Bridging Materials Science and Human Factors for Construction Worker Health and Safety: An Integrated Framework

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Abstract

The construction industry remains one of the high-risk industries worldwide. Improvement of construction worker health and safety requires a safer interaction between workers and construction tasks including materials used, tools adopted, and protective systems applied. Construction safety research has focused on human factors such as worker behavior, workload, and safety management to improve worker health and safety. In contrast, construction materials research primarily focuses on performance, durability, and sustainability of the materials themselves. It rarely considers how material properties affect worker health and safety. This paper reviews the available cross-disciplinary literature and synthesizes how materials shape worker health and safety through several pathways. These include reduced physical strain through material property changes, lower tool–hand vibration, improved thermal comfort, and reduced dust, fumes, and particle exposures. The review also summarizes Artificial Intelligence (AI) uses in materials science and ergonomic risk assessment and notes limited work that connects material decisions to measured worker outcomes. Based on this synthesis, the paper proposes an integrated framework that bridges materials science and human factors to improve construction worker health and safety. The framework links tasks to the associated risks and exposures, then uses that evidence to guide safer material choices through AI that prioritizes elimination, improvement, and substitution.

Keywords – Human Factors; Materials Science; Construction Management

1 Introduction

Construction is a high-risk industry worldwide. For this reason, ensuring worker health and safety remains a major concern. Globally, the International Labour Organization estimates that at least 200,000 workers suffer fatal injuries in construction and manufacturing industries [1]. These alarming statistics underscore an urgent global need for improved health and safety interventions in construction.

Construction safety risks are often created at the point where workers interact with materials. Heavy materials increase lifting force and cause musculoskeletal strain [2]. Dusty or toxic materials release harmful particles and fumes during cutting, grinding, or mixing [3, 4, 5]. Heavy tools generate heat stress and vibration that transfer directly to the worker's body [6]. Traditionally, construction safety efforts focus on human factors (worker behavior, physical capacity, and cognitive performance) and protective equipment. Studies have developed EMG-based systems to monitor muscle fatigue, video-based systems to detect unsafe postures, and wearable sensors to track biomechanical overload in real time [7, 8, 9]. These approaches target how workers move, perceive, and respond to hazards. Yet many risks are created before the worker acts. For example, a mason lifting a heavy concrete block is exposed to shoulder strain because of the block's mass, not because of poor technique [2]. A worker cutting engineered stone inhales silica dust because of the material's composition [10]. In both cases, the risk originates from the material itself. In parallel, materials science in construction focuses more on structural performance and durability. Worker health and safety are rarely considered as a design criterion in such material developments. This creates a separation where worker health and safety is managed through procedures such as training, method statements, and use of protective equipment, even when the risk is created at the material–task interface (for example, lifting heavy masonry units or cutting high-silica engineered stone). Bridging these fields offers a major opportunity to shift part of risk control into material and product design. Material-enabled systems, whose performance is driven by their material properties, such as building products (blocks, panels), tools, and safety equipment, can be designed and selected with worker health and safety as a design criterion. For example, design choices can reduce biomechanical loading through safer handling and load distribution. They can reduce exposure through low-dust or low-emission formulations. They can improve real-time protection through embedded sensors that detect risks and alert workers. This approach shifts risk control to the material-task interaction.

This paper highlights various studies where materials science played a role in reducing construction risk and improving worker safety. It also proposes a framework to bridge materials science and human factors in improving the health and safety of construction workers in a systematic way.

2 Literature Review

This literature review explores how innovation in materials and material-enabled systems reduce risks to construction worker health and safety. The review focuses on studies that link materials science to worker health or safety. The literature is organized around three themes, material innovations, human factors, and AI applications in material innovation/human factors. Sections 2.1 to 2.4 review how material choices and material-enabled systems influence biomechanical load, exposure, protection, and assistive devices for workers. Section 2.5 reviews how AI is used in materials science and in ergonomic risk assessment. Across these sections, the review shows that materials research and human factors research are still largely treated in parallel, and that existing AI applications have not yet been used to connect material decisions to measured worker outcomes, which motivates the integrated framework proposed in Section 4.

2.1 Materials for Biomechanical Load Reduction in Construction Tasks

Modern construction materials can play an important role in reducing physical strain and the risk of musculoskeletal disorders (MSDs) among workers. One example is the study of Autoclaved Aerated Concrete (AAC). AAC is made by adding aluminum powder to a cement, lime, and silica slurry. Gas formation creates a cellular pore network. Steam curing stabilizes this cellular microstructure. The cellular structure reduces density and unit mass compared to conventional concrete masonry units (CMUs). Lower unit mass reduces the required lifting force during placement. This lowers shoulder and upper extremity loading during repetitive handling [2]. Another example is Self-Compacting Concrete (SCC). SCC is formulated using superplasticizers and viscosity-modifying admixtures. These admixtures increase flowability and stability, allowing the concrete to consolidate under its own weight [11]. This eliminates the need for mechanical vibration during placement. Removing internal vibrators reduces manual handling demands and repetitive insertion motions. Worker postures become more neutral and consistent during concrete placement. Physical workload is reduced in comparative ergonomic assessments. Noise exposure is also lowered because vibration equipment is not required compared to conventional vibrated concrete [12]. It is evident that only limited work has systematically linked materials science to ergonomic outcomes in construction. This gap motivates the present study to clarify how material microstructure, rheology, and handling characteristics can be designed to reduce biomechanical risk for construction workers during field tasks.

2.2 Materials Substitution and Formulations for Exposure Reduction

Another approach is to replace hazardous construction materials with safer alternatives to prevent occupational illnesses. Research in industrial hygiene and materials science has identified several effective substitutions. Silica dust is a major health risk in construction. National Institute for Occupational Safety and Health (NIOSH) studies showed that replacing sand with garnet, slag, or crushed glass in abrasive blasting greatly reduced respirable dust. This lowered the risk of silicosis [13]. More recently, manufacturers have reformulated engineered stone products. Traditional engineered stones contain very high levels of crystalline silica. New low-silica composites use recycled glass and resins instead of quartz. These materials produce far less respirable silica during cutting, which significantly reduces risks for workers [10]. Another study explored biochar (charcoal derived from biomass) as an asphalt additive. They found that biochar made from certain waste (e.g., coconut fiber or wood) can absorb volatile organic compounds (VOCs) and sulfur gases from hot asphalt. In lab tests, cellulose-rich biochar captured more hydrogen sulfide and nitrogen oxides (NOx), while lignin-rich biochar absorbed more VOC vapors. This bio-based material not only reduced fume toxicity but also improved the asphalt's high-temperature performance [4]. Asbestos, once common in construction, has been largely phased out through material substitution. According to the World Health Organization (WHO), many fiber alternatives to chrysotile asbestos (such as fiberglass or cellulose fibers) pose much lower health risks. By replacing asbestos with these safer fibers in insulation, roofing, and cement products, countries have sharply reduced incidences of asbestosis and mesothelioma [3]. WHO emphasizes that stopping asbestos use and switching to low-risk materials is the most effective prevention strategy [3]. Hazardous chemicals in paints and coatings are also targeted for substitution. A recent study identified dozens of harmful ingredients (solvents, isocyanate hardeners, etc.) linked to painters' asthma, dermatitis, and cancer [5]. Such reformulation in materials science can directly improve worker health by eliminating exposures to carcinogens and sensitizers.

2.3 Smart Materials and Advanced Personal Protective Equipment (PPE) for Real-Time Risk Control

PPE is evolving with new materials and smart technologies to better safeguard workers. These materials improve comfort, reduce exposure to hazards, and minimize vibration at the body interface. For example, nanomaterials have revolutionized filter performance in respiratory PPE for construction workers. Electrospun nanofibers (polyvinylidene fluoride, polyacrylonitrile, polybenzimidazole, and nylon-6) with self-crimp structures and electret properties achieve better filtration efficiency against various particles while maintaining low breathing resistance [14]. Another compelling material-driven example is thermal protection. Cooling vests with phase change materials (PCMs) absorb heat and reduce thermal burden. In one experimental study, a hybrid cooling vest with PCM inserts and fans significantly reduced thermal strain and heart rate in hot conditions. Workers wearing the vest reported improved comfort and lower heat stress compared to those without it. This shows how a material property change can directly improve a worker outcome [15]. A study on tuned mass damper systems for controlling hand-arm vibration syndrome in hand-held tools demonstrated a reduction in vibration levels of more than 40 dB (100-fold reduction). The system used elastomeric materials installed around tool handles as passive dampers to oppose dynamic vibrational motion [6]. Research on visco-elastic polymer gloves for hand-arm vibration syndrome demonstrated that viscoelastic tool wraps reduce vibrations at both the tool handle and the hand. The viscoelastic properties of these materials enable effective energy dissipation through internal friction mechanisms [16]. This shows that advancement in material properties in PPE can significantly improve workers' health and safety. Materials science plays an important role in the development of smart PPE. One of the great candidates for composing smart PPE is polymer-based piezoelectric materials with the fabrication capability of lightweight, low cost, and easy manufacturing. Flexible piezoelectric devices play a key role in wearable energy harvesting and sensor applications [17]. Connected safety vests and workwear use conductive materials built directly into the fabric. Metal-based conductors (such as silver nanowires and silver nanoparticles), carbon-based materials (graphene, carbon nanotubes, and carbon black), and conductive polymers are deposited onto textiles like cotton, nylon, or polyurethane. These materials are applied by processes such as dip-coating, electrospinning, or vapor deposition. The resulting conductive fabrics form soft sensors that can continuously monitor heart rate (electrocardiography and pulse), body temperature, and posture or movement by tracking joint motion and body orientation [18]. In short, high-tech materials (such as nanofiber filters, phase-change gels, and impact-absorbing foams) offer better protection and comfort. Meanwhile, embedding Internet of Things sensors in PPE enables real-time risk detection that can send an automatic alert if a worker's core temperature or heart rate indicates heat exhaustion [9, 19].

2.4 Materials in Assistive Devices and Wearable Robotics for Load Distribution

A related area where materials science intersects with human factors is in the design of assistive devices that directly support or augment the human body to reduce strain. One key consideration in exoskeleton design is material selection, as the materials dictate the exoskeleton's weight, stiffness, and comfort [20, 21]. A heavy steel exoskeleton, for example, might reduce some strain when in use but could exhaust the worker just by virtue of its weight. New studies have shown that using lightweight composites and alloys can improve exoskeleton ergonomics significantly. The latest research conducted a comparative analysis of seven material types for a lower-body exoskeleton and found that lighter materials (e.g., certain carbon fiber composites) notably reduced joint loads and improved user comfort, whereas very rigid materials (e.g., steel) provided stability but at the cost of user comfort [22]. A lightweight powered back exosuit (soft exoskeleton) was recently reported to reduce muscular effort during lifting by using textile actuators and an algorithm to time the assist [23]. With iterative design (often guided by biomechanical simulation and user feedback), newer models are becoming more user-friendly. Furthermore, a new shoulder exoskeleton made from carbon fiber components offers sufficient strength and a smaller density compared to steel [24]. As this technology matures, it represents a promising embodiment of the materials-human factors nexus. The results show that material choice plays a critical role in ergonomics.

2.5 Use of AI in Materials and Human Factors in Construction

Artificial intelligence (AI) is increasingly used to optimize material properties and to assess ergonomic risk. In materials science, AI tools, such as MPpredictor and deep learning models, predict properties such as elastic moduli, band gaps, and thermal properties from composition. This supports rapid screening for target mechanical performance and optimization [25, 26]. In occupational ergonomics, wearable sensors with machine learning classify postures and estimate biomechanical load in real time [27]. Computer vision systems and AI models are also used to compute standardized ergonomic risk scores such as Rapid Entire Body Assessment, Rapid Upper Limb Assessment, and the Ovako Working Posture Analysis System in both the construction and manufacturing industries [8, 28, 29]. These systems are mainly used for posture monitoring and ergonomic risk assessment. However, no construction materials study was found that applies AI to design or select materials with measured ergonomic outcomes as the primary objective. This gap further motivates the need for integrated workflows. AI can help connect materials science and human factors by supporting risk analysis, posture and exposure assessment, wearable sensor data analysis, and selection of better materials or PPE options for specific tasks. Such workflows would use AI-driven materials discovery and optimization to improve construction worker ergonomics and reduce risk. The proposed framework utilizes this role of AI by using these techniques to map risks to tasks and to select material-based interventions.

3 Methodology

A focused literature review was conducted. Peer-reviewed journal studies, industrial studies, and official reports were collected on construction safety, human factors, and material-related interventions from 1995 to 2025. Searches were conducted in Scopus with supplementary searching in Google Scholar. Keyword combinations including construction, materials science, material properties, lightweight materials, composites, polymers, formulations, substitution, manual material handling, lifting, carrying, musculoskeletal disorders, biomechanical load, vibration, hand-arm vibration, heat stress, respirable dust, silica exposure, fumes, volatile organic compounds, smart PPE, wearable sensors, and ergonomic risk were used to capture both material innovations and worker outcomes. A total of 1,222 records were initially retrieved and screened based on titles and abstracts for relevance. Studies were retained if they explicitly linked a material choice or material property to worker health or safety outcomes. Papers focusing solely on management or training, without any connection to materials, were not prioritized. The aim was to identify sources that meaningfully connect materials science with construction safety.

Key information was extracted from each study by recording the material or product, the related construction task, and the reported worker outcome. The categories presented in the literature review were derived by comparing recurring links between material interventions, construction tasks, and worker outcomes across the reviewed studies to explain how materials shape worker health and safety. These categories were organized into four worker-facing material solution pathways. They include (1) ergonomic material innovation, (2) hazardous material substitution and safer formulations, (3) advanced PPE and smart materials, and (4) assistive and wearable devices. These four pathways do not include every possible case. They represent the main worker-related patterns found in the reviewed literature. Improved constructability and safety in design were treated as broader design strategies. They may fit within one or more of these pathways by making tasks easier, reducing exposure, or improving the worker-material interface. A conceptual framework was proposed from this synthesis because the area is still underexplored and the evidence is scattered, as described in Section 4.

4 Proposed Framework

This proposed Materials-Human Factor Safety Framework starts with evidence, as shown in Figure 1. It uses fatality data, injury data, and disease data. The data are cleaned and organized. Outcomes are ranked by severity and frequency. This step identifies the priority risks that the framework targets and provides the starting point for linking broad outcome evidence to specific material-related intervention needs.

The framework then applies AI-powered risk and task mapping using natural language processing (NLP) and machine learning, with computer vision, depending on the type of data available. NLP extracts structured risk information from incident narratives, while computer vision estimates posture and computes Rapid Entire Body Assessment (REBA) or Rapid Upper Limb Assessment (RULA) scores from site images or video. Machine learning can be applied to wearable sensor data or exposure-related measurements to estimate biomechanical demand, vibration or heat stress, and likely risk severity. Together, these methods link each priority outcome to a specific work task and to the trade, tool, material handled, and work context. The main decision outputs from this stage are task identification, risk classification, material linkage, and selection of the most appropriate intervention pathway. In this framework, AI is used as a decision-support layer to organize and interpret risk information, rather than as a replacement for engineering judgment or worker input.

After task mapping, the framework introduces a material linkage decision. It determines whether the dominant risk source is attributable to a material property, formulation, or interface. This gate entry into the material pathways and excludes purely behavioral or supervisory risks from the framework scope. If the risk is driven by material properties, the framework guides innovation toward lighter and better-handled materials for ergonomic improvement, as demonstrated by AAC reducing shoulder loading in masonry tasks. If the risk stems from chemical hazards, the framework points to material substitution or safer formulations, such as replacing silica-sand blasting media with garnet or slag. If the risk involves equipment interfaces, the framework recommends advanced PPE and smart materials, such as nanofiber filters, anti-vibration gloves, or PCM cooling vests. If the risk is primarily biomechanical, the framework selects assistive and wearable devices where material choice reduces weight and improves comfort, such as carbon fiber exoskeletons. This structure is based on the main material-related mechanisms identified in the literature review and converts them into four operational pathways for decision making. Other material-related approaches, such as safety in design and prefabrication, are also important but fall outside the current scope and represent a direction for future work. These AI-enabled pathways ensure interventions match the specific risk mechanism. This framework assumes that better material choices can reduce risk earlier. This is supported by the evidence in Sections 2.1 to 2.4.

After the material-based intervention pathway is selected, all proposed solutions will be tested in the lab. Risk to workers' health and safety is assessed using pathway-appropriate measures. Biomechanical pathways use REBA or RULA scores. Chemical pathways compare outcomes against occupational exposure limits. PPE pathways assess filtration or vibration attenuation metrics. Ergonomic risk will be assessed using task-specific measures such as the NIOSH Lifting Index or posture observation tools. The lab stage retains a solution only if it improves at least one primary risk metric without introducing an unacceptable risk and remains practically usable for the target task.

If lab results show significant improvement, the solution will proceed to a field assessment. The same risks will be assessed in real job-site conditions. The same primary metrics used in the lab stage will be reassessed in the field to confirm that the improvement is sustained under job-site conditions. Usability and adoption will also be examined. If no improvement is observed in the field, the process will return to the lab stage. The design will be adjusted and tested again. If field results confirm improvement, the solution will proceed to implementation. During implementation, the material solution is incorporated into project specifications or PPE selection guidelines, enabling its integration into practice.

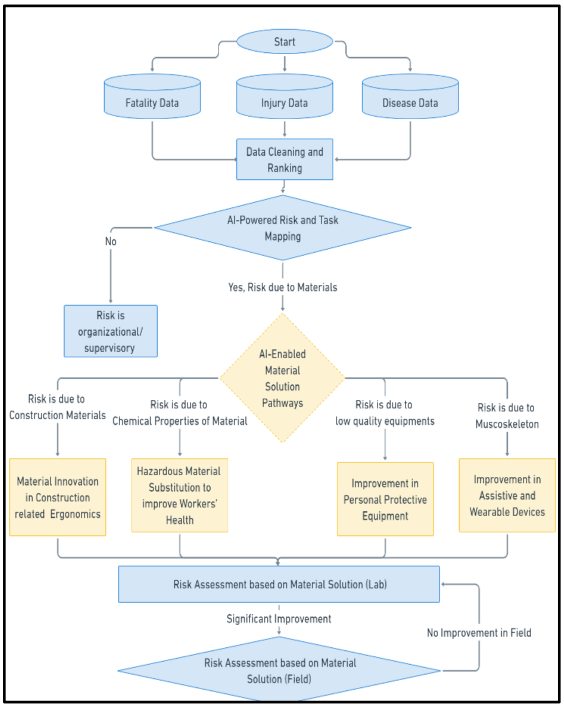

Figure 1. Proposed Materials-Human Factor Safety Framework

The proposed framework is conceptual. Its application is illustrated using a masonry study that compared masons' handling of CMUs and AACs in a field setting. All quantitative values in Table 1, including block weights, holding times, pain scores, and statistical test results, are taken directly from that study. Our contribution is to reorganize these results according to the steps of the framework. The "AI-powered risk and task mapping" step in Table 1 is conceptual in this example and illustrates how AI could be used in future implementations, although no AI methods were applied in this example. In the general framework, new material solutions would typically be evaluated first in laboratory studies and then in field trials, but in this illustrative example, both the "lab assessment" and "field assessment" steps in Table 1 are populated using the field measurements reported in [2].

Table 1. Illustrative scenario for the proposed framework

Major steps	Illustrative Scenario
Data collection	Shoulder and low back pain are reported in masons during repetitive CMU lifting and mortar application
Data cleaning and ranking	Shoulder and low back MSDs identified as priority

Major steps	Illustrative Scenario
	outcomes in the masonry trade
AI-Powered risk and task mapping	Repetitive CMU lifting (mean 15.7 kg, held 6.71 s) linked to shoulder and low back loading
Material linkage decision	Yes. Block unit mass, hold time, and mortar application method are linked to the observed worker exposure
Pathway 1. Material innovation for ergonomics	AAC selected. Two-handed handling reduces mortar application, shorter hold time (4.97 s, $p<0.001$)
Lab assessment	AAC showed lower shoulder and lower back pain with $p = 0.009$, and less left upper extremity stress
Field assessment	AAC showed lower shoulder and lower back pain with $p = 0.009$, and less left upper extremity stress
Implementation	AAC is promoted as an ergonomic CMU alternative with supporting best practice guidelines

5 Conclusion

This paper shows that materials and material-enabled systems can directly shape construction worker risk. Materials science can reduce physical strain by improving material properties. Safer substitutions and reformulations can cut dust, fumes, and toxic exposure. Advanced PPE, smart materials, and embedded sensing can improve protection and comfort. Assistive and wearable devices can reduce fatigue when materials are selected for low weight and user comfort.

The proposed framework provides a clear path to act on this link. Based on data, it connects outcomes to tasks and hazards. It then selects a material-based solution that fits the risk mechanism. Lab testing checks safety gains and any new risks. Field testing checks real-world use and adoption. The loop supports improvement until the solution works in practice. This approach helps move from reactive safety to prevention through design. It also supports safer construction without sacrificing performance and durability. The framework is conceptual and has not yet been tested in practice. Future work should pilot it in one trade and empirically evaluate the AI task mapping, lab assessment, and field assessment steps.

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