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PERSPECTIVE

Next-Generation Cement-based Engineering Materials for Reliable and Sustainable Infrastructure

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Abstract

The demand for reliable and sustainable infrastructure necessitates a fundamental shift in engineering materials, moving beyond incremental improvements toward an integrated paradigm combining intrinsic performance enhancement, functional adaptability, and intelligent design. In this perspective, we highlight the key opportunities and challenges of advanced cement-based engineering materials, focusing on high strength-toughness, long-service-life, frontier engineering materials, and intelligent design. These interdependent areas collectively pave the way for a new generation of engineering materials capable of withstanding unprecedented service conditions while substantially reducing environmental impact. Infrastructure stands as the cornerstone of modern civilization, ensuring economic prosperity, public safety, and sustainable development. Rapid urbanization, climate change, and intensifying resource constraints are reshaping performance expectations of infrastructure systems, which must increasingly withstand complex loading conditions, severe service environments, and extreme scenarios from deep-sea installations to prospective lunar construction. These challenges call for a fundamental transformation in cement-based engineering materials, driving development of a new generation characterized by inherent reliability, extended service life, environmental compatibility, and resource efficiency. Breakthroughs are needed across four interdependent frontiers: collaborative enhancement of strength-toughness, ultra-long service life under harsh environments, material functionality and scalable fabrication, and AI-driven material design. Each domain will be discussed, exploring cutting-edge advances, engineering applications, and future potential in establishing a robust material foundation for major infrastructure.

Keywords: engineering material, major infrastructure, sustainability, intelligent design.

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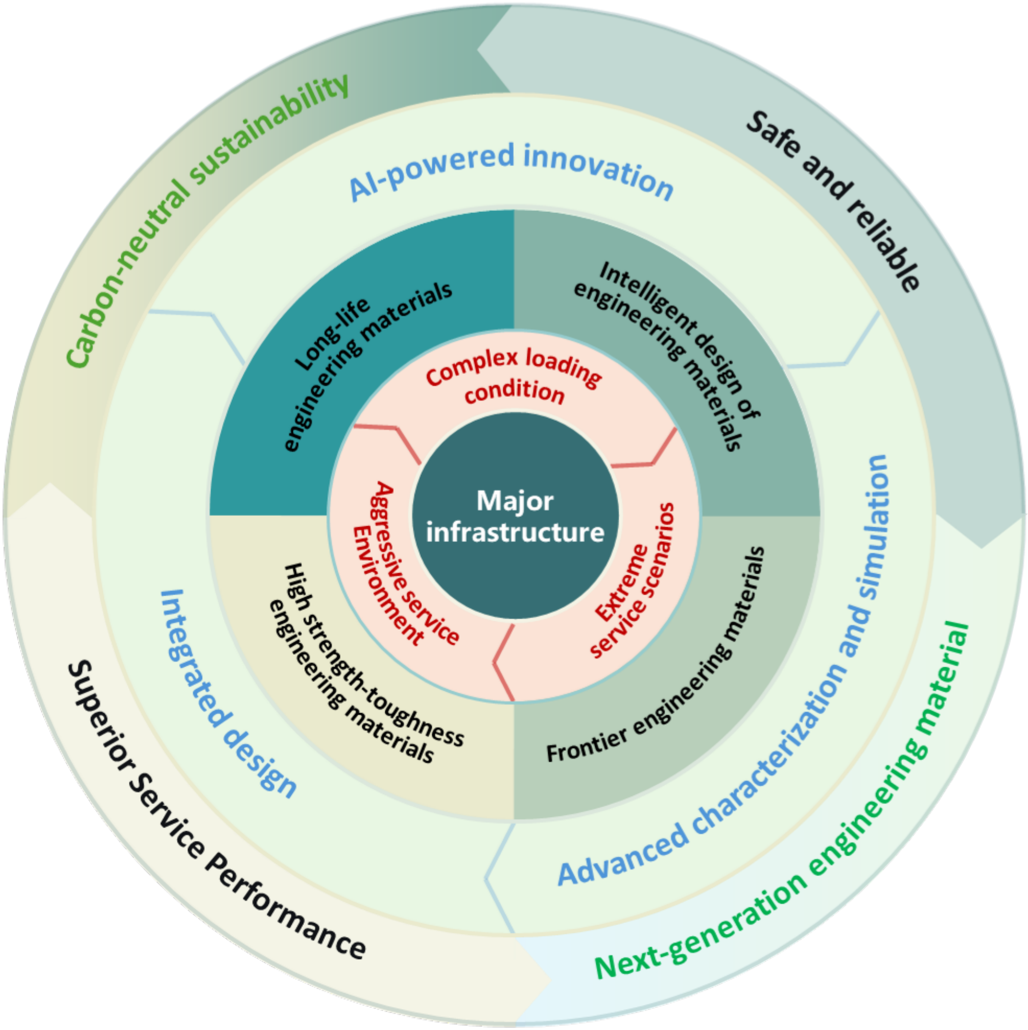

Figure 1. Overview of the challenges and requirements of engineering materials for major infrastructure.

1 High strength-toughness engineering materials

As shown in Figure 1, conventional concrete faces significant limitations under complex loading conditions involving large deformations and dynamic forces, which often lead to premature failure due to its limited resistance. Significant progress has been achieved through systematic innovation in toughening mechanisms.

The development of sodium-based hybrid high-toughness nano-reinforcement seeds has enabled refined nucleation control at the nanoscale [1]. The establishment of in-situ polymerization theory for multi-scale interfacial toughening provides the theoretical foundation for phase-boundary enhancement [2, 3]. By coupling gel-packing optimization, interfacial cross-linking, and multi-scale fiber crack-bridging, a substantial performance improvement has been demonstrated, most notably a doubling of the 28-day fracture energy in cementitious matrices [4]. On top of that, the resulting concrete achieves a tensile strength exceeding 10 MPa and tensile strain surpassing 2000 $\mu\varepsilon$ (see Figure 2).

Additionally, multi-scale mechanical transfer models and a theoretical framework for toughness-oriented design in low-carbon concrete have been proposed, allowing the prediction of tensile/compressive strength, crack initiation toughness, and constitutive behavior [5]. For high-altitude applications characterized by low atmospheric pressure and significant geothermal gradients, tailored crack-resistance methodologies have been developed, effectively mitigating shrinkage and cracking risk in tunnel linings [6]. Collectively, these advances have been successfully applied in landmark projects such as the Yigong Tunnel (Sichuan-Tibet Railway), the Shenzhen-Zhongshan Link, and the Zhangjinggao Bridge.

Although functional additives and special measures offer a potential pathway to enhance concrete, the

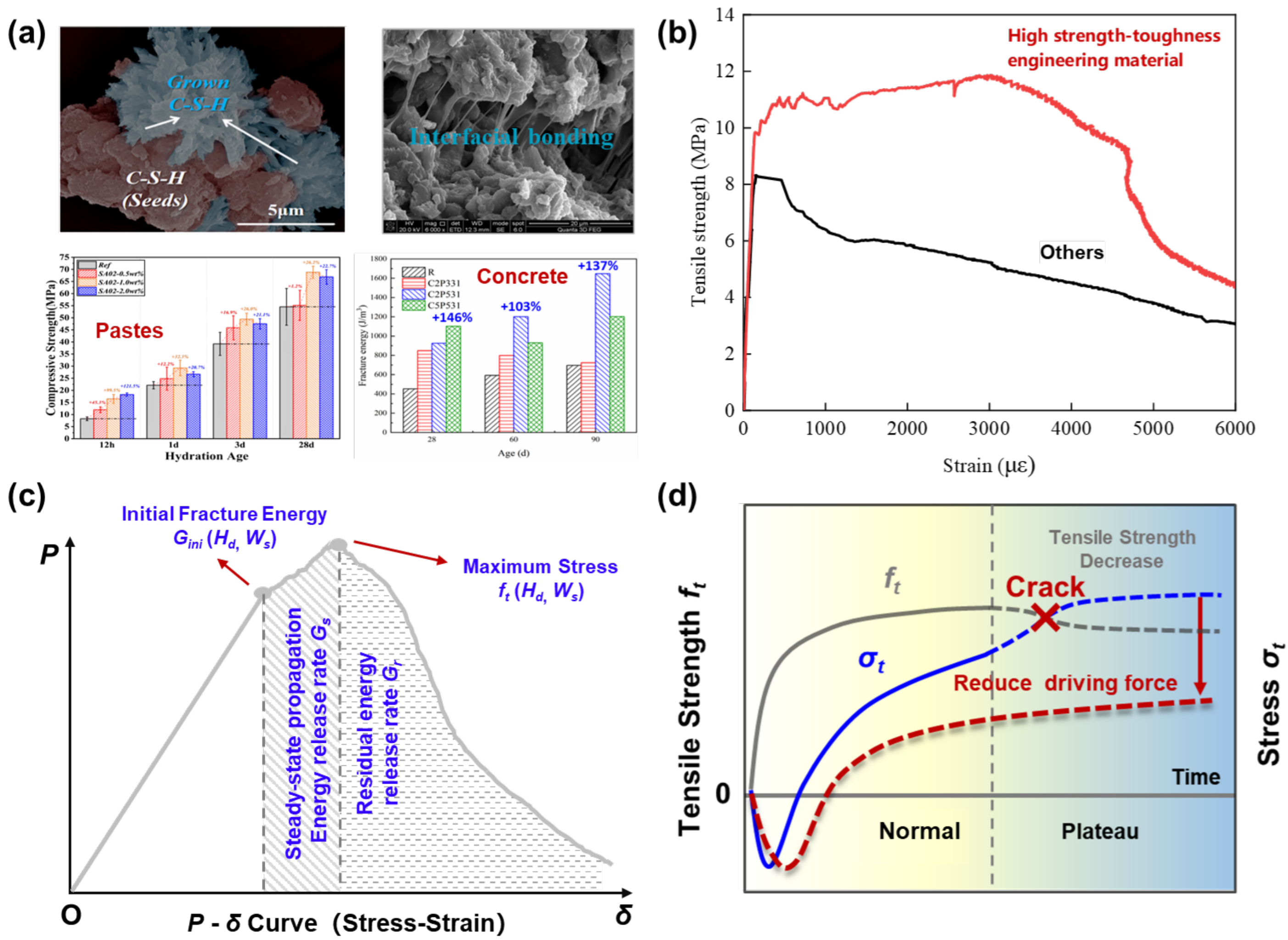

Figure 2. Development of high strength-toughness engineering material. (a) Strength-toughness enhancement of cement pastes and concrete, (b) typical tensile stress-strain curves of normal concrete and high strength-toughness concrete, (c) fracture energy of cement-based engineering material, (d) evolution of tensile strength and driving force accompanying with curing time.

chemically complex, high-pH environment of the cementitious matrix threatens their stability and effectiveness [7]. This fundamental limitation hinders precise control across scales, especially to achieve the combined properties of high strength and high toughness. To achieve further strength-toughness improvement of engineering materials, the underlying mechanisms governing mechanical property loss across scales, given the complex phase composition of concrete, should be clearly clarified. Moreover, the multi-scale toughening and crack-control strategies should be well integrated, extending the performance boundaries of high strength-toughness engineering materials.

2 Long-life engineering materials

The pursuit of extended service life stands as a defining challenge, as well as one of the most direct and effective carbon reduction strategies in civil engineering. As infrastructure expands into increasingly severe environments and unprecedented extreme scenarios, characterized by larger temperature differentials, lower humidity, higher salinity, and stronger coupling effects, the performance demands on engineering materials have surpassed conventional thresholds.

To be specific, the coupled fields primarily involve chemical attacks (e.g., chloride and sulfate ingress), physical transport (e.g., moisture and ion diffusion), and mechanical loading. In general, chloride and sulfate attack are the main causes of concrete deterioration, leading to spalling and rebar corrosion. The failure mechanism mainly includes the penetration and expansion reactions of aggressive ions: sulfate ions in marine environments convert bound chlorides into free ones by inhibiting Friedel's salt formation, lowering chloride binding capacity and raising chloride diffusivity; sulfate also lowers pH, decomposes Friedel's salt, and accelerates further chloride penetration. Meanwhile, co-precipitation of ettringite and Friedel's salt refines the microstructure. Sulfate-induced expansion densifies pores, temporarily slowing chloride ingress and delaying rebar depassivation. However, as penetrating ions upset the chemical equilibrium, calcium leaching and expansive products eventually cause expansion, cracking, higher porosity, and faster ion diffusion.

Recent researches, as shown in Figure 3, have progressively evolved from single-factor degradation models toward integrated frameworks that account for coupled chemical, physical, and mechanical interactions in harsh environments. This includes the development of multi-scale constitutive models linking microstructure evolution to macro-performance, the establishment of environmental zone mapping for durability design, and the formulation of reliability-based service-life prediction methodologies [8–11]. Concurrently, novel material systems have emerged, integrating corrosion-resistant reinforcement, low-permeability concrete, surface protection technologies, and self-healing capabilities, forming a multi-tiered resistance against deterioration [12–14].

While current advancements have enabled extended service life under conventional and certain extreme conditions, they remain inadequate for future infrastructure in harsher environments such as the Qinghai-Tibet Plateau, polar regions, deep seas, and extraterrestrial environments. Key scientific and technical barriers persist: the nonlinear degradation mechanisms of materials under strongly coupled multi-field interactions are not yet fully understood, and advanced experimental platforms capable of replicating and monitoring real-world environmental coupling are still inadequate to meet the demand. Furthermore, material innovation with intrinsic functionalities such as environmental adaptability, self-healing capability, and structural-integrated durability is urgently required.

3 Frontier engineering materials

Transformative advances in material functionality and scalable fabrication are required to ensure the safe construction and long-term service of infrastructures in extreme environments. In response, recent work has adopted bioinspired multilevel structural ordering strategies to develop a series of advanced cement-based materials with integrated functional performance. These include cement aerogels, self-powered concrete, and cement-based structural batteries and supercapacitors, each designed to extend the utility of conventional cementitious systems through properties such as ultralow thermal conductivity, self-powering capability, and built-in energy storage (see Figure 4).

Notably, cement aerogels produced via directional freeze-casting and ambient-pressure drying achieve a density of 15 $kg{\cdot}m^{-3}$, a negative Poisson's ratio, thermal conductivity of 0.02 $W{\cdot}m^{-1}{\cdot}K^{-1}$, and A1-level fire resistance. The cement aerogels feature bioinspired hierarchical porous architectures (e.g., cuttlebone-like frameworks) with interconnected micro- and nanopores and a continuous C-A-S-H skeleton, which jointly reduce heat transfer via conduction, convection, and radiation while establishing a thermally stable, oxygen-impermeable inorganic barrier, thereby enabling exceptional thermal insulation and fire resistance. These materials have been demonstrated at the square-meter pilot scale for applications in building insulation and industrial thermal protection [15, 16].

In parallel, bioinspired self-powered and energy-storage concretes integrate thermoelectric conversion with electrochemical energy storage, enabling continuous power generation under temperature gradients and reducing dependence on external grids [17]. The self-powered concrete features a plant-stem-like multilayer architecture composed of aligned cement–PVA hydrogel phases with abundant interfaces, in which selective interfacial immobilization of Ca^{2+} ions and preferential transport of OH^- ions enhance ionic diffusion asymmetry, thereby generating a pronounced thermoelectric (Seebeck) effect that converts temperature gradients into electrical energy and enables self-powered functionality. The energy-storage concrete systems are designed as integrated electrochemical architectures by incorporating redox-active phases (e.g., Zn anodes) and conductive networks into porous cement matrices, where the multiscale pore network simultaneously serves as ion-transport pathways and electrolyte reservoirs, thereby facilitating rapid ion migration and efficient interfacial charge transfer. Electrical energy is thus stored through reversible Faradaic reactions (e.g., Zn plating/stripping) in conjunction with interfacial capacitive storage within the cementitious framework.

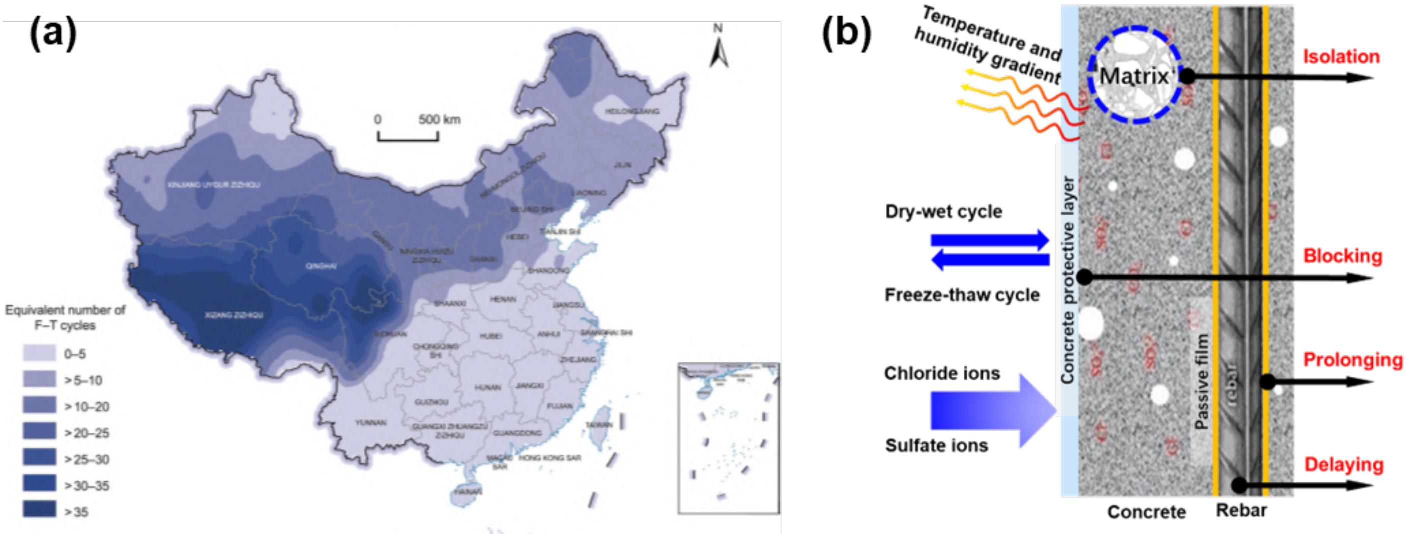

Figure 3. Development of long-life engineering materials. (a) National atlas of environmental zone mapping, (b) multiple functional materials for concrete durability enhancement.

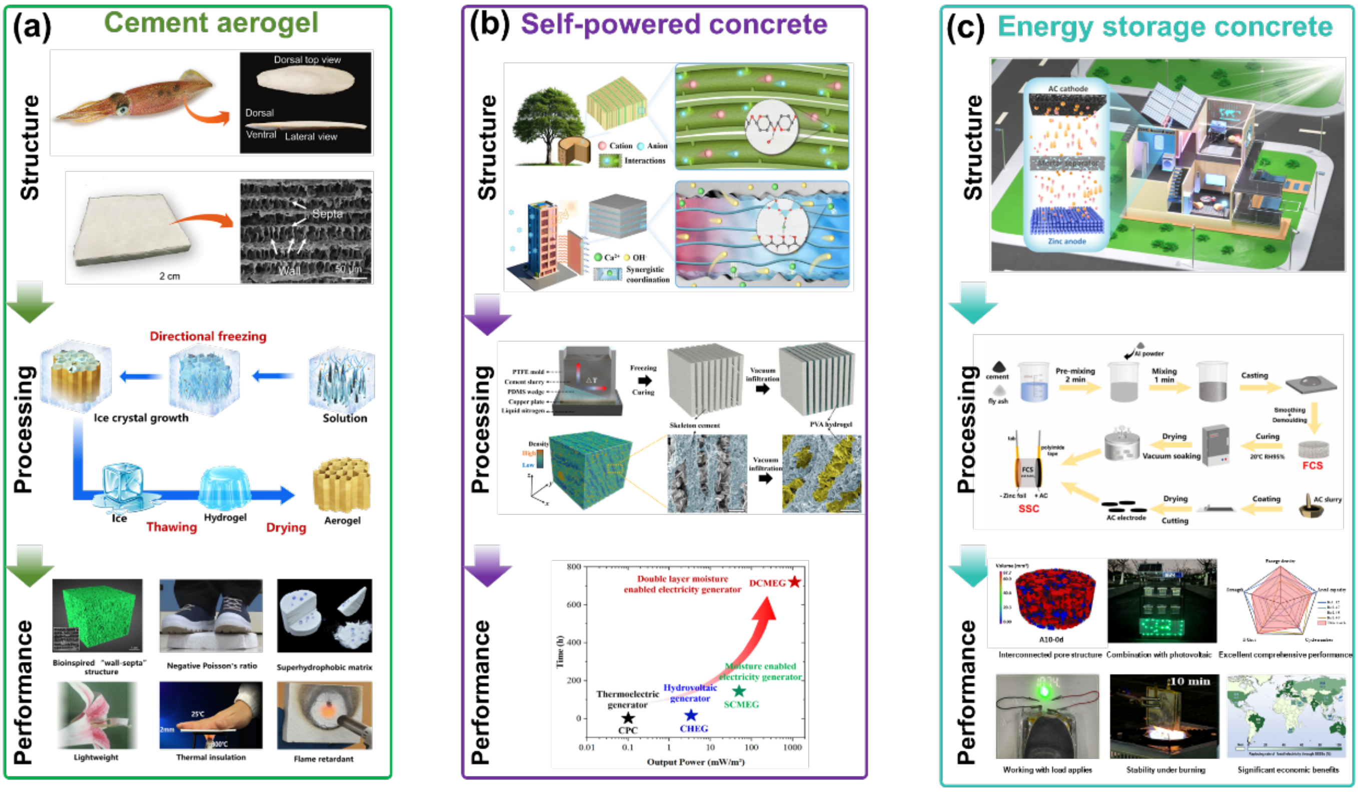

Figure 4. Structure, processing and performance of frontier engineering materials, including (a) cement aerogel, (b) self-powered concrete, and (c) energy-storage concrete.

Such systems show potential for remote base-station power supply and endurance extension of low-altitude unmanned platforms.

Meanwhile, cement-based structural battery prototypes have reached an energy density of 4 $kWh{\cdot}m^{-3}$ alongside a compressive strength of 20 MPa, capable of meeting the electricity demands of a 130 m^2 apartment with two wall units [18, 19]. A sustainability-oriented evaluation framework has also been established to guide further development of electrochemical energy-storage concretes [20]. Despite these advances, several challenges remain. The decomposition of cement hydration products above 800 °C limits the use of cement aerogels in high-temperature protection, highlighting the need for improved long-term thermal stability in

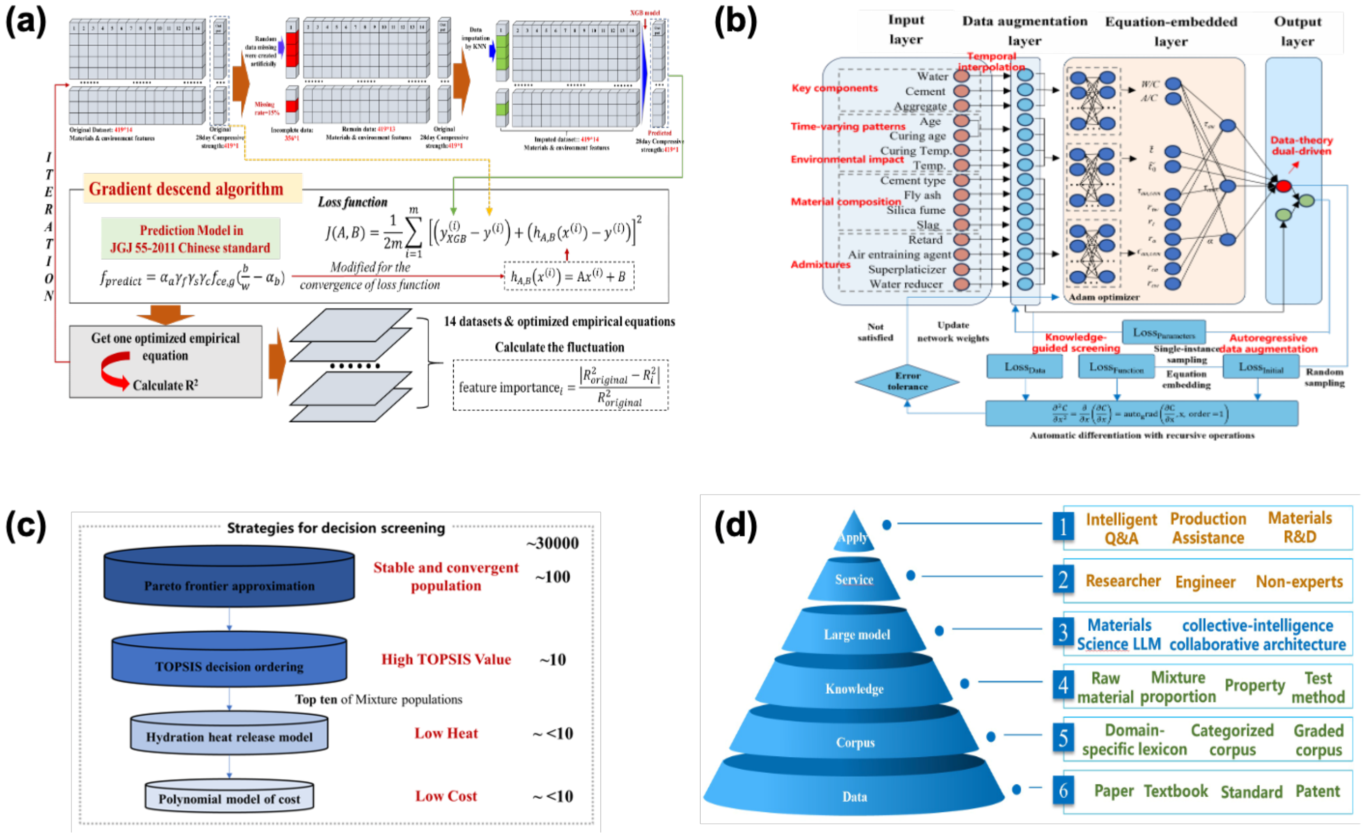

Figure 5. Recent progress and perspectives in intelligent design of engineering materials. (a) Algorithms for data-driven strength prediction incorporating loss function establishment and data imputation, (b) framework for data knowledge dual driven shrinkage prediction, (c) strategies for four-layer decision screening in multi objective design, (d) architectural design of a domain-specific Large Model for Concrete Materials.

aerospace and defense contexts. Self-powering and energy-storage concretes, while promising, are still at an early technological stage, constrained by low energy density, limited long-term durability and structural compatibility, high material costs, and scalability challenges related to manufacturing, recycling, and power-management integration. These factors currently hinder their widespread deployment in infrastructure systems.

Moving forward, research in this domain will focus on multi-material integration, multiscale structural ordering, multifunctional coupling, and multi-scenario implementation. Efforts will target fundamental design principles, enhanced functional performance, and scalable fabrication processes to accelerate the practical engineering translation and infrastructure integration of cement aerogels and self-powered energy-storage concretes.

4 Intelligent design of engineering materials

The intelligent design of engineering materials represents a paradigm shift toward big data and AI-driven, multi-objective material development, which is structured around three key objectives: establishing a multi-source integrated database, developing versatile and secure algorithms, and fostering intelligent collaborative application platforms. However, fundamental bottlenecks exist when applying AI to engineering materials: the scarcity, high cost, and poor quality of labeled data, algorithmic limitations imposed by multiscale heterogeneity and nonlinearity, poor model adaptability to temporal, environmental, and compositional variability of the materials.

Significant progress has been achieved across several domains in recent years, including high-throughput data acquisition and database construction, data-intelligence fusion methodologies, and lifecycle-integrated design systems (see Figure 5). For instance, adaptive classification models and data collection frameworks have been developed to address diverse environmental conditions, engineering scenarios, and raw material types [21, 22]. Advances in combining molecular-scale simulations with machine learning have also deepened the integration of material knowledge with large-scale data [2, 23, 24]. Moreover, a specialized large language model for engineering materials with professional question-answering capabilities has been proposed, further demonstrating the potential of AI in domain-specific knowledge discovery. The central scientific challenge ahead lies in achieving seamless cross-scale simulation and cross-modal fusion (including images, textual data, and measured test vectors) for engineering material properties.

Future efforts could focus on employing information-fusion technology to convert fragmented empirical performance data into structured high-throughput database [25]. Besides, bidirectional quantitative mapping of physical-mechanical properties between engineering material and major infrastructure needs to be established. Such advances will enable data- and knowledge-informed forward-prediction and inverse-design frameworks, significantly enhancing the precision and reliability of engineering material design [26]. Ultimately, this AI-driven paradigm will shift engineering material design from empirical trial-and-error iteration toward quantitative multi-objective optimization and design of potential metamaterials. Carbon emissions, resource consumption, recyclability and costs should be added into the objectives together with required properties of the engineering materials in the design. Therefore, a life-cycle assessment should be conducted following established standards, with calculations based on activity data multiplied by their corresponding emission factors.

In summary, a generational leap in the performance of cement-based engineering materials is within reach, propelled by the integration of enhanced mechanical properties, extended service life, multifunctional capabilities, and intelligent design. Concurrently, the pursuit of sustainability is driving a systemic transition of cement-based engineering materials from "high energy consumption, high CO_2 emission" mode toward "high-efficiency, low-carbon" mode. Together, these advances lay a critical foundation for infrastructure that is not only safer, more durable, but also inherently "smart" and sustainable. Looking beyond cementitious systems, the broader family of engineering materials, e.g. advanced alloys, offers valuable inspiration. Through twin/phase boundary engineering and gradient structuring, exceptional mechanical synergy can be achieved even under extreme conditions [27, 28]. By borrowing design philosophies across traditionally separate domains, we may ultimately transcend the persistent trade-offs that have constrained individual material systems, paving the way for a new generation of engineering materials.

Data Availability Statement

Not applicable.

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Conflicts of Interest

Song Mu and Fangyu Han are affiliated with the Jiangsu Sobute New Materials Co. Ltd., Nanjing 211103, China. The authors declare that this affiliation had no influence on the study design, data collection, analysis, interpretation, or the decision to publish, and that no other competing interests exist.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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