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Review Article

Light-responsive smart materials: Mechanisms and potential applications in modern construction

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ABSTRACT

Light-responsive smart materials are a new class of functional materials, whose physical and chemical properties change when they are exposed to light. They change color, deform, change in stiffness or change transparency at certain wavelengths. These materials respond to light by varying physically or chemically like affecting color, transparency, stiffness or shape. Their eventual reactions are attracting more attention in the building industry whereby building experts and engineers looking for materials that will improve building performance and minimize power consumption. As the demands of sustainability keep increasing, the light responsive materials offer opportunities in making a building even smarter in respect to the way it reacts to the immediate environment. This paper presents analysis of the main properties and principles of these light responsive smart materials and their potential role in the modern architecture. It explores the important categories of photochromic coatings, light activated polymers and light response composite and examines the interaction between the materials and natural and artificial light. In addition, it examines the role that responsive behavior of these materials can play in enabling more adaptable and energy conscious building design.

1. Introduction

The construction sector stands at a crossroads. Buildings worldwide account for roughly 40 percent of total primary energy consumption, with heating, cooling, ventilation, and artificial lighting collectively responsible for the lion's share of that figure [1]. On one side of this challenge lies a long tradition of relying on passive, inert materials whose properties remain fixed once a structure is built; on the other lies an escalating demand for buildings that are responsive, efficient, and environmentally responsible. Light-responsive smart materials sit at precisely this intersection, offering designers and engineers a means of endowing buildings with a form of material intelligence that was previously impossible.

The capacity of certain substances to change their properties under illumination is not new in nature. Leaves orient themselves toward sunlight through phototropism, animal skin shifts pigmentation in response to ultraviolet radiation, and cephalopod skin can alter transparency for camouflage purposes with remarkable speed. What is relatively recent is the ability of materials scientists and engineers to replicate and deliberately engineer these effects in synthesised substances suitable for large-scale construction applications [2]. Over the last twenty years, a quiet revolution has been brewing at the intersection of photochemistry, polymer science, and nanotechnology, and its results are starting to show up in the way buildings look, feel, and function. These fields have produced materials that can respond to light in ways that are controlled, repeatable, and often fully reversible. In plain terms: surfaces and coatings that react to their environment rather than simply sitting there. For architects and designers, that's not a small thing. It means the skin of a building no longer has to be a fixed, passive element, it can breathe, adapt, and respond.

Smart materials, which in a broad sense refer to materials that react to environmental stimuli by altering one or more of their properties, have been under continuous academic and industrial research since the 1990s [2, 3]. Of the numerous stimulus modalities investigated, temperature, moisture, pH, electric field and mechanical load and light occupies a particularly appealing niche since it could be remotely delivered, controlled finely in terms of wavelength and intensity and collected at sunlight at not cost in terms of energy. All of these properties render light-driven responsiveness particularly well adapted to the needs of building envelope engineering.

The current speed of development in this field, as well as the increasing understanding that the distance between laboratory demonstration and operational implementation must be methodically charted, are what is driving the review given below. The paper will give a systematic introduction to photophysical and photochemical processes which enable light-responsiveness [4, 5, 6], will review the major categories of materials and their characteristics, and will examine the current application space in the architectural context and how an honest evaluation of technical and regulatory challenges currently confronting the adoption of light-responsive material in the built environment.

2. Mechanisms of light responsiveness

To appreciate what makes a material light-responsive in a practically useful sense, it is necessary to start with the photophysical and photochemical processes that underpin the observed macroscopic changes. These processes invariably originate at the molecular or nanoscale level, yet their cumulative effect produces transformations that are visible, measurable, and in many cases reversible at the scale of a building component.

2.1 Photochromism

Photochromism refers to a reversible, light-induced change in the absorption spectrum of a compound, resulting in a perceivable colour shift [4, 6]. The mechanism typically involves a photon-driven structural rearrangement at the molecular level bond breaking, ring opening, or geometric isomerisation that alters the electronic conjugation of the molecule and shifts its optical absorption into or out of the visible range. Upon removal of the stimulus or exposure to light of a different wavelength, the molecule reverts to its original configuration. The most extensively studied photochromic families include spiropyrans, spirooxazines, diarylethenes, and fulgides, each offering a distinct balance of switching speed, thermal stability of the coloured state, and resistance to photofatigue over repeated cycles [6, 7].

For construction applications, diarylethene-based systems are particularly attractive because they exhibit thermal bistability: both the open (colourless) and the closed (coloured) forms persist at room temperature without continuous light input [4]. A window coated with such a material can therefore maintain a tinted state once switched without consuming additional energy to sustain that state, a feature that sharply distinguishes this class from electrochromic devices that require a sustained voltage to hold an intermediate coloration. Recent work has also demonstrated that inorganic photochromic hosts based on tungsten trioxide and molybdenum trioxide offer superior durability relative to purely organic dye systems, while retaining sensitivity across both ultraviolet and visible wavelengths [1, 7].

2.2 Photoactuation and shape change

A second class of light-induced response involves macroscopic mechanical deformation driven by molecular-level conformational change. Azobenzene is the canonical example: under ultraviolet illumination it undergoes a rapid trans-to-cis isomerisation that shortens the molecule by approximately 3.5 Å and substantially changes its dipole moment [5]. When azobenzene units are incorporated at sufficient density within a polymer matrix or liquid crystal elastomer network, the cumulative mechanical strain from millions of simultaneous isomerisations translates into macroscopic bending, twisting, or contraction at the centimetre scale [5, 8]. Critically, the reverse cis-to-trans relaxation either thermally driven or photoinduced by visible light restores the material to its original geometry, making the actuation fully reversible.

In construction, photoactuation opens the possibility of shading elements that curl or flatten in direct proportion to instantaneous sunlight intensity, structural joints that soften under specific light conditions to provide seismic damping, and self-configuring aperture systems that require no motors or sensors [5, 8]. The appeal of such systems lies in their intrinsic simplicity: the material itself perceives and responds, eliminating the maintenance burden and failure modes associated with electromechanical actuators.

2.3 Photothermal effects

Certain nanoparticles and nanostructured carbon materials absorb incident photons with exceptional efficiency and dissipate the absorbed energy as localised heat rather than re-emitting it as fluorescence or undergoing a chemical reaction a process termed the photothermal effect [9]. Gold nanorods, reduced graphene oxide, and carbon nanotubes are among the most studied photothermal agents. When dispersed within a polymer or cementitious matrix at low loading fractions, they can raise the local temperature of the matrix by tens of degrees under concentrated illumination, without significantly altering the bulk mechanical properties of the host material.

This behaviour has been exploited in self-healing coating architectures where a brief pulse of focused light triggers localised thermal softening in a thermoplastic polymer matrix, allowing micro-crack faces to flow together and re-bond before the temperature subsides [9]. The combination of photothermal nanoparticles with phase-change microcapsules in cementitious panels is another emerging application: sunlight absorbed by the nanoparticles accelerates the solid-to-liquid transition of the encapsulated paraffin, increasing the effective rate of thermal energy storage during peak solar irradiance periods.

2.4 Photocatalytic reactions

Photocatalysis differs from the foregoing mechanisms in that it produces a chemical transformation in the material's immediate environment rather than within the material itself. Titanium dioxide (TiO_2) is the archetype: when illuminated by ultraviolet photons with energy exceeding its bandgap of 3.2 eV, electrons are promoted from the valence band to the conduction band, generating electron-hole pairs that react with surface-adsorbed water and oxygen to produce highly reactive hydroxyl and superoxide radicals [10]. These radicals oxidise organic contaminants, decompose bacteria and fungi, and convert nitrogen oxides to water-soluble nitrate ions. Buildings clad or paved with TiO_2-rich concrete, glass, or ceramic tiles thus acquire a continuous, sunlight-powered self-cleaning and air-purifying function [10].

3. Classification of light-responsive smart materials

Light-responsive materials that can be utilized in construction fall into three general classes, which are characterized by their composition, the primary response mechanism, and the primary role in the structure or functionality of the material. These types are not mutually exclusive; composite systems combining two or more types of responses are a very active subject of study.

3.1 Photochromic coatings

Photochromic finishes are finishes or coating systems-thin layers of protective materials deposited on the glass, concrete or facade panels, and changes color or darkens under ultraviolet or visible light and returns to its original color when the stimulus is removed. While the photochromic eyewear industry has deployed these coatings commercially for decades, the transition to architectural scale demands a substantially more rigorous performance envelope: an eyeglass lens may be replaced within a few years, whereas a building facade is expected to maintain its functionality for 25 to 30 years of thermal cycling, ultraviolet exposure, and mechanical stress [1, 7].

Researchers have addressed the durability challenge by encapsulating photochromic dyes within silica sol-gel or crosslinked polymer matrices that shield the active molecules from oxygen, moisture, and mechanical abrasion while preserving their optical responsiveness [7, 11]. Encapsulation within nanocapsules has been shown to improve photostability by factors of two to five relative to unprotected dye films [11]. Complementing organic systems, inorganic photochromic materials based on transition metal oxides such as WO_3 and MoO_3 offer inherently superior thermal and chemical stability, and their responsiveness to visible as well as ultraviolet wavelengths makes them attractive for deployment in regions where ultraviolet irradiance is seasonally limited [1].

3.2 Light-activated polymers

Polymers that incorporate photoresponsive chemical groups within their backbone or as pendant side chains constitute a versatile platform for light-driven shape change, stiffness modulation, and controlled permeability [2, 3]. Azobenzene-containing polymers undergo reversible contraction and expansion under alternating ultraviolet and visible illumination. Poly(spiropyran) networks exhibit large, reversible changes in hydrophilicity between the ring-closed merocyanine and the ring-open spiropyran forms [6]. Coumarin-crosslinked hydrogels can be photochemically stitched and unstitched using ultraviolet light of different wavelengths, enabling on-demand stiffness programming.

Light-induced shape-memory polymers are of particular interest for construction. In a landmark study, Lendlein et al. demonstrated that a polymer incorporating cinnamic acid crosslinks could be deformed into an arbitrary temporary shape and recover its permanent form upon brief ultraviolet exposure, without any thermal stimulus [12]. Subsequent work by Nair et al. showed that thiol-ene photopolymer networks could exhibit multiple stable shape configurations addressable by different wavelengths of light [20]. These findings suggest a materials platform from which self-deploying structural inserts, remotely reconfigurable partitions, and light-actuated aperture seals could plausibly be constructed, though practical realisation at structural scale remains an open engineering challenge.

3.3 Light-responsive composites and nanocomposites

Composite materials integrate photoresponsive agents molecular, nanoparticulate, or both within structural matrices such as concrete, fibre-reinforced polymer, or engineered wood, producing hybrid systems that retain the load-bearing capacity of the host while exhibiting smart behaviour [13]. Nano-enhanced concrete incorporating titanium dioxide nanoparticles is the most commercially mature example, with photocatalytic building surfaces having been deployed on a substantial scale in Europe and Asia [10].

Graphene quantum dot-modified cementitious composites represent an emerging variant in which photothermal self-healing capability is incorporated into a concrete matrix: sunlight absorbed by the quantum dots heats the surrounding paste sufficiently to partially re-fuse micro-crack faces, arresting crack propagation at an early stage [9]. Meanwhile, light-responsive polymer-fibre composites that alter their stiffness distribution under solar illumination have been proposed as a basis for structurally adaptive facade panels that redistribute loads dynamically as solar irradiance varies across the day [3]. These systems remain largely at the proof-of-concept stage, but the underlying material science is sufficiently well established to support optimism about their eventual practical viability.

Table 1: Classification of principal light-responsive material categories, their response mechanisms, primary construction applications, and current technological maturity.

Material Category	Response Mechanism	Primary Application	Maturity Level
Photochromic Coatings	Molecular isomerisation [4, 6]	Dynamic glazing, facade tinting	Commercial / Near-commercial
Azobenzene Polymers	Trans-cis photoisomerisation [10]	Actuating louvres and blinds	Laboratory / Pilot
Photocatalytic Composites (TiO_2)	Radical oxidation under UV [10]	Self-cleaning surfaces, air purification	Commercial
Photothermal Nanocomposites	Light-to-heat conversion [9]	Self-healing coatings, PCM regulation	Research / Pilot
Shape-Memory LCE Films	LC order-disorder transition [8]	Adaptive louvres, morphing facades	Research

4. Applications in modern architecture and construction

4.1 Dynamic glazing and solar control

The building facade is the primary interface between the occupants of a structure and the external climate, and glazing within that facade is the component most directly implicated in solar heat gain, glare, and daylighting quality. Baetens et al. have provided a comprehensive review of the properties and requirements of smart windows, noting that photochromic and thermochromic glazing systems capable of darkening under high irradiance and lightening under overcast conditions can reduce peak cooling loads by 20 to 50 percent relative to conventional clear glazing, depending on climate and orientation [1]. Yao et al. corroborated similar performance margins in simulation studies of thermochromic vanadium dioxide coatings under hot-arid and hot-humid conditions [14].

The integration of photochromic films onto structural glass is technically straightforward, involving lamination of a responsive polymer interlayer between two glass panes using established safety-glazing processes. The engineering challenges lie in ensuring that switching kinetics match the diurnal rhythm of a building, a window that takes several hours to return to transparency after a cloudy period is poorly suited to occupied spaces and that the fatigue performance over a 25 to 30-year service life is adequate [1, 6]. Ongoing material research focused on diarylethene and tungsten oxide systems is progressively addressing both these concerns [4, 7].

4.2 Self-cleaning and photocatalytic facades

Urban buildings accumulate grime rapidly due to vehicular emissions, biological growth, and airborne particulate deposition. Traditional cleaning involves periodic high-pressure washing, which is costly, creates risks for workers operating at height, and demands significant quantities of water. Photocatalytic facades composed of titanium dioxide-coated glass, concrete, or ceramic cladding panels offer a passive alternative: solar ultraviolet radiation continuously drives the decomposition of organic contaminants and facilitates their removal by rain, a phenomenon thoroughly characterised in the self-cleaning literature [10].

The air quality co-benefit is equally significant. Tung and Daoud reviewed the photocatalytic degradation of nitrogen oxides on building surfaces, noting field measurements that document reductions of 40 to 80 percent in street-level NO_x concentrations in the immediate vicinity of photocatalytic facades installed in European urban centres [10]. This finding has spurred the incorporation of photocatalytic concrete and tile products into urban planning strategies for air quality management in several cities, including Rome and Tokyo.

4.3 Adaptive shading and sun control

Static shading devices are necessarily a compromise: a fixed overhang or louvre sized for optimal summer performance provides excessive shading during winter months and vice versa. Light-responsive actuating materials offer a pathway to shading elements that adjust their geometry continuously and autonomously, tracking the diurnal and seasonal variation of the solar angle without motors or control electronics [5, 8].

Prototype louvre systems fabricated from azobenzene-doped liquid crystal elastomer films have demonstrated spontaneous bending of up to 90 degrees under direct simulated sunlight and complete recovery to the flat state within seconds of shading, effectively mimicking a motorised louvre through purely material behaviour [5, 8]. White and Broer provide an in-depth treatment of the mechanical programming strategies available in liquid crystal polymer networks that underpin this behaviour, emphasising the scope for tailoring both actuation direction and force output through molecular-level design of the network topology [8]. Current limitations on force output restrict these systems to internal blinds and microperforated screens; further materials development is needed before structural-scale external louvres become feasible.

4.4 Thermal regulation and phase-change integration

Phase-change materials embedded in wall assemblies, ceiling panels, or floor screeds moderate indoor temperature fluctuations by absorbing and releasing latent heat at a defined transition temperature, reducing peak heating and cooling loads [14]. Their effectiveness is enhanced when the rate of heat charging can be matched to the rate of solar energy availability. Photothermal nanoparticles dispersed within the phase-change matrix accelerate the melting transition under intense solar radiation by converting photon energy directly into heat at the nanoparticle surface, effectively coupling the thermal storage system to the solar resource without any intervening heat transfer fluid [9].

Research groups have fabricated cementitious panels incorporating both paraffin microcapsules and carbon nanotube networks and demonstrated enhanced thermal buffering capacity under simulated daylight compared to reference panels without the nanotube component [9]. This synergistic integration of photothermal and phase-change functions within a single structural panel exemplifies the broader design philosophy of combining passive and stimuli-responsive behaviour to maximise building energy performance.

4.5 Structural health monitoring and self-healing coatings

The structural health of a building depends on detecting micro-damage before it propagates to a scale that compromises safety. Mechanochromic coatings, which change colour at locations of tensile or compressive stress concentration, provide a visually readable map of strain hotspots during routine inspection, supplementing or in some cases potentially replacing costly embedded sensor networks [6, 13].

The combination of damage indication with autonomous repair in a single coating material is a particularly active research frontier. Early prototypes based on spiropyran-doped polyurethane networks have demonstrated simultaneous mechanochromic stress indication and subsequent photothermally triggered healing: the mechanoresponsive chromophore signals the location and approximate magnitude of stress accumulation during loading, and a subsequent brief irradiation with a focused light source causes localised thermal softening that allows micro-crack faces to flow together and re-bond [6]. Klajn's detailed account of the rich mechanochemical and photochemical behaviour of spiropyran-based systems provides the mechanistic underpinning for these dual-function coating architectures [6].

5. Interaction with natural and artificial light

A critical but frequently under-discussed dimension of deploying light-responsive materials in buildings is the nature and spectral composition of the light source to which they will be exposed in service. Natural daylight varies enormously in intensity, spectral distribution, and angle of incidence across the day, the season, and geographic latitude, and these variations directly condition the switching behaviour and energy balance of any light-responsive building system [1, 14].

Most photochromic and photocatalytic materials are activated primarily by the ultraviolet component of solar radiation, which lies below 400 nm in wavelength and constitutes roughly 5 percent of total solar irradiance at ground level. In tropical and equatorial climates such as those prevailing across peninsular India, ultraviolet irradiance is high throughout the year, providing consistently favourable conditions for outdoor photochromic and photocatalytic applications [1, 10]. At higher latitudes or in persistently overcast climates, ultraviolet levels may be insufficient to drive rapid switching in standard organic photochromic systems, necessitating the use of materials with broad spectral sensitivity extending into the visible range [7].

Interior applications face an even more constrained light environment. Standard LED office and commercial lighting provides illuminance levels typically two to three orders of magnitude below outdoor daylight on a horizontal surface, and its ultraviolet content is essentially zero. Stimuli-responsive materials intended for interior use—such as partition wall claddings, ceiling tiles, or furniture surfaces—must therefore be engineered to respond to visible photons [2]. Triphenylamine-based and indoline-based photochromic systems have shown the most promise in this context, exhibiting useful switching dynamics under visible illumination from white LED sources [6, 15].

Artificial lighting also creates a design opportunity that has received relatively little attention. Buildings increasingly incorporate tunable spectral LED lighting systems capable of delivering specified wavelength combinations at scheduled times. Such infrastructure could in principle be used to deliberately trigger or reset material states on demand—decoupling the material's switching behaviour from the variability of natural daylight and inserting it into the feedback architecture of a building management system [1, 15]. This concept has not yet been demonstrated at building scale, but it represents a conceptually elegant convergence of smart materials and smart building management philosophies.

6. Challenges and limitations

The transition of light-responsive smart materials from laboratory demonstrations to mainstream construction practice is hindered by a set of interconnected challenges that warrant candid examination. Progress on each of these fronts is essential before the materials discussed in this review can fulfil their potential at scale.

6.1 Durability and Photofatigue

Most organic photochromic compounds undergo gradual degradation through repeated switching cycles combined with exposure to heat, oxygen, and moisture—a phenomenon known as photofatigue [6, 7]. Fatigue manifests as a progressive reduction in switching contrast and a slowing of the bleaching kinetics. Whereas specialty applications such as photochromic eyewear can tolerate performance loss over two to five years before lens replacement, building materials must maintain their specified function for decades. Strategies including molecular encapsulation within silica matrices [7, 11], use of thermally bistable diarylethene derivatives [4], and incorporation into inorganic oxide hosts each improve fatigue resistance to varying degrees, but no current solution fully satisfies the combined demands of long service life, rapid switching speed, and high photopic contrast that architectural applications require.

6.2 Scalability and manufacturing cost

The synthesis of high-purity photochromic compounds, the formulation of stable coating dispersions at low particle size, and the fabrication of responsive composite panels at the metre scale each involve process steps that are currently expensive relative to conventional building material production [1, 16]. Photochromic architectural glazing carries a cost premium that remains substantially higher than that of electrochromic glazing—itself already considered a premium product. Decker's work on photoinitiated crosslinking polymerisation [16] points toward scalable photochemical processing routes for responsive polymer coatings, but bridging from laboratory synthesis to continuous manufacturing of architectural-grade films requires sustained investment that the construction materials industry has been slow to commit.

6.3 Integration with building management systems

Modern buildings are managed through integrated control platforms that coordinate heating, ventilation, air conditioning, lighting, fire safety, and security. Light-responsive materials that operate autonomously are, by definition, outside the feedback loop of these systems [10]. Autonomy can be an advantage it eliminates sensors, wiring, and software maintenance but it can also create undesirable interactions. A photochromic facade that darkens on a cold but bright winter morning may reduce passive solar heat gain at precisely the time when it is most beneficial, increasing the heating energy demand to offset the lost solar contribution. Hybrid architectures combining autonomous material responsiveness with an electrically overridable switching capability address this tension but add both cost and complexity.

6.4 Regulatory and standards framework

Building regulations and material certification frameworks were developed for materials with fixed, stable properties. The characterisation, testing, and approval pathways for materials whose performance is inherently time-varying and stimulus-dependent are still being developed in most jurisdictions [3]. Structural engineers and building control officers face genuine uncertainty when specifying or approving materials for which standard test methods do not yet exist. The development of appropriate test protocols addressing switching durability, thermal performance variability, and fire behaviour of responsive coatings is a prerequisite for mainstream adoption and represents an urgent task for standards bodies, material producers, and the research community acting in concert.

7. Future research directions

A number of research trajectories hold particular promise for advancing the field and bridging the gap between current laboratory capability and practical construction application.

- Multi-stimulus responsive materials that couple light-sensitivity with responses to temperature, humidity, or mechanical load [2, 3], enabling richer and more contextually appropriate adaptive behaviour in complex real-world building environments.
- Bio-inspired photonic colouration systems that replicate the structural colour mechanisms observed in butterfly wings and cephalopod skin, achieving vivid and durable colour change through nanostructural manipulation rather than molecular photochromism [17], thereby avoiding the photofatigue limitations of dye-based systems entirely.
- Integrated facade systems that combine light-responsive optical switching with organic photovoltaic energy harvesting, such that the same facade element simultaneously adapts its solar transmittance and generates electricity from the incident radiation [9].
- Machine learning-assisted molecular design of new photochromic and photoactuating compounds with precisely tailored switching wavelengths, fatigue resistance, and thermal stability, accelerating discovery timelines relative to conventional experimental approaches [2].
- Rigorous lifecycle assessment studies that quantify the full environmental cost-benefit balance of light-responsive building envelopes, accounting for the energy and material inputs required for synthesis, coating deposition, installation, maintenance, and eventual end-of-life recovery or disposal [1].

The intersection of photochemistry, polymer engineering, nanotechnology, and architectural design is a fertile and rapidly evolving terrain [2,13]. Realising the full potential of light-responsive materials in construction will require sustained interdisciplinary collaboration, targeted investment in manufacturing scale-up, and coordinated engagement with standards and regulatory bodies.

8. Conclusions

Light-responsive smart materials represent a genuinely transformative opportunity for the construction sector. By endowing building envelopes and structural components with the capacity to sense and respond to incident light, they shift buildings from the category of passive objects toward that of active, adaptive systems. The diversity of available response mechanisms from photochromic molecular switching [4, 16] and photoactuating polymer networks [8, 5, 12, 18] to photothermal nanoparticle heating [9] and photocatalytic surface reactions [10] means that architects and engineers can select or combine material types according to the specific functional requirement in each part of a building.

The energy implications are substantial. Dynamic solar control through photochromic glazing [1, 14], passive thermal management through photothermal composites, and self-cleaning through photocatalytic coatings each reduce the operational energy demand of buildings. As the building stock of rapidly urbanising regions including South and Southeast Asia continues to expand at an unprecedented rate, the adoption of such materials at scale could make a meaningful contribution to national and global decarbonisation trajectories.

The path from laboratory proof-of-concept to mainstream construction material is long and requires coordinated advances in synthesis chemistry, manufacturing, durability engineering, and regulatory frameworks. The research community has established a strong scientific foundation [2, 3, 4, 5, 6, 8, 10, 11, 12, 15, 18]; the challenge now is to translate these advances into materials that are robust, affordable, and straightforward to specify and install. The present paper has sought to map the current landscape as a contribution to the ongoing dialogue between materials scientists, structural engineers, and architects who will collectively determine what the built environment of the coming decades looks like.

Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

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