Nanoparticle-reinforced building materials with applications in civil engineering

During the past several decades, cement-based building materials have been used widely in the area of civil engineering. Among all kinds of cement-based building materials, concrete has the largest consumption and production output because of its low production cost, easily available raw materials sources, and simple construction. The most famous advantage of concrete is its high compressive strength. At the early development stage of concrete materials, most researchers focused on the strength of concrete. However, with increased usage of concrete materials, many reinforced concrete structures could not reach their designed life, and many investigators considered undesirable construction quality or nonstandard design as logical explanations. With the further study of concrete materials and structures, many study results indicated that the main reason for failure of these structures was their low durability under various working environments. Concrete materials can also present other weaknesses, such as low anti-cracking performance, poor toughness, and low tensile strength. With development of economy, the serving environment of most concrete structures becomes more demanding, which indicates that measures must be taken to improve the durability of concrete materials. As a result, a large number of researchers have devoted themselves to improve durability of concrete materials by adding some reinforcement materials into traditional concrete materials, such as various short fiber reinforced materials (including steel, polypropylene, and polyvinyl alcohol fiber), mineral admixtures (such as fly ash, silica fume, and blast furnace slag), and nano-materials (nano-SiO$_2$, nano-CaCO$_3$, nano-Fe$_3$O$_4$, nano-TiO$_2$).

Nanotechnology encompasses manipulation of the structure at the nanometer scale to develop a new generation of tailored, multifunctional, cementitious composites with superior mechanical performance and durability. Potential novel properties of these materials include low electrical resistivity, self-sensing, self-cleaning, self-healing, high ductility, and self-control of cracks. Nanoparticles are those with at least one dimension of less than 100 nanometers (nm). Nowadays, nanoparticles have been gaining attention and have been applied in many fields to fabricate new construction materials with novel functions owing to their unique physical and chemical properties. Nanoparticles can act as a very active artificial pozzolan to improve cement-based materials. Due to the particular nano-effects of nanoparticles, such as surface effect, quantum size effect, small size effect, and macroscopic quantum tunneling effect, there is a global interest in investigation of the influence of nanoparticles in concrete composites. The addition of nanoparticles can greatly improve their compressive, flexural, tensile strength, and durability. Nanoparticles can act as heterogeneous nuclei for cement pastes, further accelerating cement hydration because of their high reactivity, as nano-reinforcement, and as nano-filler, densifying the microstructure and leading to reduced porosity. At present, numerous nanoparticles have been applied to improve properties of cementitious composites, such as nano-clay, nano-fly ash, nano-limestone, nano-TiO$_2$, nano-Fe$_3$O$_4$, nano-Al$_2$O$_3$, nano-CaCO$_3$ and nano-SiO$_2$. SiO$_2$ and CaCO$_3$ nanoparticles have broad applications because of their large activity and specific area. As a result, the pozzolanic activity in cementitious composites can be exhibited at high levels. Besides, nano-SiO$_2$ accelerates the generation of C-S-H (calcium silicate hydrate) and dissolution of C$_3$S (tricalcium silicate) because it is a highly reactive material.

This Special Collection aimed to bring investigators from industry and academia together to report and explore new techniques, preparation methods, and basic material properties, testing methods, and standardization in civil engineering. We also considered studies on fresh properties and constructability, shrinkage and creep, structural performance and modeling, functional coatings for buildings, durability and sustainability, and field applications in nanoparticle reinforced concrete materials. Seven research articles were published in this Special Collection because of their quality and relevance to its themes. The selected articles address various aspects, including the micro-macro properties of plastic concrete anti-seepage wall materials mixed with low-liquid limit clay, microstructure and micro-wave absorbing properties of reduced graphene oxide/
Ni/multi-walled carbon nanotubes/Fe$_3$O$_4$ filled monolayer cement based-absorber, preparation of C-S-H seeds by means of mechanochemical method and its effect on the early hydration of cement, a simplified estimation approach for service life of steel bar within concrete, effect of nano-SnO$_2$ on early-age hydration of Portland cement paste, the effects of particle size of colloidal nanosilica on hydration of Portland cement at early age, and the effect of expansive agent and internal curing agent on crack resistance of C50 silica fume wet-mix shotcrete.

Plastic concrete is generally used to construct cutoff walls, which reduce or prevent seepage under dams. Clay is one of the main raw materials to manufacture plastic concrete. The low-liquid limit clay has some properties of low-liquid limit, small plasticity index, low strength, poor water stability, and reduced compactability, which indicate that it can effectively improve the fluidity, cohesiveness, and water retention capability of the mixture. The paper titled “Micro-macro properties of plastic concrete anti-seepage wall materials mixed with low-liquid limit clay” is authored by Shi et al.$^{20}$ They used micro-macro test methods to carry out experimental studies on the mechanics, deformation, and impermeability of plastic concrete containing low-liquid limit clay based on the cofferdam cutoff wall made of plastic concrete of the Jinsha River in order to make full use of low-liquid limit clay by leveraging its advantages and limiting its shortcomings. The micro-properties of the hydration products and pore structure of the hardened paste were also investigated in their study. They found that the strength of plastic concrete containing low-liquid limit clay gradually increased with increments in cement content, and clay content had a significant effect on the strength of the plastic concrete. When the cement content increased, the relative permeability coefficient decreased, and the plastic concrete became more impermeable. With the increase of age, the degree of hydration of the cement paste mixed with low-liquid limit clay increased, internal structure gradually became denser, and pore diameter became smaller.

Traditionally, some accelerators are used to accelerate the early hydration of cement to increase the early strength of cement paste. However, commonly used accelerators can have adverse effects and weaken the cement paste. The application of calcium silicate hydrate seeds can prevent such weaknesses. Wang et al. conducted a study on the preparation of C-S-H seeds by mechanochemical method and its effect on the early hydration of Portland cement. They prepared calcium silicate hydrate nanoparticles with various CaO/SiO$_2$ ratios using a mechanochemical approach. Through experiments of heat flow calorimetry and compressive strength, the effectiveness of calcium silicate hydrate seeds on the cement hydration of ordinary Portland cement and early strength white cement was evaluated. Their results showed that crystalline calcium silicate hydrate is the main crystalline phase in the final product. With the usage of calcium silicate hydrate seeds, they found an acceleration of 6.08 h or 28.3% on hydration of P.O 42.5 type cement and 78% increase in early (24 h) compressive strength after the water was added. Compared to the P.W white cement, calcium silicate hydrate nanoparticles seemed to be more effective in the P.O cement.

Numerical simulation methods are often used to evaluate corrosion of steel bars within concrete cross sections in order to predict the durability of reinforced concrete structures. However, for most of the numerical simulation work, most of the configuration of the steel bars was similar only on condition that the geometric locations of the steel bars were different. In fact, the difference in temperature, moisture, and concrete composition of the concrete materials must be considered in the process of numerical simulation. The paper titled “A simplified estimation approach for service life of steel bar within concrete” is authored by Tu et al.$^{22}$ In this study, they introduced a shape-based estimation approach to simply assess the durability of concrete structures using numerical simulation and proposed a mathematic model regarding the length of involving outline within a circular region with given radius. For this shape-based estimation approach, the similarity of geometric configuration may be the major consideration on the basis of penetration condition and diffusing media. In the case study reported in this article, corrosion history of rebar within concrete in terms of boundary condition, service life, and operating stress, had great influence on the simulation. According to the sign of cross product of vectors, the relation between the given point and one element can be determined, which is helpful for locating the rebar.

With the development of nanotechnology and the application of nanoparticles in cement based materials, there are many types of nanoparticles suitable for use in cementitious composites. Among common nanoparticles, nano-SnO$_2$ was rarely used in concrete materials and the relative study result is very rare. Zhu et al. carried out a series experiments to investigate the effect of nano-SnO$_2$ particles on the strength development and hydration characteristics of Portland cement paste with nanoparticle contents of 0%, 0.08%, and 0.2%. Their paper is titled “Effect of nano-SnO$_2$ on early-age hydration of Portland cement paste.” From their results, it can be found that the early compressive strength of cement paste was greatly improved with 0.08% dosage of nano-SnO$_2$ incorporation. The addition of nano-SnO$_2$ in cement paste promoted the cement hydration process and increased the total amount of heat released from cement hydration. Their scanning electron microscopic results also indicated
that the cement microstructure became more densified with the addition of 0.08% nano-SnO₂.

Most of the nanomaterials are solid powdered, while some of the nanomaterials are colloidal, in which the nanoparticles uniformly disperse and keep initial particle size, and this has advantages to perform nanometer effects. Colloidal nanosilica is a common colloidal nanomaterial used in cementitious composites. The particle size of colloidal nanosilica has great influence on hydration of Portland cement. The paper titled “Effects of particle size of colloidal nanosilica on hydration of Portland cement at early age” is authored by Zhang et al. They conducted a series of experiments including flowability, mechanical properties, and microstructural characterization tests to study the macroscopic and microscopic properties of cement paste containing different particle sizes of colloidal nanosilica. Their experiment results indicated that flowability of the paste decreased with the decrease of colloidal nanosilica particle size, because more sol formed flocculation restricting more free water under ion environment. Moreover, the paste containing colloidal nanosilica with 60 nm was higher than that of the other two particle sizes. Microstructure images also showed that the cement paste containing colloidal nanosilica with 60 nm was more compact than the other two kinds of pastes.

In order to discuss the theoretical development a new type of monolayer cement-based absorber mixing with rGO, Ni/MWCNTs, and nano-Fe₃O₄, Y. Sun et al. took a monolayer of cement-based absorbers as the research objects to study the influence of rGO, Ni/MWCNTs, and nano-Fe₃O₄ on the fluidity, mechanical strength, microstructure, resistivity, and wave absorbing properties of cement paste. Their paper is titled “Microstructure and microwave absorbing properties of reduced graphene oxide/Ni/multi-walled carbon nanotubes/Fe₃O₄ filled monolayer cement-based absorber.” Their results indicate that the fluidity and resistivity of the paste was decreased due to a small load of decreased graphene oxide and other nano-absorbents, while the mechanical strength of the paste was improved due to the improved pore structure. The growth of a large number of flower-like and compact bulk crystals and the thickening and increasing in the cement hydration products can be found due to the reduced graphene oxide by scanning electron microscopy images.

Shotcrete plays a significant role in the durability repair of underground and other structures, especially in the construction of mines and tunnels, where shotcrete can keep surrounding rock stable effectively and timely. However, low cracking resistance is the main critical factor affecting the durability of shotcrete and the related structures. F.W. Ning et al. demonstrated the method of using expansive and internal curing agents to improve the crack resistance of shotcrete materials containing 10% silica fume. Their paper is titled “Effect of expansive agent and internal curing agent on crack resistance of C50 silica fume wet-mix shotcrete.” The cracking resistance of shotcrete was evaluated through ring and thermal stress tests by simulating relative humidity, constraint, and actual temperature. The restriction in cracking of expansive internal curing agents was accessed by measuring restrained deformation, pore structure, and autogenous volume deformation. Their results indicated that the expansive agent with 4% content can efficiently improve cracking resistance of C50 shotcrete. With the addition of internal curing agent, the cracking resistance of C50 shotcrete containing expansive agent can be further improved due to the reduction in auto-shrinkage by decreasing the loss of internal relative humidity with the resistance of internal curing agent.

It has been our pleasure and honor to organize this Special Collection in Advances in Mechanical Engineering. We sincerely hope that it will be of great help to promote related research in nanoparticle reinforced building materials and provide a theoretical foundation for the application of nanoparticles in civil engineering.

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