ADVANCES IN CONCRETE TECHNOLOGY AND CONSTRUCTION – AN OVERVIEW

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Abstract

This overview paper first discusses some developments in concrete mechanics, and then highlights the issues and challenges in concrete sustainability through material manufacturing, use of concrete as well as construction automation. The role of Artificial Intelligence (AI) in predictive modeling is emphasized. It is envisioned that there is a new era of concrete materials possesing synergy with advanced technologies and construction automation so as to achieve a sustainable built environment.

Keywords: artificial intelligence, concrete mechanics, construction automation, sustainability, 3D printing.

1. INTRODUCTION

Concrete is currently the major construction material of our modern built environment. It is the most used material on earth with an annual production of more than 30 billion tons. This trend will continue to be the case since it appears there is no currently available construction material to meet the global needs for buildings and infrastructures. Cement provides the binding phase of concrete, and its energy intensive production currently exceeds 4 billion tons per year. The global demand for concrete and cement in construction has seen an unprecedented growth in the past fifty years. Use of concrete in construction has steadily increased with the advances in understanding its complex material behavior on one hand, and on the other, the rapid developments in computer science, computational mechanics, and modeling. Concrete mechanics and design developments aim at the creation of resilient and durable buildings and infrastructure capable of withstanding critical environmental and mechanical loadings. In recent years, motivated by the concerns for climate change effects, research efforts have been rapidly oriented towards sustainability of the built environment. Grand challenges for developing sustainable built environment include climate change mitigation, urban growth management, and infrastructure robustness. Climate mitigation responds to the increasing global greenhouse gas emissions which is significantly contributed by construction and building operation. Concrete, as the major construction material plays a big role in this process. The advances in concrete technology and construction pave the way towards a more sustainable and robust built environment.

This overview paper first discusses some developments in concrete mechanics, and then highlights the issues of concrete sustainability from the viewpoints of material manufacturing, use of concrete as well as construction automation and the role of Artificial Intelligence (AI) in predictive modeling.

2. CONCRETE MECHANICS

Concrete is a highly heterogeneous material with a complex nonlinear deformation and fracture behavior. Due to this complexity, which stems from the multiscale/ multiphysics nature of its property development, concrete studies have been a challenging active research field for many years. These research efforts and developments have been directed towards explaining the observed behavior from experiments and developing predictive analytical/numerical methods as a basis for design of reinforced and prestressed concrete structures. In what follows, a brief overview is provided of several developments primarily by the first author with his students and postdoctoral associates.

2.1. Interfaces

Fundamental concrete behavior and analytical studies that were initiated at Cornell University goes back to late 1960's and early 1970's with the definition of concrete as a two-phase particulate composite and introduction of microcracking at interfaces in explaining the deformation behavior and fracture of concrete [1, 2]. This involved both experiments and one of the first applications of the finite element method to concrete analysis. Elastic-plastic constitutive relations and associated material and computational models for concrete, including reinforcement modeling, in the context of general-purpose finite element programs were then developed [3, 4]. These developments continued in an evolutionary fashion including studies on modeling of shear transfer at cracked interfaces [5] in complex reinforced/prestressed concrete structures such as nuclear containment structures and precast segmental concrete bridges, as well as developments on thermomechanical behavior and design of high temperature concrete linings [6].

The basic concept of interface, its characterization, and modeling has been employed by many researchers up to the present time in a wide scope of mechanics and material design challenges. In concrete and cement, interfaces between the matrix material and inclusions as well as those between various material phases at nano and meso levels play a critical role in mechanical and durability properties. Application of fiber reinforced polymers (FRP) as external concrete reinforcement for improved strength and ductility has led to opportunities for further development in interface fracture characterization. A major challenge in this strategy has been in understanding and quantifying the mechanisms of fracture along critical interfaces [7, 8]. Atomistic modeling concepts were then introduced to provide structural solutions to capture the influence of moisture on the concrete-epoxy interface using molecular dynamics (MD) [9]. These findings were also extended to macroscopic length scales through finite element analysis (FEA) of the continuum behavior and development of a fundamental model for predicting irreversible weakening in bond strength under moisture cycles leading to a service life prediction tool [10]. A novel experimental method was also developed for robust characterization of organic–inorganic interfaces at the nanoscale [11]. Combining theory, experiments, and molecular simulations, it was shown that debonding between layers of materials can be controlled through residual stresses in a deposited metallic layer.

2.2. Multiscale mechanics

Cement paste is the matrix phase in mortar and concrete that exhibits a complex structure spanning orders of magnitude in length scales. As a pioneering effort a computational multiscale framework for connecting molecular details with macroscale performance in concrete materials has been developed employing a multiple layer-based modeling to study the structure and interactions within calcium-silicate-hydrate (C-S-H) [12], the main binding phase in cementitious materials. A cohesive-frictional force field (CFFF) is then proposed to realistically capture the intrinsic strength anisotropy of the interfaces between larger-scale assemblies of colloidal C-SH nanoparticles (13). This is accomplished through a multiscale model that captures the essential structures and interactions across atomistic (~1 nm), colloidal (~100 nm), and microstructural (~100 μm) length scales. Mesoscale simulations of colloidal assemblies indicate that cohesive-frictional interactions have a significant influence on deformation processes and strength behavior [13]. Also, a novel method was developed combining nanoindentation experiments with random field modelling to capture the complex heterogeneity within a cement paste microstructure connecting to the cm scale [14]. This work provides a foundation for future explorations and enables a paradigm shift in engineering the next generation of sustainable and durable cementitious structural materials using locally available waste materials and additives [15].

3. CONCRETE SUSTAINABILITY

There are multi-faceted challenges encompassing various aspects of concrete sustainability. In order to reduce the environmental impacts of concrete materials, several innovative approaches and research studies have emerged from the aspects of material composition, concrete utilization and construction process. These cover from enhancing the sustainability of clinker production, capturing and reusing carbon dioxide (CO_2) in concrete mixtures, replacing cement with supplementary cementitious materials, wastes and fillers, to minimizing the concrete usage via topology optimization. In addition, the implementation of construction automation and 3D printing of concrete extends the concrete sustainability.

3.1. Reduce CO_2 in clinker production

Clinker sustainability is a crucial aspect for developing more sustainable concrete structures. The energy-intensive and CO2-rich production process of clinker, which involves a high temperature treatment of limestone and clay in a cement kiln, is responsible for approximately 90% of total emissions from cement manufacturing process. Thus, the enhanced sustainability of clinker production and usage can significantly mitigate the environmental impact of concrete structures. Potential approaches include the exploration of alternative raw materials, alternative fuels, and improvement of energy efficiency in clinker production. Industrial by-products, such as steel slag and coal fly ash, can be regarded as partial replacement of limestone, so as to decrease both the consumption of natural resources and CO_2 emissions. The integration of advanced technologies such as waste heat recovery systems and energy-efficient kilns can further improve energy efficiency as well as decrease the overall carbon emissions. However, the mechanical properties of the clinker can possess large variations by introducing alternative raw materials which requires further quantification and inspection. The availability, quality, and cost of industrial byproducts are not unlimited. Besides, improving equipment energy efficiency requires a substantial amount of investment, which imposes a significant financial pressure on many manufacturers. In order to address these challenges, future research should focus more on developing affordable and feasible clinker substitutes and improving energy efficiency during cement production process.

3.2. Reuse CO_2 in capturing and curing

Improving concrete sustainability through the capture and reuse of CO_2 in concrete mix design demonstrates another innovative approach. Here, we discuss two potential approaches covering the implementation of carbon capture and storage (CCS) during cement production and the exploration of carbon mineralization within concrete mix. CCS technology, capable of capturing up to 90% of CO_2 emissions directly from the waste gas system by post-combustion, oxy-fuel combustion and pre-combustion, lays a foundation for the captured CO_2 underground storage and utilization in concrete mix. Meanwhile, carbon mineralization presents a transformation of CO_2 through chemical reactions with calcium-rich or magnesium-rich materials into carbonates which can be used as aggregates in concrete during carbonation curing. Even though CCS technology may be promising, it is considered as a costly, energy-intensive, and long-term storage solution. Regarding carbon mineralization, it is difficult to ensure that the mechanical properties such as strength and durability of concrete can maintain the expectation from the industry. Besides, currently there is a controversy as to the efficiency of CO_2 use in curing or mixing [16]. Hence, further research on cement chemistry should be conducted on this aspect.

3.3. Reduce cement in concrete

The replacement of cement with supplementary cementitious materials (SCMs), wastes and fillers becomes more sustainable in concrete production process. SCMs, such as fly ash and slag, are typically industrial by-products derived from coal combustion and steel production processes, respectively. These materials can serve as partial replacements for cement due to their inherent pozzolanic properties. Pozzolanic materials contain siliceous or alumina-siliceous compounds that can undergo a chemical reaction with calcium hydroxide and water to form compounds with cementitious properties. The incorporation of SCMs in concrete not only mitigates CO_2 emissions, but also augments the durability and other performances of the concrete. This dual benefit underscores the role of SCMs, thereby making the concrete industry more sustainable. Replacement of Portland cement by natural pozzolanic volcanic ash to reduce CO_2 emissions in manufacturing of concrete has been studied [17] potential of such replacement at the material, building and city scales is discussed [18]. A recent development has been reported on the use of modified post-consumed plastics as a cement replacement additive in concrete making for major structural application [19].

Various waste materials which are usually destined for landfill, such as crushed glass, repurposed concrete, and specific types of untreated plastic waste, have been identified as suitable substitutes for traditional aggregates in concrete mix, replacing virgin materials and thereby contributing to waste reduction and enhanced sustainability in concrete production. Crushed glass can improve the aesthetic appeal and potentially the insulation properties of concrete. Recycled concrete can help maintain strength and durability, and certain types of plastic waste can reduce the weight of the concrete, making it more suitable for decorations. However, the incorporation of waste as fillers raises potential concerns about potential contaminant leakage. To mitigate these limitations, the establishment of standards and further chemical investigations contribute to the collection and refining process of SCMs and wastes and remove contaminants from the final products.

3.4. Add functionality

In recent years, with the rapid development of smart and sustainable city, there is a great demand for an improved load capacity with suitable functions embedded in construction materials, which is necessary for both existing structures and new construction. Compared with the traditional construction materials including concrete and steel, engineered cementitious composites and natural fiber composites have emerged as viable candidates for being functionalized construction materials which can be developed in line with the smart and sustainable concept. In particular, the increasing applications of natural fiber reinforced composites correspond with the theme of reducing building energy consumption and advocating environmental protection in the field of civil engineering. The major functionality covers energy harvesting and energy storage in an effort to address the smart and sustainable development.

3.5. Use less concrete in design: topology optimization

The implementation of topology optimization decreases the concrete usage in building structures and improves concrete sustainability. Topology optimization is a mathematical approach utilized in the design process to optimize material distribution within a predefined space, under specific load and boundary conditions, with the goal of maximizing concrete performance. This method can lead to significant reductions in concrete usage. Concrete is often overused in traditional structural design due to conservative estimation or safety concerns. Topology optimization addresses the issue by identifying the optimal arrangement of materials to support specified loads with the least amount of concrete. This is achieved by redistributing material from regions of low stress to regions of high stress, ensuring maximal efficiency of utilizing material. Consequently, structures can maintain their required performance while using less concrete. The accuracy of topology optimization is limited to the complexity of the optimization algorithms and the ideal assumptions of constant loadings and consistent material conditions in concrete structures, which requires the assistance of machine learning (ML) in order to simplify the topology process and improve the prediction accuracy.

3.6. AI based predictive models

Cement hydration is a complex process involving a series of chemical reactions. Material properties of cement hydration products are affected by the interactions between different constituents and the microstructures. Both the long-term and short-term performances of cementitious materials are highly correlated to the chemistry between the materials system and the surrounding. Without an accurate predictive model of cementitious materials, it is difficult to produce reliable cementitious materials in an efficient manner, which can meet the growing demands in construction. In order to meet the market demand, cementitious materials should be more durable and sustainable. Good quality control of mechanical properties of cementitious materials requires an in-depth understanding of the mechanism during the cement hydration process. However, there is still a lack of comprehensive knowledge of cement hydration, and the chemical reaction during this dynamical process is still difficult to be well characterized at the atomistic level. In recent decades, reactive molecular dynamics (MD) simulations have been employed to investigate the chemical reactions in various material systems. Such process requires refinement of reactive forcefield used in the simulations. In order to facilitate the simulation process and find out the chemical pathway in an efficient manner, artificial intelligence (AI) and machine learning (ML) assisted reactive MD simulations have been adopted to investigate the cement hydration process, leading to the development of AI-based predictive models [20].

Within the AI scheme machine learning is a rapidly developing field of study. The ML concept is to build a system of a predictive model that learns from data sets, and thus, learns patterns and relationship between variables or group of variables [21]. ML can be used for almost any application that involves understanding data. Due to the complex nature of the information additional use of computational/numerical approaches to draw conclusions and understand the behavior is required. In civil engineering, neural networks have been applied to detection of structural damage [22], structural system identification, modeling of material behavior, structural optimization and so on. For concrete strength property predictions and mix design optimization researchers use multiple linear regression (MLR) and artificial neural network (ANN) schemes. MLR is a statistical method whose general purpose is to generate a relationship between several independent variables and a dependent variable. The predictive value of a single dependent variable is a linear transformation of one or multiple independent variables. ANN is a powerful data-modeling tool that can capture and represent complex input and output relationships (i.e., nonlinear relations). The design of the ANN model requires identifying a network architecture (i.e., number of input neurons, output neurons, hidden layers, and neuron in each hidden layer) and the network settings (activation function and learning rate). In constraining the output to physically realistic values, available physics knowledge can be incorporated into the deep learning model. This improves the robustness of the trained model for a more reliable prediction scientifically consistent with the physics [23].

4. CONSTRUCTION AUTOMATION

To have an effective urban growth management which can address the development of sustainable built environment, we need innovative construction strategies with better construction efficiency. Building automation and 3D concrete printing are two promising approaches to address this challenge. Building automation, ranging from automated building information modeling (BIM) systems to autonomous construction robots, have revolutionized the built environment. BIM enhances the efficiency and accuracy of building design, while autonomous construction machines or robot increases productivity as well as reduces the error coming from poor workmanship. However, building automation technology is still facing challenges of high initial cost and training time. On the other hand, by using a computer-controlled robotic arm to arrange concrete layer by layer, 3D concrete printing allows for the rapid on-site construction of low-rise complex building forms which is impossible to achieve with traditional construction methods. 3D concrete printing reduces the amount of waste during construction as it only uses the exact amount of concrete needed. By using 3D printing, the timber formwork for complex concrete structures is no longer needed, which means that deforestation can be avoided. Besides, the flexibility of 3D concrete printing for different forms shortens the construction timeline and minimizes the associated carbon footprint. The concept of additive manufacturing has started to be applied in full-scale construction components [24]. Yet, concrete mix used in 3D printing demands fluidity for extrusion and rapid setting for structural solidity, which brings a huge challenge for coming up with suitable concrete mix design and hinders its widespread applications [25].

In view of the durability and sustainability of the built environment, the relevance of regional climates and specific scenarios should be considered. Mix design predictive models and artificial intelligence (AI) applications offer immense potential to construct infrastructure robustness against both natural disasters and human-related catastrophes. Predictive models can help us develop tailor-made performance of concrete mix design. The interpretability of predictive models for concrete mix design is determined by the availability of comprehensive and reliable dataset of concrete, making it difficult to generate high-quality predictions. Therefore, the implementation of AI and machine learning can further refine the predictive models as mentioned above. Learning from large and diverse datasets of practical concrete mix design and associated performances, AI algorithms can predict the optimal mix design and curing conditions for specific performance requirements.

5. FINAL STATEMENT

In summary, the evolution of advanced concrete technology has been instrumental in addressing the challenges of global climate impact, urban expansion and infrastructure resilience. The decarbonization role of concrete in climate-related issues has been enhanced with the development of low-carbon concrete. Advances in construction automation and 3D printing have further shaped the application of concrete, increasing the precision and efficiency of urban expansion management. These advancements mitigate the environmental impact of rapid urbanization and contribute to effective urban planning. In addition, the predictive models of concrete mix design based on machine learning strengthens the infrastructure robustness. The incorporation of AI in concrete mix design allows for the customization of concrete mixtures to meet specific needs, such as the special mix used in 3D printing, and improve the infrastructure resilience. The continuous advances in concrete technology and construction methods are the key focuses to further promote a sustainable and resilient built environment through a combination of sustainable concrete, construction technology innovation and AI integration.

A final note is about civil engineering education and the need for reforms in traditional education programs. Climate mitigation requires sustainability and robustness of the built environment. Buildings and infrastructures need to be strong and durable under the effects of natural disasters and human-related catastrophes. The related engineering problems are complex and highly interdisciplinary requiring knowledge, skills, and real innovations.

Fundamental changes are therefore needed in the undergraduate education philosophy, curriculum, and course content and sequence. Specifically, civil engineering educational programs should be streamlined to involve multidisciplinary courses, undergraduate research activities as well as joint interdepartmental degree programs e.g., with material science and engineering, computer science and engineering, and earth sciences). Based on strong scientific foundation, application oriented hands-on style training programs should be developed with industry collaboration. Mechanisms for improved communication skills and team-oriented project activities should be enhanced.

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