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Investigation of advanced self-healing concrete applications in construction

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ABSTRACT:
Preventing cracks in concrete is a critical issue in the construction industry. The self-healing concrete phenomenon can be a good solution for mitigating cracks in concrete without any direct intervention. Construction industry researchers are developing many different self-healing concrete materials using a variety of sub-materials and techniques. This research project investigates self-healing concrete applications that use various cementitious materials, such as fly ash, slag, and polymeric materials, which can easily be applied in the construction industry. To present this application, experimental tests on different concrete mixes have been conducted using Ultrasonic Pulse Velocity and compression tests. For this experimental study, samples were placed under various environmental conditions, such as water-saturation and frozen temperatures. The results of the investigation are detailed and discussed in the study. The graphs illustrate behavioral differences between fly ash, slag, and polymeric materials. Based on the experimental results, healing capacity existed in all mixture types in the saturated and frozen environments. In the results, samples were characterized by good mechanical properties represented by damage resistance, aggregate/mortar adhesion, and compressive strength.

KEYWORDS:
construction industry; concrete; surface cracks; polymers

1. Introduction

Concrete is one of the primary construction materials used around the world. In construction, various additives increase concrete strength or help repair the damaged concrete structures [1, 2]. Cracked concrete, in particular, may cause significant problems in the structural resistance of buildings [3]. After the concrete is placed, it may develop cracks due to numerous placement conditions at the construction site. The external environmental components, such as liquids and gasses, may attack concrete over time, where capillary cracks may widen, and structural failure could occur due to rebar corrosion. Traditional repairing methods, such as epoxy injection, can reduce the effects of concrete cracks. However, maintaining or repairing damaged concrete with conventional methods can be expensive [4]. Therefore, researchers have started developing different approaches to provide convenient solutions to concrete crack problems. The self-healing phenomenon offers alternative solutions that can be integrated into the concrete industry.

With the current technology, different types of self-healing concrete materials have been developed to serve the construction industry. There are many available products and contractors may be confused about picking the suitable material for the proper purpose. Many research articles have discussed the advantages of blending different healing components with a concrete mixture. A lack of research compares the concrete properties and strengths of different concrete

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samples containing different healing materials. This study investigates the different types of concrete that contain self-healing agents and will determine the optimum type of self-healing agent that can be used by constructors and practitioners working in the construction industry to produce self-healing concrete. The study is intended to conduct a set of lab experiments using concrete cylindrical samples containing different healing agents containing both cementitious and polymeric materials to develop practical and applicable results. In general, concrete cracks are driven by various reasons. This study mainly focuses on the capillary cracks that developed during the hydration process or other internal non-structural cracks that might turn into larger cracks during concrete structure's service life. Cracks that originate from other sources such as the structural cracks resulting from overloading the concrete members, seismic activities, and vertical building settlement are not part of this study. Therefore, the purpose of this study is to determine an optimum self-healing agent that can provide an ultimate result in repairing concrete micro-cracks using appropriate resources.

Self-healing concrete can be defined as concrete that is intended to seal cracks generated in the concrete structure using healing agents mixed with base materials or integrated within the concrete mixture during production. Different self-healing concrete methods have been developed, such as polymer-modified concrete, fly ash concrete, silica fume concrete, and bio-concrete. Termkhajornkit et al. [5] focused on using fly ash to heal the generated cracks inside concrete samples. The literature evaluated the behavior of concrete after the dry shrinkage cracks occurred after 28 days. The number of cracks was not measured but implied through experimental tests, such as compression strength, porosity, chloride diffusion coefficient, and hydration degree. The literature found that fly ash has a self-healing ability for micro cracks. A similar conclusion was also reached by Na et al. [6]. Other researchers claimed that the self-repairing capability of slag cement was less than the different types of cementitious materials. According to the literature, slag cement showed a lower hydration ratio in cooperation with a cement clinker, which is the framework for cement production. In fact, there are many unreacted particles in slag cement paste even after several years of pouring [7]. Huang et al. [8] indicated that "unreacted blast furnace slag in the bulk matrix can contribute to self-healing of micro-cracks if it is activated by saturated $CaOH_2$ solution".

Cementitious materials are pozzolanic materials that can react with $CaOH_2$ and produce a C-S-H to seal micro-cracks and increase concrete performance. Many researchers have discussed self-repairing concrete based on investigations of different self-healing methods and applications in concrete manufacturing. Autogenous healing was first reported by the French Academy in 1836 in the fractured concrete of a water-retained structure [9]. Gupta et al. [4] discussed healing could provide alternative solutions for concrete cracks. Kadam and Chakrabarti [10] used the void former technique by placing polyurethane tubes in the tension zone of a slab specimen. Another creative idea was presented by Song et al. [11], which discussed coating the concrete structure with a unique coating matrix mixed with a micro-encapsulated healing agent. Abd-Elmoaty [12] carried out research focusing on the polymer-modified concrete by mixing an organic polymer with the concrete paste to investigate the self-healing capability of this polymer. Lukowski and Adamczewski [13] conducted a research project focusing on developing polymer-cement concretes (PCC) by mixing an epoxy resin with the concrete mixture without hardening.

Presently possible applications for the construction industry have been discussed with prior research. This study is prepared as a pilot study on investigating self-healing concrete applications using various cementitious materials, such as fly ash, slag, and polymeric materials, which can easily be applied in the construction industry. To present the application, experimental tests on the different concrete mixes were conducted using the Ultrasonic Pulse Velocity and compression tests. For the experimental study, samples were created in various conditions, such as saturated water and freezing conditions. The results of the experimental investigation were detailed and discussed in the study. Behavioral differences between fly ash, slag, and polymeric materials were illustrated.

2. Methodology

An experimental study was conducted to test concrete samples with two different techniques. The first testing method utilized a set of Ultrasonic Pulse Velocity (UPV) tests to evaluate the self-healing process within the concrete samples. The UPV test is a cost-effective test that can be employed easily and rapidly [14]. This process assists in the continuous evaluation of concrete structures during their service life, which minimizes the possibility of internal deficiencies [15]. The UPV test is a non-destructive test that sends an electrical pulse through the concrete samples. The pulse speed and transit time are measured by the UPV machine, which depends on the consistency and density of the tested materials. The existence of concrete microcracks will affect the speed of UPV waves. Higher speeds means higher concrete quality with fewer microcracks. The healing process was evaluated by measuring the changes in the UPV wave speed (e.g., increasing UPV speed indicates better healing).

The second testing method is concrete compression tests conducted on concrete cylinder samples. Both tests were carried out in the lab at the Eastern Michigan University. In the first stage, a UPV test was conducted on each concrete sample before applying a compression load using the compression test to measure the initial integrity of the concrete cylinders. A compression test was conducted to assist in developing microcracks in the concrete specimens. Then, the UPV test was conducted on each sample immediately after performing the initial compression test. Thereafter, the samples were left in different healing states for a specific duration, followed by a repeated UPV test on the samples to measure the healing capability and evaluate the healing process. Finally, the compressive strength of the samples was determined by cracking the samples to assess the concrete strength using different healing agents.

Different material types were used in preparing the concrete samples. In addition to typical concrete mix components, slag and fly ash cementitious materials were used in different mixing ratios, as shown in Table 1. In addition, a chemical admixture, Styrene-Butadiene Rubber (SBR) polymer, was used to prepare the concrete mix for some of the samples.

A total of 24 cylindrical specimens were prepared for the study to define the self-healing capability. The cylinder sizes were 12-inch (30.5 cm) in height and 6-inch (15.25 cm) in diameter, and were designed according to ASTM C192 Standard for concrete sampling. The samples were prepared with different mix proportions of supplemental materials and SBR. Four samples were considered for each mix; three items were tested in a water-saturated environment, and one was tested in a frozen environment. The first four samples were prepared without cementitious and polymeric materials. The remaining 20 samples were prepared using different percentages of slag cement, fly ash, and SBR. Therefore, six different concrete mixes were used in the research. The percentage of cementitious material used in this research was according to the maximum cementitious requirements stated in ACI 301-10.

3. Evaluations

Table 1 shows values for different mix types, and Table 2 illustrates the mix proportion of the samples. After curing the concrete cylinders for 28 days in a water tank, as shown in Figure 1, one sample from each mix was placed in the freezer for two days before moving to the next step. The other samples were removed from the water on day 30. As seen in Figure 1, the UPV test was performed on each specimen following the ASTM C597-02 Standards from three different positions in the cylinder's axial direction; the specimens were subjected to (2.0 MHz) sound waves during the test. The benefit of documenting the UPV values at the beginning was to indicate the initial pulse velocity value, which helps assess the internal integrity of the concrete cylinders before applying any compression load. In addition, the initial UPV test results were used as base values during the evaluating process of the self-healing capability by estimating the damage level for each cylinder.

Table 1
Different mix types

Mixes	Type
Mix 1	Control mix without any supplemental or polymeric materials
Mix 2	Concrete mix with 50% slag
Mix 3	Concrete mix with 25% fly ash
Mix 4	Concrete mix with 25% slag and 25% fly ash
Mix 5	Concrete mix with 15% SBR
Mix 6	Concrete mix with 15% SBR, 20% fly ash, and 20% slag

Table 2
Mix proportion of concrete

	W/C	Concrete volume [ft^3]	Mix proportion [lb/ft^3]					
			Cement	Slag Cement	Fly Ash	SBR	Fine Aggr.	Coarse Aggr.
1	0.45	1	21.43	0	0	0	42.85	85.72
2	0.45	1	10.72	10.72	0	0	42.85	85.72
3	0.45	1	16.1	0	5.36	0	42.85	85.72
4	0.45	1	10.72	5.36	5.36	0	42.85	85.72
5	0.45	1	21.43	0	0	1.45	42.85	85.72
6	0.45	1	12.85	4.286	4.286	1.45	42.85	85.72

Fig. 1. Concrete samples and UPV test

After measuring the initial UPV values as illustrated in Figure 2, a compression load was applied to concrete cylinders up to approximately 40,000 lb and 1,500 psi, as seen in Figure 3. The purpose of this step was to induce enough internal stresses to generate microcracks within the concrete sample. The UPV test was performed again on the same day for all samples to measure the changes in pulse velocity values compared to those measured at the beginning. Some changes in the UPV indicated that the applied compressive stress on the specimens generated cracks during the loading process. The saturated samples were then placed back in the water tank, while the frozen samples were returned to the freezer for 30 days. Hence, the first stage of the testing procedures was completed. After 30 days, the second stage was started by removing the samples from the water and freezer to perform the next UPV test. The samples were placed back in the water and freezer for another 30 days. After 60 days from the first pulse velocity evaluation, the final UPV test was executed for all concrete samples. The purpose of applying the UPV test in different periods was to build a relationship between each concrete mix and healing degrees in time. At the end of the investigation, the samples were crushed using compression testing equipment by applying an axial compression load until failure. Compression test results are given in Table 3.

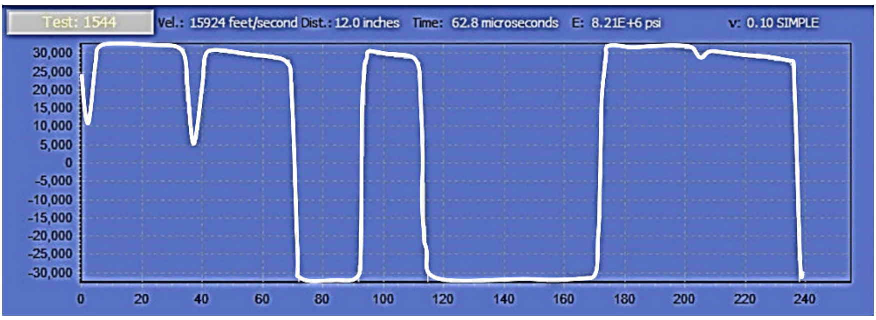

Fig. 2. Ultrasonic pulse velocity test outputs

Fig. 3. Concrete compression test performance

After applying compression loads, the damage level was determined to understand the concrete sample's self-healing ability. The damage level was calculated using the following expression:

$$Damage\ Level\ \% = \left[1 - \left(\frac{Average\ UPV\ After\ Cracking}{Average\ Intial\ UPV}\right)\right\} * 100$$

Table 3
Compression test results

Concrete mixes	Compressive strength [psi]				
	Sample 1	Sample 2	Sample 3	Avg. highest	Frozen sample
Control mix	3,689	4,772	4,580	4,676	6,756
Slag 50%	5,189	3,727	3,977	4,583	5,741
Fly ash 25%	4,528	3,870	3,701	4,109	4,871
Fly ash + Slag	3,931	3,444	3491	3,711	7,202
SBR	3,120	4,501	4,207	4,354	4,501
SBR + Fly ash + Slag	4,505	4,031	3,654	4,268	4,774

Fig. 4. Damage levels and average UPV values

The level was also used to evaluate the effects of different design mixes in resisting micro-crack formation due to compression, also presented in Figure 4, the level given in the chart provides damage levels for all samples. Additionally, the specimens created using SBR gives the minimum damage level compared to the other samples prepared without SBR. Using SBR in both frozen and unfrozen samples increased the resistance to the compression stress. Higher performance can be seen for mixes with SBR. The difference is due to the SBR bonding capability, which increases the adhesion between the concrete particles. As a result, the damage level was less than the other samples which did not have SBR.

Figure 4 also shows that using cementitious materials such as slag and fly ash in the concrete mix design increased the damage level compared to the control mix. It should also be noted that the increment in the damage level reduced the efficiency of the healing process. The damage level is not constant for each mix of saturated and frozen samples. As a result, the damage level due to compression stress is correlated to concrete sample components' coherence. As the cohesion between concrete components increases, the level of damage decreases.

The UPV test results significantly differ in ultrasonic pulse velocity values between the saturated and frozen concrete specimens. Frozen samples resulted in higher UPV values than the saturated samples at different test stages. This is mainly caused due to the frozen water inside the micro-voids and cracks within the concrete internal structure, which helps provide a solid structure to the transit of the ultrasound waves.

4. Results

As a result of the study, it is found that, the samples containing SBR and/or fly ash exhibit faster wave speeds than the other samples that do not include them within the concrete mix, as Figure 4 illustrates the UPV values for all samples tested. This mix showed a higher healing capability for samples containing fly ash than other samples. In addition, adding SBR to the mix along with the fly ash increases the UPV wave speed, indicating a lower damage level.

5. Conclusions

An experimental study was conducted on concrete cylinders in a water-saturated and frozen environment during different periods. Six concrete mixes were prepared for four samples containing various percentages of cementitious and polymeric materials, for a total of 24 samples. Although the primary purpose of this research was to study the self-healing phenomenon, the quality of the concrete mixes was also evaluated through some test data, such as damage level and compression test results. The study results revealed that the investigated samples prepared with SBR polymer were more consistent under saturated and frozen conditions.

As a result, the damage level values were less than the other samples with no SBR. Adding cementitious materials to the concrete mix gave a higher damage level than the control mix. The percentage of increment in the damage level was 18.95%, 25%, and 53.5% for Samples 1, 2, and 3, respectively. The other important conclusion was that the damage level varied among the different concrete mixes related to the coherence between concrete components. As a result, ultrasonic pulse velocity values decreased as the damage level increased. The current findings help the understanding of the environmental effects on the UPV values, including freezing temperature and water-saturated environments. The freezing temperature increased the pulse velocity for the frozen samples in comparison with the saturated samples.

From the ultrasonic pulse velocity data, it was found that all concrete mixes had a self-healing capability. However, this capability changed with the mix types and healing environments. In the saturated environment, analysis of the computed results showed that replacing 25% of the cement with fly ash as a supplemental material increased the crack healing capability. However, the healing rate was less in three of the experimental mixes. Additionally, samples made by using fly ash, SBR, or both, increased the healing rate, especially after the first 30 days. The results indicate concrete mixes containing SBR and fly ash will provide higher performance in terms of high healing capability and lower damage levels.

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Badanie zastosowań budowlanych zaawansowanych samonaprawiających się betonów

STRESZCZENIE:
Zapobieganie pęknięciom betonu to kluczowa kwestia w branży budowlanej. Zjawisko samonaprawiającego się betonu może być dobrym rozwiązaniem do łagodzenia pęknięć w betonie bez jakiejkolwiek bezpośredniej interwencji. Badacze z branży budowlanej opracowują wiele różnych samonaprawiających się materiałów betonowych z użyciem różnych materiałów i technik. Zaprezentowany projekt bada zastosowania samonaprawiającego się betonu, który wykorzystuje różne materiały cementowe, takie jak popiół lotny, żużel i materiały polimerowe, które można łatwo zastosować w przemyśle budowlanym. Aby przedstawić tę aplikację, przeprowadzono testy eksperymentalne na różnych mieszankach betonowych z użyciem ultradźwiękowych testów prędkości impulsu i ściskania. W tym badaniu eksperymentalnym próbki umieszczono w różnych warunkach środowiskowych, takich jak nasycenie wodą i przemarzanie. Wyniki badania szczegółowo omówiono w artykule. Wykresy ilustrują różnice behawioralne między popiołem lotnym, żużlem i materiałami polimerowymi. Na podstawie wyników eksperymentów stwierdzono, że wszystkie rodzaje mieszanin w środowiskach nasyconych i zamarzniętych miały zdolność regeneracji. W uzyskanych wynikach próbki charakteryzowały się dobrymi właściwościami mechanicznymi reprezentowanymi przez odporność na uszkodzenia, przyczepność kruszywa do zaprawy oraz wytrzymałość na ściskanie.

SŁOWA KLUCZOWE:
budownictwo; beton; pęknięcia powierzchniowe; polimery