Ecological high-performance concrete for sustainable concrete infrastructure

With a background in structural engineering (at the Master's level) and in concrete technology (at the Ph.D. level), I am aspiring to leverage my expertise in concrete technology and in structures to develop innovative solutions in cement and concrete composites for sustainable concrete infrastructure. With concrete being the most widely used manmade material on the planet [1] (and a Canadian annual production exceeding 36 million cubic meters [1]), I want to develop concrete formulations with enhanced performance, reduced ecological footprint, and maximum performance-to-investment ratio. My approach for realizing this vision involves: (*i*) improving the performance of concrete at the structural scale by developing new recipes using fibers with different scales (from macro to nano) and (*ii*) developing concrete formulations with low cement content. In the following lines, I will first underline my previous contributions falling within the framework of this vision before presenting my future research agenda.

I) Past research

At the onset of my research endeavour, I worked for my Master's thesis with W. R. Grace and Richard Lee Decking to develop a fiber-reinforced concrete (FRC) recipe capable of resisting a significant level of in-pane shear such as those due to winds or earthquake events. For that, I used synthetic macrofibers to replace the conventional steel mesh in full-scale composite deck slabs. With fibers being added to the concrete during the mixing process, this option (favoring fast-track construction) does not only cut labor work hours (associated with the time-consuming placement of the steel mesh), but also resulted in composite slabs exhibiting higher in-plane shear capacity and ductility [3-6]. My Master's thesis (which won the Best Thesis Award) contributed in the field of composite decking with new insights into the performance of synthetic macrofibers as secondary reinforcement for composite deck applications where in-plane shear is critical, particularly in high-rise buildings where composite deck slabs act as diaphragms to resist lateral loads [3–6]. The scientific output of this research was communicated via three original journal articles [3–5] and two conferences presentations [7, 8]. Through this project, I acquired hands-on expertise (in fiber-reinforced concrete) which was further propelled by my Ph.D. project on nanomodified ecological concrete.

II) Present Research

My research at the Ph.D. level shaped a forward step in designing sustainable cement and concrete composites and acquainted me with an expertise spanning four major areas: (*i*) nano-modified concrete, (*ii*) high-performance fiber-reinforced cementitious composites, (*iii*) low clinker cement and concrete composites, and (*iv*) innovative structural products made with sustainable materials.

i. ***Nano-modified concrete***:

My Ph.D. research unveiled for the first time how nanoscale cellulose filaments (CF) sustainably-sourced from Canadian forests can be used as a novel tool to manipulate the nano-structure of concrete in order to control its macro-behavior, a project with which I won the Vanier Scholarship from the Natural Science and Engineering Council (NSERC) of Canada (the most competitive doctoral scholarship nationwide) [9]. I was able to use CF to improve the properties of concrete in its three major phases (fresh, hardening, and hardened), and accordingly, I developed three novel applications of CF in concrete: (*i*) a viscosity modifying agent (for fresh concrete) enabling designing concretes with adaptable rheology [10], (*ii*) a shrinkage reducing agent (for hardening concrete) enabling controlling volumetric instability [11], and (*iii*) a nano-reinforcing agent (for hardened concrete) imparting cracking resistance at the scale of hydrates [12–14]. Deployment of CF-concrete at the industrial context is currently underway (in collaboration with Kruger Biomaterials and Euclid Chemicals) to catalyze technology transfer and implementation in real-life construction projects. CF used in this perspective represents an ecological advantageous alternative to carbon nanomaterials (such as carbon nanotubes and carbon nanofibers) which are exorbitantly expensive and pose some issues on human and environmental health, particularly when used at dry state [15].

ii. High-performance fiber-reinforced cementitious composites

While working on my Ph.D. exploring the versatile opportunities offered by the nano-modification of concrete using cellulose filaments (CF), I developed a new formulation of ultra-high-performance concrete (UHPC) with improved volumetric stability [11] (i.e., low autogenous shrinkage UHPC) building upon the works on UHPC conducted earlier by my advisor Prof. Arezki Tagnit-Hamou and his former Ph.D. student [16]. As the autogenous shrinkage represents one of the major handicaps of UHPC, this technological contribution (development of low-autogenous shrinkage UHPC) facilitates *in-situ* casting of UHPC where autogenous shrinkage is a major concern [11]. I further leveraged the nano-reinforcing effect of CF to develop a multi-scale reinforced UHPC such that CF and the mainstream steel fibers work synergistically to improve crack resistance. This allowed to produce UHPC formulations demonstrating not only an improved volumetric stability, but also a reduced content in steel fibers [17] which positively influences UHPC cost.

I also developed, a novel strain-hardening cementitious composite (SHCC) incorporating high-volume glass powder (HVGP) from post-consumption glass as an alternative to the conventional high-volume fly ash SHCC to yield composites with higher strength and durability [18]. I further exploited the reinforcing ability of CF to nano-reinforce the SHCC matrix as well as to impart a characteristic slip-hardening effect at the level of matrix/fiber interface micromechanics [19] and to develop a nano-modified SHCC. This resulted in SHCC incorporating up to 100% GP in replacement of FA while exhibiting improved strength, ductility, and durability [20]. The development of ecological SHCC using GP and the enhancement of the ductility of this concrete (using nanocellulose) is a new research direction. Thus, in the emerging field of nano-modified concrete, my work stands-out to be the first to utilize nanocellulose to impart a slip-hardening (β) effect to favor higher ductility in concrete [19]. As part of this research, I also developed a new method for the preparation of test samples for single-fiber pull-out test (necessary for micromechanical tailoring of SHCC). The method utilizes discreet fibers as opposed to the common technique requiring long continuous fibers which are not always readily available in the market [19].

iii. Low clinker cement and concrete composites

While working on high-performance fiber-reinforced cementitious composites, focus was made on reducing the cement content by using supplementary cementitious materials (SCMs), particularly post-consumption glass powder (GP). The UHPC formulations were designed with GP replacing up to 50% of cement [11]. Similarly, in the development of HVGP-SHCC, I was able to completely replace fly ash (FA) with GP. This bears a significant technological impact as the supply of FA in North America is declining due to new policies in the energy sector leading to closure of coal-fired energy plants. On the other hand, the valorization of GP in concrete not only shapes a solution to the socioeconomic and environmental burdens created by landfilling post-consumption colourmixed glass which has low recycling value, but also reduces the total amount of cement in concrete, hence reduces the emission of CO_2 as cement manufacturing accounts for about 5% of global green house gaze emissions from human activity [21].

iv. Innovative structural products made with sustainable materials

To exploit the advantages of high-performance fiber-reinforced cementitious composites (along with their sustainability features represented by the low-clinker content) at the structural scale, as part of interest in developing innovative solutions for sustainable concrete infrastructure, I developed a new type of high-performance composite deck slabs. For this, I used my newly developed nanomodified SHCC incorporating high-volume glass powder (HVGP-SHCC) as a topping in full-scale composite deck slabs such that the compatibility between the steel deck and the ductile concrete (SHCC) is improved. This allowed to obtain composite deck slabs with an improvement in flexural capacity and ductility of up to 55 and 35%, respectively. Composite deck slabs constructed with my nano-modified HVGP-SHCC exhibited high resistance to shear bond failure (one of major failure types in composite deck slabs due to the discrepancy in ductility between the steel deck and its conventional concrete topping).

Therefore, my research findings did not only unveil new application of nanocellulose for enhancing the properties of concrete in terms of rheological control, volumetric stability and mechanical strength, but also optimized the advantages of nanocellulose to develop a new formulation of high-performance concrete incorporating recycled glass powder. Project outcomes culminated into eight stand-alone journal articles [10-13, 18-20, 22] and contributed with several new insights on nanomodified concrete including: (*i*) the effect of CF on the microstructure of cement and concrete composites [13] (to accomplish this part of the project, I collaborated with experts in Nano-indentation: Luca Sorelli from Laval University and William Wilson from Ecole Polytechnique Federal de Lausanne), (*ii*) the effect of nanocellulose on imparting a bottom-up (nano-to-macro) strengthening effect from the scale of cement hydrates (at the microstructure) to the structural scale, (*iii*) the effect of nanocellulose on improving the interface properties in fiber-reinforced concrete, (*iv*) the combined effect of nanocellulose and high-volume glass powder content on the pseudo-ductility of SHCC.

As such, the newly developed SHCC (implemented from the material level at the nanoscale to the structural level at the macroscale) has benefited from a twofold ecoefficiency perspective. The first concerns the valorization of post-consumption recycled glass into the development of high-performance concrete, thereby contributing to relieve the socio-economic and environmental burdens created by landfilling post-consumption glass. The second concerns exploiting the power of cellulose, the most abundant naturally occurring polymer on the planet, towards a biomimetic design of high-performance multiscale-reinforced cement composites necessary for sustainable and resilient concrete infrastructure systems.

III) Future research Agenda

In line with my main goal of developing innovative solutions in cement and concrete composites for sustainable concrete infrastructure, I am planning to work during my tenure track on four major research areas:

First, I will work on pushing the boundaries of ecoefficiency of ultra-high-performance concrete (UHPC). Owing to its exceptional mechanical and durability properties, this class of concrete is highly promising, but despite all efforts, UHPC remains relatively expensive. I will work on optimizing the use of local/cost-effective ingredients to redesign UHPC formulation in order to reduce its carbon footprint, lower its cost, and spread its utilization.

Second, I will work on developing test methods for UHPC (particularly direct tensile test). Due to the remarkable tensile properties of UHPC, conventional test methods developed for normal concrete/fiber-reinforced concrete have been proven inadequate. On the other hand, indirect tensile strength obtained from flexural testing does not properly reflect UHPC material behavior under uniaxial tensile solicitation. As such, while the tensile properties are of paramount importance in structural application, there are currently no practical test methods directly assessing the tensile properties of UHPC.

Third, I will extend my work on nanotechnology in concrete in two separate sub-subjects: (*i*) I will continue tailoring the formulation of strain-hardening cementitious composites (SHCC) using nanoscale fibers to control crack width due to its high impact on durability properties. (*ii*) I will also work on developing a nano-modified high-performance concrete (HPC) featured by high elastic modulus targeted for high-rise buildings. This will be an advantageous alternative to the current techniques for increasing the elastic modulus such as increasing the binder content or using stiffer aggregates.

Fourth, I will work on developing repair solutions for retrofitting concrete infrastructure. I will leverage my works on UHPC and SHCC to develop composites (with adaptable rheology and tensile strain capacity) for retrofitting aging concrete infrastructure. Owing to the remarkable economic burden created by the rehabilitation/replacement of aging concrete infrastructure, cost-effective retrofitting techniques are imperative. UHPC or SHCC sprayed or jacketed can replace current exorbitant retrofitting techniques. Those repair solutions can also be applied to extend the service life of historic buildings to contribute in the conservation of cultural heritage.

While conducting the project
following stakeholders in the mark

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During my tenure track, I will be delighted to maintain collaboration with relevant faculty members such as (to mention a few):

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