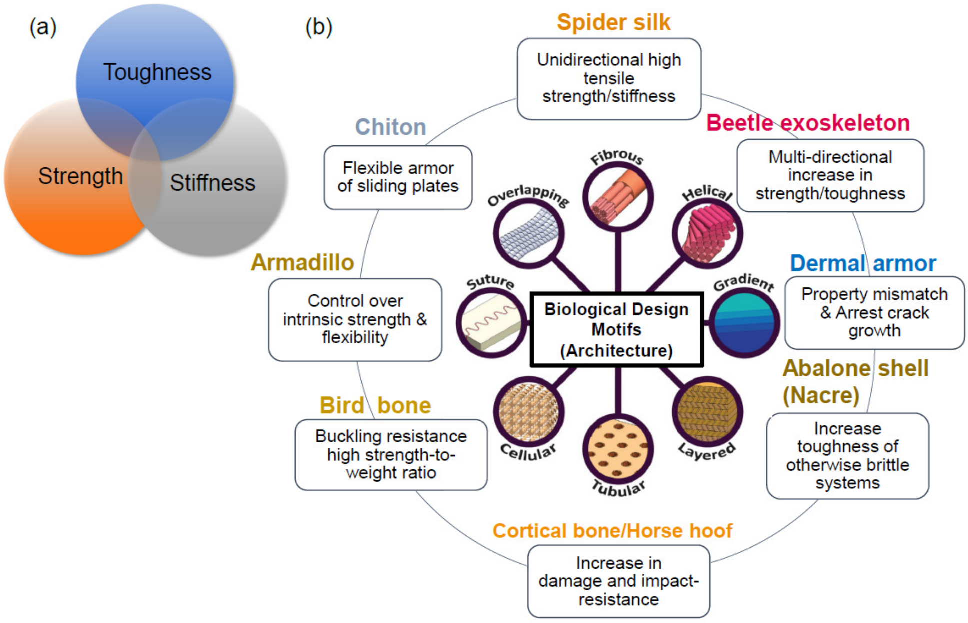


Fig. 3. (a) Competing and often mutually exclusive mechanical properties in engineered materials that are overcome in natural material by considering (b) Abundant design motifs and modest materials, balancing and enhancing certain mechanical properties (reproduced and modified from [41]).

4 Recent progress in the field across construction materials

The progress in the field of architected construction materials in the past decade has largely been motivated by advancements in additive manufacturing across small to large scales [58–64]. This includes advancements in direct extrusion-based methods that facilitate relatively complex designs [65–67], powder-bed techniques that provide three-dimensional control over the morphology [68,69], and hybrid 3D-printing of mold and casting of materials into bespoke geometries that enable alternative solutions to achieve spatial structures [70,71]. Extrusion-based techniques, in comparison to other often complex techniques, owing to their ease of adoption and widespread use across scales, have significantly facilitated the exploration of architected materials, particularly in the realm of cementitious materials (Fig. 4). At a small mm scale, desktop additive manufacturing has facilitated rapid prototyping as a tool and has allowed numerous experimental studies for probing genuine design of materials using cement paste, for instance with honeycomb [8] and sinusoidal architecture [72] (Fig. 4). At the cm scale, the mid-size additive fabrication techniques, have provided larger nozzle sizes, thus has allowed for up-scaling from cement paste to mortar [73] such as those seen with helical and sinusoidal examples (Fig. 4). At the m scale, robotic and gantry-based additive manufacturing methods using a variety of end-effectors, has allowed scaling up and realization of architected materials towards infrastructure components scale [74], for instance in components with helical designs produced using a two-component extrusion technique (Fig. 4) [74,75]. The combination of the ability to probe architected designs across small to large scales (Fig. 2a) can help to study, mature, and develop well-examined architected materials for future deployments.

The progress in the development of architected infrastructure materials can be viewed in various materials, processes, scales, and functions. Here, we focus on three classes of infrastructure materials: cementitious materials, alternative non-ordinary portland cement (OPC) materials, and cementitious composite materials, including reinforcements. A brief review of these classes of materials and the ways in which engineering new designs of materials architectures can enhance mechanical response are highlighted:

4.1 Architected cementitious materials

Several studies have attempted to engineer enhanced mechanical properties into cement-based materials using bouligand (helical) architectures [8] based on the helical microstructure found in the endocuticle of the mantis shrimp dactyl club [76]. In bouligand architecture, a pitch (rotation) angle (γ) is imposed on the orientation of discrete filaments in a selected direction. Past studies have aimed to use the design of bouligand architecture in cementitious material to enhance flexural strength [77], flexural and compressive strength with and without the use of steel fibers [78], impact resistance [79], and toughness (work-of- failure) [8].

More specifically, it has been reported that bouligand design of materials architecture enabled by 3D-printing with cement paste, can enhance toughness (work-of-failure) and resistance to cracking without sacrificing the strength [8]. It was proposed that the weak interfacial zones induced by layer-wise 3D-printing can be harnessed in favor of mechanical properties and be exploited by crack deflection into the interface [80,81]. Characterized by the ball-on-three-ball test method [8], crack deflection into the interface, along with crack twisting in the solid bouligand architecture at a small pitch angle (γ=8°) was reported while the spread of the damage and multiple cracking, was found to take place in cellular bouligand architecture at large pitch angle (γ=45°) (Fig. 5a). These two unique toughening mechanisms gave rise to improved toughness in solid and cellular bouligand architected cementitious material.

In one study, researchers have demonstrated that bouligand architecture with various pitch angles (γ=10°, 20°, 30°) provides additional flexural strength over unidirectionally printed plain (no fibers) cement paste counterparts, when examined in three-point-bending (3PB) in the same orientation they were 3D-printed [78].

In other studies, researchers have reported on the dynamic performance of bouligand architected designs of cementitious mortar enabled by 3D-printing [79]. Using the drop-weight-impact test, materials with and without steel fibers with varying pitch angles (γ=15°, 30°, 45°) were compared against the unidirectional designs (γ=0°) (Fig. 5b). It was found that fiber-reinforced bouligand architecture outperforms unidirectional counterparts in terms of impact duration, peak impact force, and energy absorption [79].

Such enhancement in performance under dynamic loading conditions was attributed to complex cracking phenomena. Using post-mortem micro-CT, mixed-mode cracking in the form of crack deflection, twisting, and branching was found to give rise to toughening mechanisms. Moreover, using fibers contributed to additional energy absorption as it activated crack bridging, given the effective fiber alignment achieved along the toolpath orientation during 3D-printing. Unlike fiber-reinforced samples, the presence of bouligand architecture did not lead to any significant improvements with respect to impact.

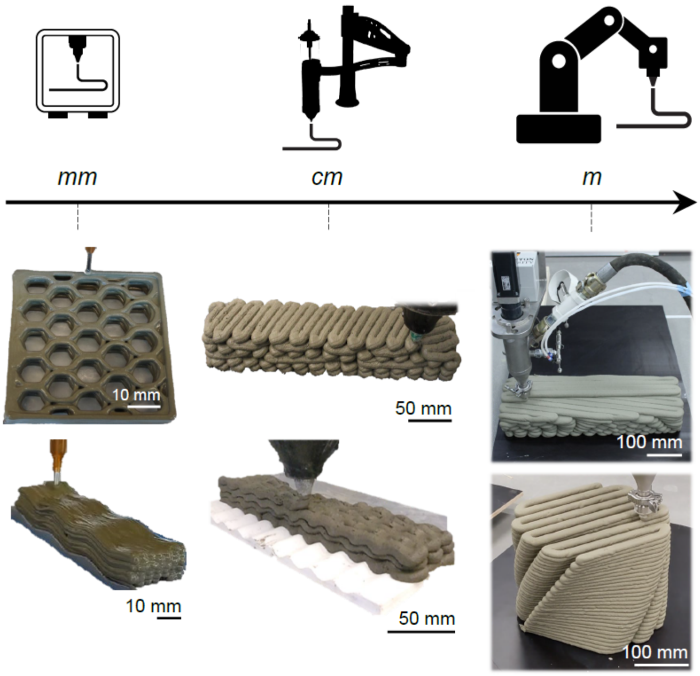


Fig. 4. Additive manufacturing using extrusion techniques across small (left), mid-size (middle), and large (right) scales and the corresponding design examples, demonstrating the utility for the development of architected construction materials.

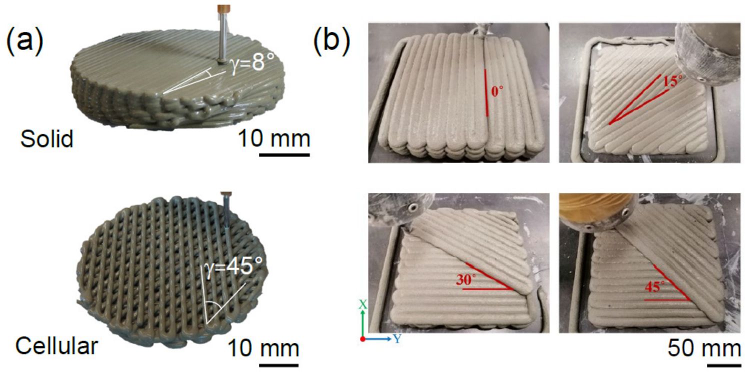


Fig. 5. Bouligand architecture of (a) solid cement paste with a small pitch angle (γ=8°) and cellular cement paste with a large pitch angle (γ=45°)[8], and (b) solid cementitious mortar with small to large pitch angle (γ=8°-45°)[79].

Numerical modeling of the same types of bouligand design of materials with varying pitch angles (γ=15°, 30°, 45°) has been studied in comparison with unidirectional designs (γ=0°) [77]. Comparing the numerical approach with experiments by making use of 3D-printing, researchers have attempted to capture the anisotropic mechanical properties stemming from the helical architecture and understand the associated crack pattern under 3PB loading conditions. More specifically, XFEM was utilized to predict crack patterns. An agreement between the results obtained from the numerical experimental approaches was highlighted. Anisotropy can often be present in some architected materials. Micromechanical modeling was used to analyze anisotropy. More specifically, stress distribution along the depth of bouligand architecture was reported to vary depending on the presence and the magnitude of the pitch angle.

Despite significant progress in understanding the mechanical behavior of bouligand architectures, few studies have focused on the study of the fracture toughness using notched samples such as in single-edge- notch-bend (SENB) test at any scale [82,83]. Only recently, fracture toughness was examined using bouligand architected concrete material by large-scale two-component robotic additive manufacturing [74].

Besides bouligand architecture, cement-based architected materials have been designed and studied in several other arrangements. In one study, researchers have developed tailored cellular architected nano- clay-modified cement paste and have 3D-printed these materials to examine their stiffness and toughness under compression [84] (Fig. 6a). It was demonstrated that using honeycomb architecture leads to non-brittle progressive failure under compression provided by multiple crack pathways for energy absorption within the structure.

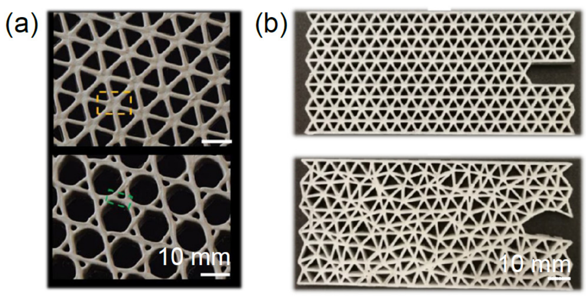


Fig. 6. (a) Architected cellular designs with cement paste [84] and (b) Architected lattice design of regular and randomized schemes with cement paste [85].

Lattice architected cementitious materials (Fig. 6b) have recently been numerically and experimentally studied under tension [85]. A hybrid fabrication process was deployed that utilizes 3D-printing of a negative mold, silicon impregnation, and casting of cement paste. Regular and randomized lattice designs were fabricated and experimentally studied. The macroscopic lattice mechanical response was simulated using a multi-linear behavior for capturing pre-peak cracking and post-peak softening of lattice cement paste materials under tension. The results from the model were then compared against experiments for the regular and randomized lattice, where the former represented slightly higher tensile strength and similar stiffness compared to the latter.

In addition to bouligand and cellular architected cementitious materials, a more specific arrangement of cellular architected cementitious materials, with auxetic behavior, have been studied experimentally for their negative Poisson's ratio under uniaxial compression and cyclic loading [86]. It was found that a negative Poisson's ratio can be obtained in cementitious materials, enabled by the arrangement of elliptical voids in the specimen [87], up to a certain strain above which the Poisson's ratio becomes positive [86].

Strain-hardening was reported under compressive loading, which can lead to higher energy absorption compared to monolithic counterparts [86]. More recently, a three-dimensional auxetic material with a cementitious mortar core and polymeric shell was developed to overcome the brittleness of cementitious constituent and low strength of polymeric constituent that, under uniaxial compression, can similarly provide negative Poisson's ratio [71].

Auxetic architectures have also been studied using numerical and machine-learning approaches [88]. Researchers have extended the study of auxetic cementitious materials, using machine learning approaches where the data is generated using FE simulations with a large number of meso scale design variables, including void volume fraction and aspect ratio. The development of such a strategy aims to frame initial design rules for the realization of architected materials with auxetic behavior.

Similarly, researchers have looked into tubular architecture inspired by weak interface surrounding osteons in cortical bone to engineer crack deflection toughening mechanisms found in the 'cement line' surrounding the osteons in the event of crack propagation [83]. The research has shown how a brittle response in cement paste under 3PB can be tailored toward a non-brittle one by the hardening or softening characteristics stemming from the tubular architecture design [83].

Although the study of the mechanical attributes of bouligand, cellular, auxetic, and tubular designs of cementitious materials has begun, several open questions remain in better understanding of the design-performance relationships at the small and large scales. Addressing the questions embedded in these fundamental relationships remains in the development of experimental and numerical frameworks for the study of the anisotropic and non-linear fracture response.

4.2 Architected non-OPC materials

The development of architected construction materials has not remained limited to cement-based binders. Researchers have used a direct-ink-writing (DIW) method to fabricate SiC whisker/geopolymer composites [89]. Relatively high concentrations of whiskers (3 wt.%) were used to enhance the yield stress in developing a 3D-printable ink, compared to a neat geopolymer ink. The design of materials architecture was then explored by investigating 3D-printed cellular disk samples with pitch angles ranging from γ=15° to 90° (Fig. 7) under flexure and compression compared to monolithic cast counterparts. It was found that higher pitch angles (γ=90°, 60°) outperform the smaller ones (γ=45°, 15°) and the cast counterparts in terms of work-of-failure or the overall energy absorption under compression. This work reports on the advantages of higher energy absorption using helical design of materials architecture in brittle geopolymer materials, similar to what has been reported for brittle cement paste [8].

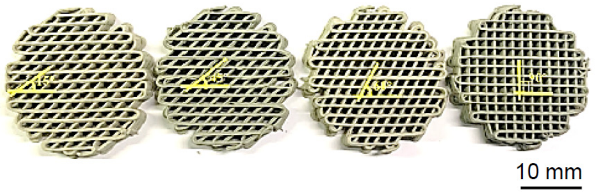


Fig. 7. SiC composite materials with bouligand architecture (pitch angle γ=15° to 90°) [89].

MgO binders gain strength mainly through a carbonation process. Researchers have exploited the design of MgO-based materials architecture to promote strength development [90]. By tailoring the materials' rheological properties and developing a 3D-printable ink, the design of the cellular architecture with intentional void space (Fig. 8) was enabled for the examination of carbonation and compressive strength. It was found that increased surface area induced by the design of materials and porosity, hypothesized to be induced by the early water evaporation, can improve both early (3-days) and mature (28-days) compressive strength compared to conventionally cast counterparts. As a result, it was hypothesized that the CO_2 intake could be enhanced by further engineering the architected porosity and the microstructural porosity due to the loss of water during the stages of hardening.

Fig. 8. Architected MgO binders with cellular and solid architecture [90].

In other studies, researchers have used calcium-silicate cement (CSC) binders (e.g., wollastonite/pseudo-wollastonite) and attempted to design cellular architecture as a strategy to improve the degree of carbonation, carbonation depth, and flexural strength [91]. Besides post-printing carbonation, in-situ carbonation was also considered during additive manufacturing to promote early carbonation reaction. It was found that 3D-printing cellular designs can enhance flexural strength by 168% compared to the solid conventional cast carbonated counterparts.

While a few non-OPC binders, including low-lime cement [92] and magnesia-based cement [93,94] have been explored for improvement of carbonation and mechanical properties, other opportunities remain to enhance solidification in several other binders, such as geopolymers [95] and LC3 cement [96]. Additive manufacturing hydraulic and non-hydraulic binders can be used to design materials architecture and overcome material-specific bottlenecks regarding solidification kinetics, strength, and durability.

4.3 Architected cementitious composites

Beyond studying and engineering the mechanical response of a single construction material, researchers have attempted to develop novel architected materials using a secondary material, commonly as reinforcement.

A few studies have attempted to tailor the microstructure of cementitious composites to mimic brick-and-mortar architecture [24,97,98]. By adding steel reinforcement or fiber mesh [24], researchers have aimed to increase energy absorption or strength. Researchers have used the layering method with perforated PVC membrane between fiber-reinforced engineered cementitious composite layers to increase flexural strength and load-bearing capacity [97], have incorporated polymeric (polypropylene, polyester) mesh between layers of fiber-reinforced cementitious material to enhance compressive and flexural strength [24], or have weaved steel mesh into layered cementitious materials to improve compressive strength, ductility, and energy absorption [98]. Although enhancements have been achieved, examining fracture phenomena and characterization of fracture toughness using notched experiments has rarely been studied.

Using a cementitious composite design, researchers have also used a hybrid fabrication process in which ultra-high-performance concrete was reinforced with a 3D-printed polymeric (ABS and PLA) lattice (Fig. 9) [99]. It was claimed that the design of the lattice orientation was based on the tensile stress and was proposed to provide additional ductility under bending. Compared to the brittle response of plain UHPC, two toughening mechanisms of polymeric-lattice-reinforced UHPC under bending, including multiple cracking and tortuous crack paths, were attributed to the strain-hardening response based on DIC profiles.

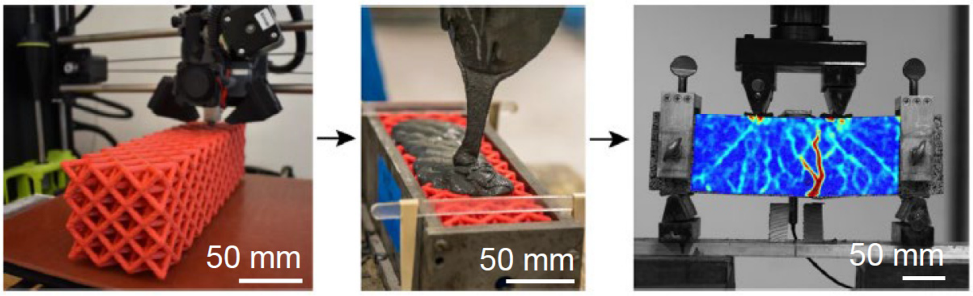


Fig. 9. A 3D-printed polymeric lattice (left) used to design an architected cementitious composite of reinforced ultra-high-performance concrete (middle) investigated under four-point-bending (right) [99].

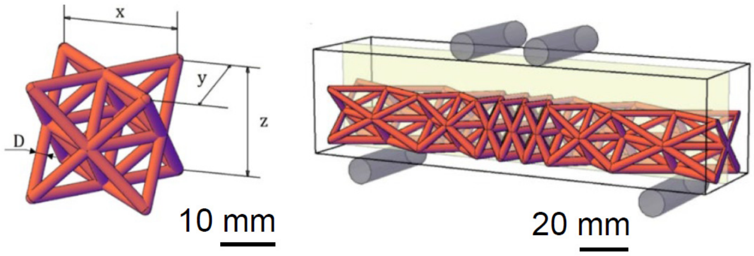


Fig. 10. Octet lattice (left) and functionally graded design of lattice reinforcement in cementitious mortar beam (right) [100].

In other studies, researchers have used a functionally graded polymeric (ABS) octet lattice as reinforcement in cementitious mortar to develop a cementitious composite material with enhanced ductile behavior compared to plain mortar in the four-point-bending experiment [100]. The graded polymeric cells, made by 3D-printing, were used to reduce the otherwise high reinforcement ratio of polymers compared to steel rebars. The design of the lattice was based on the bending moment and tensile stress distribution under flexural loading conditions. It was found that the addition of the lattice enhances the total energy of failure (when normalized for reinforcement volume) compared to the plain mortar. In addition, some degree of enhancement in ductile failure strength (defined in the study as maximum stress after the hardening branch) was reported for the lattice-reinforced cementitious composites (when normalized for reinforcement volume). Finite element simulation was used to provide insight into strain-hardening mechanisms observed in the stress-deflection curves of lattice-reinforced cementitious composites. The study highlights the viability of additive manufacturing for tailored designs of reinforcement, an alternative to steel, to enhance the overall performance of cementitious composites.

The bio-inspired strategies for designing polymeric reinforcement itself have also been explored [101] for applications such as cementitious composites. Bouligand, sinusoidal, grid, triangular, and hexagonal design schemes were explored in 3D-printing patterns and were examined using dog bone specimens under tension. It was reported that sinusoidal and bouligand design attributes, yield higher ductility and toughness under tension than parallel counterparts, without sacrificing the strength due to the higher tortuosity in fractured surfaces of these schemes.

More recently, an auxetic truss lattice architecture has been proposed for confinement in steel-reinforced concrete [102](Fig. 11a). A concrete and steel composite unit cell of reentrant auxetic lattice reinforcement (Fig. 11b) was studied numerically and experimentally under compression. It was found that auxetically confined concrete leads to significant improvements in strength and ductility, compared to both conventionally confined reinforced concrete and unconfined plain concrete (Fig. 11a). It was found that by taking advantage of the unique behavior of auxetic lattices in terms of the lateral contract under compression and transitioning from bending to stretching dominated behavior, increasing confinement can be activated. The potential of this reinforcement strategy has been discussed for applications in extreme loading conditions such as earthquakes.

(a)

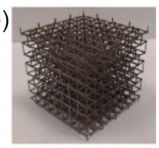

(b)


Fig. 11. (a) undeformed specimen (left) compared with deformed unconfined (middle) and confined specimen (right) and (b) 3D-printed steel auxetic lattice [102].

Researchers have also explored the design of a unique helical motifs in lightweight cementitious-polymer composite under compression to promote both strength and toughness [103]. It was reported that using an asymmetrical rotational design can enhance a progressive failure that preserves materials integrity with up to 60-80% load-bearing capacity. The study highlights the potential of the design for a wide range of material properties for applications in energy absorption.

One of the key aspects in designing architected cementitious composites using secondary polymeric and metallic materials is the elastic mismatch between the two dissimilar materials. Understanding the effect of elastic mismatch can play a crucial role in designing these types of composites or reinforced materials. In addition, the use of dissimilar types of materials in composites introduces interfaces, the constitutive properties of which need to be characterized and considered in the design and analysis. The LEFM approach presented in Eq. 1 can be extended to dissimilar brittle layered materials (i.e., graded layered materials) to account for both the elastic mismatch and the presence of the interface and to probe the fracture characteristics of the composite in a simpler arrangement. These simple experiments and simulations informed by theory can shed light on engineering the mechanics of more complex architected cementitious composites.

In another study, cellular architected cementitious-polymer composites were fabricated using a hybrid templating and casting approach [104]. Cement paste was cast into a 3D-PVA polymer template, which, upon solubilization, produced cellular cement paste architecture (Fig. 12) with a surface polymer coating. Higher energy absorption was achieved under compressive loading conditions for these cellular materials compared to cast counterparts.

Based on 3D graphic statics, other studies have used the equilibrium of forces, polyhedral frames, and force-form reciprocity to propose a design strategy for cellular and shellular (shell-based cells) architected materials. Using homogenization of representative volume elements, systematic designs of architected materials from bending-dominated to stretching-dominated were enabled [9], and was corroborated with experiments. Using DLP as the 3D-printed technique, photosensitive polymeric materials were used to enhance stiffness under compression, alluding to flaw-tolerance in funicular architectures. However, these types of architected materials are yet to be realized in cementitious materials or cementitious composites. To date, the closest study has only used a hybrid fabrication technique that includes 3D-printing a PLA mold and casting concrete for the realization of a Gyroid of cementitious composite, in an attempt to capture the response and modes of failure and optimal strength-to-weight ratio under compression [105].

In short, there are several opportunities to utilize a secondary material to enhance the mechanical attributes of cementitious composites or to develop new reinforcement strategies. However, a careful comparison of relevant mechanical properties needs to be conducted with respect to reference plain or reinforced concrete counterparts. In addition, using multiple materials can lead to material or geometric non-linearity depending on the composite and fabrication process, which has to be handled properly in the design of the experiment or the development of the numerical frameworks.

Fig. 12. Cellular architected (Schwarzite) cementitious-polymer composites [104].

5 Summary and future directions

In summary, several architected materials have been shown to enhance mechanical response across various classes of construction materials. Bouligand architecture demonstrated to enhance toughness in plain cementitious material without sacrificing the strength, engineered by mechanisms such as crack twisting and crack deflection into weak interfaces of material under tension. A diverse range of designs of cellular architectures can introduce non-brittle progressive failure in cementitious materials under compression by providing multiple damage pathways. Under tension, the response can vary depending on the specific design features in the cellular architecture. Given a strain limit, the auxetic architecture of cementitious materials can allow for a negative Poisson's ratio under compression provided by the elliptical design of void systems.

Learning from advancements in architected cementitious materials, the development of purposeful (intentionally cellular) architected materials brittle cementitious materials using alternative non-hydraulic binders has begun using MgO-based and Calcium-Silicate-based binders as an opportunity to promote carbonation and strength development.

Moreover, in cementitious composites, several polymer-concrete composites have been shown to introduce enhanced mechanical response. For instance, using auxetic reinforcement demonstrates the potential to activate significantly higher load-bearing capacity due to the lateral contract of the design under compression. Similarly, using lattice polymers as reinforcement has been explored in cementitious composites to introduce enhanced stress-strain responses such as strain-hardening under flexure.

However, careful analysis compared to reference unreinforced and reinforced materials is necessary to understand the contributions from the design of materials architecture. Bio-inspired nacre-like architected cementitious composite has been shown to provide higher toughness and load-bearing capacity. However, examination of fracture toughness using notched experiments and analysis of competition with mechanical properties such as strength are yet to be studied in cementitious composites.

Based on the current state of the field of architected infrastructure materials, the following future direction can be conceptualized:

- Design, manufacturing, and materials mechanics are three related components of the field. Advancement in one area can significantly contribute to our ability to pose and attempt to address new questions in other areas or to postulate new questions beyond the currently 'known' knowledge.
- Bio-inspired designs coupled with advanced manufacturing (beyond additive manufacturing) can help scratch new surfaces and open new trajectories for the future development of the field. Despite recent progress, design, and fabrication have remained largely unexplored. Bio-inspired efforts can benefit the design; however, future endeavors can focus on engineering the underlying mechanisms that enable specific mechanics of materials rather than merely mimicking the natural patterns.
- Architected materials can be non-isotropic, entail internal specific morphologies of solid and pore networks, and be composed of single or multiple materials. Understanding architected materials mechanics may require revisiting the existing experimental procedures conventionally developed for isotropic monolithic construction material and formulating new experiments sensitive to design features in architected materials, interfaces, and geometric imperfections.
- Fracture is an inevitable and challenging aspect of understanding and engineering the mechanics of architected materials, especially those with brittle or quasi-brittle construction constituents. Future research efforts must delve into capturing crack initiation and propagation phenomena and developing suitable fracture models and computational frameworks considering the heterogeneities. In addition, toughening mechanisms in some architected materials can occur both behind (extrinsic) or ahead (intrinsic) of the crack tip. The development of suitable experimental and computational approaches to characterize such sensitivities, for instance, through the investigation of fracture toughness vs. crack extension or force vs. crack-mouth-opening displacement, can inform improvements in the design of tough construction materials.
- Development of 'purposeful' over and 'exploratory' designs of architected material requires an analytical or computational framework. Developing numerical frameworks that can consider the constitutive behaviors of constituent materials (and interfaces) can help inform design strategies in architected materials.
- The use of multiple materials in the development and engineering of architected composite materials is a promising avenue, however, depending on the types of secondary non-OPC-based materials used (e.g., polymers), material constitutive behavior and non-linearity need to be handled carefully in experimental or computational approaches.
- Advancements in architected cement-based material to date can, in principle, be applied to other (quasi)brittle construction materials such as limestone calcined clay binders, low-lime binders, magnesia-based binders, and geopolymers, among others. Purposeful designs can take a different form for some of these binders in which alternative solidification mechanisms can occur.
- Advancements in small-scale additive manufacturing techniques can help in understanding the fundamental aspects of materials mechanics and is an accessible and worthwhile effort to be continued for the development of future research questions in the field and adoption of study of promising designs at large scale.
- Accessible design tools, manufacturing platforms, and software are necessary for continued research and development across scales and can greatly determine the faith of the field. For instance, in additive manufacturing, bespoke designs cannot currently be easily handled using widely used commercial slicers. Efficient tool path-generation algorithms and shape-design tools [106] can be developed into user-friendly platforms for broad use and training by and for the community.

Research is architected infrastructure material is at a nascent stage. Moving forward, a diverse array of applications for these materials are foreseeable in civil and energy infrastructure. This includes applications where unique combinations of material properties or enhanced damage resistance are necessary. It can also involve scenarios where bespoke designs are viable using advanced manufacturing techniques but cost-prohibitive using conventional casting methods. For example, these materials can find new applications in the growing 3D-printed concrete houses with vertical and horizontal components by introducing slight mechanically favorable geometric modulations to the otherwise rectilinear components (walls, façade). They can be engineered for unreinforced (blocks, unreinforced beams) or reinforced (post-tension beams) applications, allowing more efficient utilization of materials that can take the form of less usage, enhanced performance, or long-term damage resistance and longevity. Dynamic and impact loading applications of architected materials can be recognized for harvesting additional load-bearing capacity, ductility, and crack-resistant characteristics from the same constituent material. This can include extra- terrestrial applications in which earthquake and impact loads impose important considerations in material selection. Moreover, these materials can find coastal applications (e.g., building components, wave barriers), providing another degree of freedom through the materials to overcome susceptibility to damage and failure in extreme loading conditions (coastal tornado, fire, and flooding). Applications in the ocean can involve design of certain water-structure interactions for utilization in certain energy infrastructures (e.g., off-shore infrastructure, two-body wave energy converters). These applications can be highly advantageous due to the ability to eliminate the cost of formwork and advance the design and manufacturing process.

Authorship statement (CRediT)

Reza Moini: Conceptualization, visualization, writing, original draft, review and editing, funding acquisition.

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