Forum

Incorporating Disaster Debris into Sustainable Construction Research and Practice

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Need for Realizing the Resource Potential of Disaster Debris in the Built Environment

Extreme climate-related disaster events cause significant damage and generate large quantities of debris. Although the magnitude of the debris constitutes a major management challenge, it can be capitalized on to support the recovery of the affected built environment through debris recycling and reuse in postdisaster reconstruction applications. The inert nature of some of the constituents of disaster debris (e.g., concrete, metals, masonry, asphalt, bricks, tiles) provides high potential for recycling and reuse as building materials, which can alleviate concerns about postdisaster material availability and resource scarcity (Chang et al. 2011). Despite the significant benefits of material diversion and recycling in the aftermath of disaster events, most disaster debris in practice is disposed of in landfills, thereby losing the potential value present in the debris stream that could help in conserving virgin resources.

The construction sector is recognized as the largest consumer of raw materials globally, with an annual consumption exceeding 3 billion tons (WEF 2016). The sector also accounts for 39% of global carbon emissions (Munaro et al. 2021), with half of the entire carbon footprint of new construction by 2050 expected to come from the carbon emissions associated with the production phase of building materials, also known as "upfront carbon" (WorldGBC 2019). Because the need to reduce the stress exerted by the built environment on the natural environment is increasingly acknowledged, sustainable material use and management principles are prioritized in construction research and practice. The adoption of the circular economy concept, which is based on closing material loops by applying principles of reducing, reusing, and recycling (Hill et al. 2023), has been particularly emphasized as critical to achieving sustainability in construction (Munaro et al. 2021). Circular economy-related research in construction, however, has primarily focused on the management of peacetime construction and demolition (C&D) waste, with limited emphasis placed on postdisaster waste management practices. The unique characteristics of disaster debris (i.e., in terms of enormity, degree of mixing, areal extent, potential contamination, and material properties) and the distinctive challenges surrounding its management operations (e.g., priority for search and rescue operations, requirements for rapid response and restoration of basic lifelines, limited capacity of existing waste management facilities, risk of environmental hazards, and funding requirements) make it hard to apply established circular economy approaches used for the management of peacetime C&D waste. In anticipation of increasing frequency and severity of extreme disaster events as a result of global climate change (Nickdoost et al. 2022), we need to expand our vision of sustainable material management within construction research and practice to integrate the recycling and reuse of postdisaster materials. Realizing disaster debris as a source of materials for rebuilding is fundamental to promoting circularity in the built environment, contributing to reductions in raw material use as well as upfront carbon emissions.

The US National Science Foundation sponsored two national workshops, the first in 2019 and the second in 2022, bringing together an interdisciplinary group of researchers and practitioners from both public sectors and private institutions to identify critical multifaceted data and research needs to address current and future sustainable disaster debris management challenges. Based on the findings of these workshops, along with a review of some relevant emerging studies in the construction engineering and management literature, we present in this forum the critical data needs and recommended future directions in sustainable construction research and practice to facilitate the recycling and reuse of postdisaster materials in construction applications.

Data Informing the Feasibility of Disaster Debris Recycling and Reuse in Construction

Several interdependent technical, environmental, social, economic, funding, and regulatory factors affect the sustainable management of postdisaster materials and their valorization in the built environment (Jalloul et al. 2022b). Creating value in the otherwise end-of-life materials requires conducting a data-based investigation of these diverse factors that impact the feasibility of postdisaster recycling and reuse. The main identified data needs to conduct such an investigation can be grouped under three themes:

(1) debris estimation and management pathways; (2) environmental and social concerns; and (3) economics, funding, and regulations. To better guide the timely collection of the identified data, we provide examples of relevant data collection methods and indicate the time frame of data availability, including predisaster, postdisaster response, short-term recovery, and long-term recovery phases.

Debris Estimation and Management Pathways

Critical design factors in the process of sustainably managing disaster debris within the built environment are the quantity and composition of the disaster debris (Park et al. 2020). They inform the (1) type and amount of materials that could be potentially salvaged for recycling or reuse in reconstruction applications; (2) space, machinery, and labor resources needed to sort, process, and store the debris; and (3) required capacity and throughput of the material recovery and recycling facilities. The data needed to make reliable modeling predictions of the quantity and composition of disaster debris vary depending on the debris modeling method, ranging from geographic information (e.g., hazard zones, land use, housing density, and vegetation properties) and material stock information (e.g., breakdown of construction materials used and internal contents of structures) to the characteristics of historical disaster events (e.g., seismic intensity, wind speed, storm category, flooding depths, etc.). All of this debris modeling information can be obtained from public archives and databases upon request and private debris hauling records during the predisaster phase. Following the occurrence of the disaster event, the quantity and composition of the generated debris can be determined through field reconnaissance by conducting ground-level investigations (e.g., street-level imaging) or through the use of remote sensing techniques (e.g., airborne sensors and aerial or satellite imaging). In addition, both crowdsourced and social media data (e.g., images, videos, or texts tagged with geolocations) can augment the data formally collected by researchers in the field. During the postdisaster short-term recovery phase, the mass, volume, and composition information of the disaster debris can be obtained from debris hauling records retrieved from public agencies or private debris contractors. Such data can serve to corroborate field estimates obtained from reconnaissance efforts and validate initial modeling predictions.

The operational characteristics of the available waste recycling or reuse infrastructure also significantly impact the extent to which disaster debris can be recycled or reused (Lorca et al. 2017). In this regard, data pertaining to approved debris staging and processing sites and available material recovery facilities (e.g., location, types of materials accepted, capacity, and throughput) are needed to facilitate the proper allocation of debris materials to sustainable management pathways that can yield recycled building materials.

Environmental and Social Concerns

The main environmental data needs to evaluate the feasibility of disaster debris recycling and reuse in construction applications include the characteristics of hazardous pollutants of chemical and biological origins in the disaster debris streams that pose harm to both humans and the surrounding environment. Such environmental data (1) inform safe debris handling practices to minimize human health impacts, (2) enable prediction of relevant pollutant fate and transport pathways, and (3) guide application of decontamination or remediation best practices to facilitate recycling and recovery of the waste materials. Examples of hazardous materials that should be separated from the disaster debris before recycling and reuse in rebuilding include asbestos-containing materials (e.g., ceiling, flooring, roofing, and insulation of old structures), lead-containing materials (e.g., lead-based paints and old plumbing systems), fuels (e.g., propane or gasoline tanks), electronic wastes, and chromated copper arsenate-treated wood, among others (USEPA 2019). Identification and quantification of such hazardous pollutants can be achieved using a combination of predictive or field-based approaches. Predictive approaches involve the use of modeling techniques, which can be applied during the predisaster phase with available building interior or exterior material inventories and product chemical composition databases. Field-based approaches include debris monitoring, sampling, and laboratory testing during the postdisaster short-term and long-term recovery phases.

Ensuring sustainability in disaster debris management also requires accounting for the greenhouse gas (GHG) emissions generated throughout the debris management process (Habib et al. 2019). Information about these emissions is needed to develop detailed, spatiotemporally explicit life cycle assessments comparing the environmental impacts of conventional construction materials and recycled or reused disaster debris. GHG emissions can be quantified both from the waste materials themselves and the equipment used during each step of debris management, ranging from transportation, sorting, and storage to processing at material recovery facilities and landfilling. This analysis can be based on probabilistic estimates using information obtained from carbon footprint databases during the predisaster phase or using emissions measurements conducted during the postdisaster short-term and long-term recovery phases.

In addition to environmental considerations, social aspects can also impact the potential to recycle or reuse disaster debris in the built environment (Jalloul et al. 2022a). Information about the values, cultural norms, emotional experiences, and level of engagement of the disaster-affected communities in the postdisaster debris separation, sorting, and collection operations is needed to assess the priorities, concerns, and support of the general public for debris recycling and reuse in postdisaster construction applications. The primary collection methods for the highly qualitative social data needs are longitudinal surveys, focus groups, and interviews with members of the disaster-affected communities, conducted during the postdisaster short-term and long-term recovery phases. In addition, information about public safety, health risks, vulnerability, resilience, and adaptive capacity of the disaster-affected communities is critical to ensure that the disaster debris management process is not only sustainable but also equitable, effectively assisting disadvantaged communities in their rebuilding and recovery efforts. These social equity and environmental justice–related data needs can often be met from publicly available and proprietary databases.

Economics, Funding, and Regulations

The economics of the disaster debris management operations, the available funding mechanisms, and the governing debris management and building regulations can either enable or preclude the recycling and reuse of disaster debris in the built environment (Brown and Milke 2016). Assessing the economic viability of disaster debris recycling and reuse for reconstruction requires (1) data on the costs associated with the debris collection, sorting, processing, and treatment operations, as well as (2) information about the market demand for recycled building materials and their valuation metrics. As a requirement for any cost reimbursement from state and federal funding agencies, monitoring data on the debris management operations (i.e., actual debris quantities, employed resources, incurred costs, etc.) need to be documented during the postdisaster

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short-term and long-term recovery phases. In addition to the relevant funding-related policies, disaster debris–related and building materials–related regulatory information needs to be collected during the predisaster phase. Specifically, state and regional disaster debris management guidelines as well as provisions on the sustainable design and construction of buildings and infrastructure projects need to be examined to inform the development of sustainable debris management plans and their adherence to governing regulations.

Recommended Future Directions in Sustainable Construction Research and Practice

Timely collection and public availability of disaster debris data support recommended future directions in sustainable construction research and practice, covering (1) postdisaster materials-focused research; (2) advanced disaster debris management technologies and processes; and (3) supportive postdisaster recycling funding, regulatory, and economic frameworks (Fig. 1). These directions are critical in addressing the current barriers to promoting the recycling and reuse of postdisaster materials in construction applications, including technical challenges, operational inefficiencies, legal constraints, and cost-effectiveness concerns.

Postdisaster Materials-Focused Research

One of the main impediments to the recycling and reuse of disaster debris, particularly in construction applications, is the current limited understanding of the characteristics and material properties of the debris generated from disasters. Overcoming this knowledge gap starts with establishing a hierarchy of debris materials that can be prioritized for postdisaster rebuilding as a function of extreme event type (e.g., earthquakes, hurricanes, tornadoes, wildfires, landslides) using data on quantity and composition of debris streams from previous disaster events. Similar to existing construction engineering research investigating the properties of recycled construction materials (Damdelen and Tansu 2022), new research efforts can be directed toward studying the unique engineering properties of postdisaster materials that impact recyclability in construction applications. Specifically, criteria for the salvageability of disaster debris for recycling and reuse in the built environment need to be established based on relevant physical, mechanical, chemical, and biological characteristics (e.g., density, deformation, moisture content, organic decay, contamination) through laboratory testing of sampled debris as well as application of modeling approaches using previously collected debris characteristics data. Because the quality of recycled building materials depends on how they are processed and treated (Wang et al. 2020), postdisaster materials-focused research should also identify best practices for handling and processing different types of debris materials and indicate the most appropriate treatment methods for enhancing engineering properties (e.g., strength, toughness, stiffness). Existing research on the performance of recycled construction materials (Gao et al. 2018) should be extended to study the impact of incorporating recycled postdisaster materials on the performance of building and infrastructure components. Specifically, these components should be tested under simulated real-life conditions to predict their short-term and long-term performance. Findings from these research investigations can be used to recommend the best end-use construction recycling applications for different types of postdisaster materials based on their characteristics and performance behavior.

Advanced Disaster Debris Management Technologies and Processes

The implementation of disaster debris recycling and reuse practices within the built environment is challenged by uncertainties in debris quantification, adversities in contamination detection, and

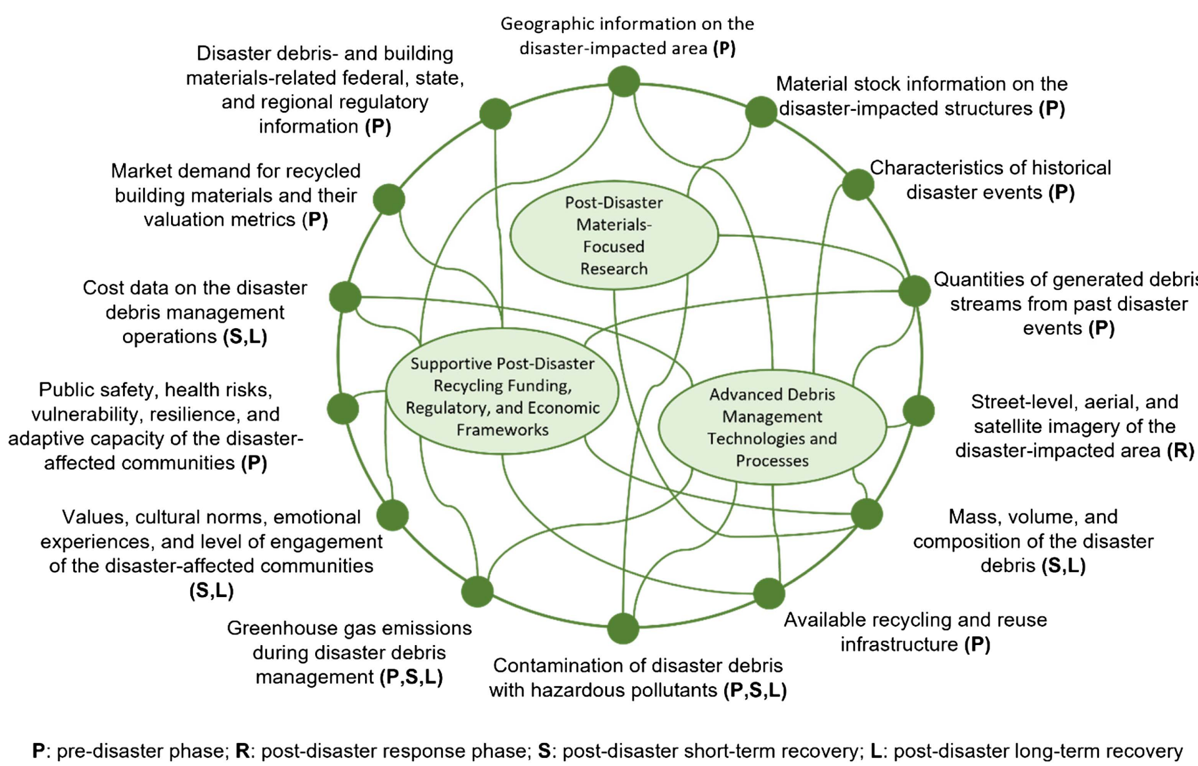

Fig. 1. Recommended future directions in sustainable construction research and practice and their data needs.

inefficiencies in management operations. Research in innovation and technology adoption in construction should incorporate innovative methods and technologies throughout all stages of the disaster debris management processes. Uncertainty associated with currently available model-based and field-based debris quantification methodologies is significant, resulting in potential critical increases in disaster debris management costs due to overestimations or underestimations of actual debris quantities (Marchesini et al. 2020). Existing construction research efforts to automate and increase the accuracy of construction material estimation processes for project cost control purposes (El-Omari and Moselhi 2008) can be adapted for disaster debris quantity estimation to enable proper control of the costs associated with debris recycling and reuse in construction applications. Efforts should also be made to enhance the accuracy of existing disaster debris estimation models by calibrating the models using large datasets from historic disaster events, including geographic properties of the disaster-impacted regions and the amount and composition of the generated debris. Advancements in ground-level imaging–based and remote sensing–based debris estimation methods are further needed for estimating composition of materials in debris piles. For detection of disaster debris contamination, construction research efforts investigating the use of semidestructive testing methods in identifying defects in construction materials and analyzing their properties (Jaskowska-Lemańska and Sagan 2019) can potentially be extended to detect some of the hazardous materials in disaster debris. Transformative research in construction to automate repetitive and time-consuming construction operations (Aghimien et al. 2020) can be expanded to cover the automation of debris sorting and processing operations. The use of artificial intelligence, smart vision, and robotics technologies is recommended to reduce the duration of debris management operations and minimize human exposure to potentially contaminated disaster debris. Furthermore, similar to existing studies on optimizing construction operations and materials logistics under resource availability constraints (Liu and Lu 2018), research should be directed toward optimizing the allocation of postdisaster waste materials to the existing recycling pathways to improve overall operational efficiency and cost-effectiveness. This direction of research can leverage advanced analytical models and simulation-based methodologies, using information about the quantity and composition of the debris to be recycled as well as data on the available debris recycling infrastructure.

Supportive Postdisaster Recycling Funding, Regulatory, and Economic Frameworks

Sustainable disaster debris management planning within the built environment requires robust and strategic funding and regulatory support. In line with recent construction research examining funding and legislation-related barriers to and enablers of the use of recycled materials in construction applications (Jin and Chen 2019), future research should be directed toward overcoming the funding and regulatory bottlenecks that impede effective recycling and reuse of disaster debris in construction applications. The currently available federal assistance mechanisms to fund the management of disaster debris only cover debris management options with the lowest direct economic cost (i.e., not considering the indirect environmental costs and the depletion of resources) and only for a short period of time following the disaster event (Brown and Milke 2016). These funding mechanisms often indirectly promote solid waste landfills as the primary debris management and disposal pathway. Practical research is recommended to investigate potential changes in federal funding policies on disaster debris management to relax duration constraints, tax environmental burdens (i.e., carbon taxes), and incentivize carbon sequestration in the built environment as well as provide funding incentives for debris recycling and reuse in rebuilding. Findings from such research can demonstrate to policy makers the benefits of modifying current funding mechanisms and resource allocation to promote recycling and reuse of disaster debris in reconstruction over landfilling. In addition to examining relevant funding regulations, findings from postdisaster material-focused research and scientific assessments can be used to revise current building codes and construction standards. By better incorporating performance-based measures and fortified construction provisions, structures can be more resilient to extreme disaster events, ultimately reducing the amount of disaster-generated debris. Furthermore, building codes supporting the application of a certain level of recycled or reused materials or building materials with net zero embodied energy can incentivize communities to work toward a circular economy in the aftermath of a disaster event.

Research is needed to investigate how the economic viability of disaster debris recycling and reuse in construction applications can be achieved and maintained. Similar to current construction research in circular business models (Munaro et al. 2021), future research should be directed toward exploring cost-effective disaster debris recycling business models and optimized supply chain frameworks, informed by debris management economics data. Maintaining the economic viability of sustainable disaster debris management practices within the built environment requires the presence of well-developed postdisaster markets for recycled building materials. Investigation of market matching mechanisms for the development of robust new end-markets for recycled building materials from debris are recommended, accompanied by the needed economic instruments (e.g., taxes and subsidies) to regulate these.

Conclusion

Increasing resource depletion and material availability challenges, coupled with the intensifying effects of global climate change, necessitate a paradigm shift in the conventional management of disaster debris. Postdisaster materials should be regarded as a valuable resource to be recovered rather than disposed of. To achieve circularity in the built environment, sustainability within construction research and practice must be expanded to incorporate recycling and reuse of postdisaster materials. This forum calls attention to critical new directions in sustainable construction research and practice, along with their data needs, focusing on (1) material science for disaster debris and reuse in construction applications; (2) advanced technologies and processes that facilitate disaster debris quantification, contamination detection, processing, and recycling; and (3) establishing necessary funding, regulatory, and economic frameworks to incentivize the valorization of postdisaster materials within the built environment. The authors hope that the recommended new directions serve as viable pathways for construction researchers and practitioners to establish the resource potential of disaster debris through postdisaster recycling and reuse.

Data Availability Statement

No data, models, or code were generated or used during this study.

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