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Development and recovery of mechanical properties of self-healing cementitious composites with MgO expansive agent

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HIGHLIGHTS

- Study self-healing capability of new cementitious composite with MgO expansive agent.
- Self-healing capability of samples is evaluated based on the recovery of strength and UPV.
- Variables used are specimen type, age, curing conditions and cracking/damage types.
- Air cured MgO composites show better self-healing capability compared to water cured ones.

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ABSTRACT

This paper presents the performance of engineered cementitious composites (ECCs) produced with MgO utilized as expansive self-healing agent to heal micro cracks. ECCs capability to keep small crack width of less than 60 μm even under ultimate loads can stimulate the autogenous crack healing and thus, improving the mechanical properties of structural elements. Different test schemes were adopted to quantify the long-term self-healing capability of proposed ECC-MgO system (made of 5% MgO expansive agent 'MEA' as fly ash replacement in ECC matrix) through studying the development and recovery of strength (compressive and flexural) and Ultrasonic Pulse Velocity (UPV) of pre-loaded multiple damaged (cracked) cubic and prismatic specimens subjected to long term water and natural curing conditions. Test results indicated that preloaded cracked ECC-MgO specimens had high tendency to recover original mechanical properties of virgin (un-cracked) specimens through healing of micro-cracks. This study confirmed the self-healing capability of proposed ECC-MgO system.

1. Introduction

Cracking in concrete structures can occur due to errors in structural design, poor construction practices or undesirable interactions with the surrounding environments. The concrete cracks can be very small microcracks connected to each other throughout the microstructure and then forming considerable internal damages before being visible at the exterior surfaces. In many cases, the presence of concrete cracks might not affect dramatically the load carrying ability of structural elements. However, the long-term durability of concrete structure can be affected directly by allowing easy ingress of aggressive agents through cracks which might accelerate the concrete deterioration. Therefore, the development of new concrete technologies is essential in order to solve the problems related to both reliability and durability of concrete elements [1].

Early studies have proven that concrete cracks can be healed by themselves when exposed to water over time [2]. Subsequent crack-healing studies can be divided into three techniques: the first is "intrinsic healing" which has indicated that the crack-healing phenomenon in concrete might be due to several factors such as: (a) further hydration of un-hydrated cementitious particles [3–5]; (b) swelling of matrix (Calcium Silicate Hydration) products (C-S-H) [6]; (c) subsequent carbonation of $Ca(OH)_2$ to produce $CaCO_3$ precipitation; and (d) closing the cracks by water impurities or by loose particles due to concrete cracking [7]. Among these factors, the precipitation of $CaCO_3$ is considered as the main reason of autogenous crack healing [8]. The second technique is capsules based healing which can sense the damage without human intervention. The

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self-healing mechanism is triggered when the healing agent released outside the broken tubes to fill up the cracks in the damaged region. The third is vascular based healing which can sense the damage as well but with human intervention. After crack formation, an external healing agent which is isolated in a network of hollow tubes will be vacuumed from exterior side of structure into concrete matrix as an attempt of crack healing. Among all promising self-healing techniques, it was concluded that only intrinsic healing studies were culminated by achieving significant reduction in crack width water permeability, and improvement in the recovery of the mechanical properties [2,7,9–12].

Engineered Cementitious Composite (ECC) made of random poly vinyl alcohol (PVA) fibers was developed to achieve multiple cracking behaviour and high tensile strain capacity [13,14]. By using only 2% of PVA fiber content, the cracks in ECC can be restricted to less than 60 μm even under ultimate loading. By controlling the ECC's crack width, autogenous crack healing can be stimulated and cracks might heal completely – thus improving durability and mechanical properties of structural elements [15].

MgO concrete was discovered in China during the construction of Baishan dam. Although the concrete was exposed to extreme hot and cold consecutive weathers, no cracking was observed in concrete dam foundation. This was related to the presence of high amount of delayed MgO type expansive agent in cement which compensated effectively the thermal shrinkage in mass concrete at later age [16]. In addition, Mo et al. [17] revealed that the use of MgO as drying shrinkage compensated agent was better than conventional ettringite expansive additive. This is due to lower water demand of MgO than ettringite leading to form "magnesium hydroxide" $Mg(OH)_2$ which is considered the dominant part to compensate autogenous shrinkage in concretes with low water to cement ratios. In addition, the delayed MgO-based expansive additive provides more cohesive cementitious properties than the conventional ettringite which generates the expansion only at early age. Based on ASTM C150 [18], the use of MgO should be limited to ≤6% in cement along with a maximum expansion of 0.80% in order to get sound cement. The standard test method to evaluate the expansion effect of MgO is autoclave expansion test adopted in 1940 [19].

The recovery of durability through improved permeability and water or air tightness is very important in order to assess the quality of self-healing technique. However, many researchers have shown interest in the recovery of mechanical properties of self-healed concrete as well and considered it as an important tool in self-healing studies. According to Tittelboom and De Belie review [6], the mechanical properties of self-healed cracks were mostly inferior compared to the virgins. Even after filling the cracks with $CaCO_3$ precipitation and/or newly formed C-S-H gel compared to primary hydration products, these fillers did not have proper bond with the crack faces and cracks might present again at the same previous locations of damaged regions. This might be attributed to the fact that over 80% of $CaCO_3$ precipitation formed through the cracks was done within the first 3–5 days only while the rest of $CaCO_3$ crystal was formed over longer periods [8]. Therefore, the need for later formation of a cementitious material which can provide a proper bond between the crack faces and subsidies the early formation of $CaCO_3$ crystals is important.

The controlled tight crack width in ECC and the presence of un-hydrated cementitious particles duo to low water to cement ratio can promote the crack-healing phenomena. The chemical cement hydration within the crack cavities will be activated to form C-S-H products once moisture which mixed with carbon dioxide (CO_2) flows through cracks and starting to accumulate around the un-hydrated cementitious particles [8]. Furthermore, PVA fibers in ECCs can stimulate the crack-healing as well. Attracting calcium ions in pore solution by negatively charged hydroxide ions present at PVA fibers can form $Ca(OH)_2$ and help pozzolanic reaction to form new hydration products [20,21]. However, low water to cement ratio in ECCs can sluggish the continuous hydration of cementitious particles due to insufficient space for hydration products to be formed. Therefore, lower water demand of MgO than other expansive agents can be used successfully in low water to cement ratio of ECC matrix to form expansive materials. Additionally, the delayed formation of magnesium hydration products can supplement the early formation of C-S-H products in order to fill the cracks. Finally, hydration products of M-S-H are featured with cementitious gel properties which might subsidies the C-S-H products by providing a proper bond between the crack faces and thus forming cracks in newly locations after applying re-loadings.

As reported by many researchers, no matter what the type of self-healing technique adopted in intrinsic healing studies is, all researchers agreed that the presence of water is essential especially when ECC cured under controlled laboratory conditions [6]. However, Herbert and Li [15] reported in their study that ECC was cured for one year outdoor in natural environment.

Research team at Ryerson University developed ECC-MgO self-healing system by incorporating MgO expansive agent (MEA) in fly ash based ECC mixtures. Specimens made of ECC-MgO were cured for more than one year under laboratory, water and natural environment curing conditions in order to explore the expansion effect of MEA. Since ECC mixtures controlled the crack width to ≤60 μm and provide prolonged pozzolanic hydration due to the presence of fly ash while MEA enhances effectively the thermal shrinkage at later age and increases resistance to cracking, ECC-MgO self-healing system has the capability to heal micro cracks. There is a need to conduct research on developing this novel ECC-MgO system and on exploring its capability of crack healing to enhance mechanical and durability properties.

This paper presents the effectiveness of proposed ECC-MgO self-healing system based on the development and recovery of mechanical properties (compressive strength, flexural strength, ultrasonic pulse velocity, deflection capacity, crack filling and energy absorption capacity) of cubic and prismatic specimens when MEA was employed as self-healing agent to heal micro cracks. The influences of curing conditions (water and natural), curing age (up to 350 days), and multiple damage due to repeated loading on mechanical properties of ECC-MgO specimens are described compared to their ECC counterparts. The subject matter of this paper is new and the findings will contribute significantly to the existing technology of self-healing concrete. In addition, professionals from construction and manufacturing industries will be benefitted from the recommendations of this research in understanding and implementing self-heling ECC-MgO system in durable infrastructure applications.

2. Experimental investigations

An extensive experimental investigation was conducted to assess the effectiveness of developed ECC-MgO self-healing system (compared to controls: ECCs without MEA) based on compressive strength, load development and recovery of the control specimens, reloaded pre-cracked specimens, and repeated reloaded multiple damaged specimens (repeatability of loading) exposed to water and natural (field) curing conditions over long period of time (up to 360 days). Moreover, the development and recovery of deflection capacity and ultrasonic pulse velocity (UPV) were described in addition to the analysis of energy absorption capacity and crack healing aspects.

2.1. Materials and ECC-MgO mixture proportions

The materials used to produce ECC mixtures were type GU cement (general use), Class-F fly ash with low calcium content of