Advanced Engineering Technology and Application
An International Journal

http://dx.doi.org/10.1857/aeta/090101

Preparation and Characterization of Eco-friendly and Sustainable Building Materials with Encouraging Healing Efficiency

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Received: 1 Jun. 2019, Revised: 1 Nov. 2019, Accepted: 1 Dec. 2019.
Published online: 1 Jan. 2020

Abstract: The most widely used building materials worldwide are cement as well as concrete in construction site, while these materials have well-known phenomenon which is cracking in concrete engineering. Concrete repairs are foreseeable to enhance its service life and provide additional expenditure separate to the building cost; so it necessary to seal cracks which occur due to drying shrinkage or exposed to external factors. Recently, the most promising healing materials that can be applied for concrete repairs are alkali activated materials which have high efficiency in dealing with crack propagation, while this efficiency can be increased by immersion in saturated lime solution or using fibers to heal the produced cracks or even suppress the crack formation. The current work focus on the formation alkali activated materials that exposed to artificial cracking then immersed in water, saturated lime, and using steel fiber as well as basalt fiber to examine their capability in healing the produced cracks. Results demonstrates the healing of the formed cracks with most of the used techniques, while the most promising were those used steel fiber as well as basalt fiber where the crack propagation were terminated and diminished.

Keywords: Slag, Steel fiber, Basalt fiber, Damage.

1 Introduction

The destruction of concrete more often due to an accumulation processes. Not all preliminary micro-cracks turn into destructive or unstable one. In the event that the micro-cracks can be mended once it formed, at that point the progress of concrete deterioration can be dodged. The protection of structures can be moved forward while the sustenance costs can be incredibly diminished. Numerous analysts have investigated this curiously phenomenon of concrete. Hannant et al.(1983) examined the self-healing progression of micro-cracks in concretes. Stefan et al. (1995) found that there were needle of ettringite as well as Ca(OH)2 seen navigating the cracks at a few area through checking using scanning electron microscope (SEM) when concretes weakened under freeze and thaw . Stefan et al. (1996) considered the disintegration and self-healing on chloride transport in OPC concretes. Nataliya (1998) talked almost the contrasts of self-healing, autogenous healing along with proceeded hydration. Liu et al. (2005) carried out tests to recognize the impacts of diameter of reacting particles on concrete's self-healing performance. Later on, Li et al. (2004) stated the complete closing of the cracks without leaking Reinhardt et al. (2003) examined the effect of temperature and crack width on self-healing behavior of concrete and they the fastest self-healing at the concrete surface. Geopolymer is an inorganic polymer, synthesized by alkali activation of aluminosilicate materials and results in three-dimensional Si-O-Al-O bonds Davidovits, (1994). Despite its strength and versatility as a construction material, geopolymer concrete has a significant drawback resulting from its defects, which could affect its durability and service life.

The major defects are either direct cracking, or other forms of defects which are linked to cracking [Zhu and Popovics (2007)]. Cracking is generally initiated by the formation of micro- cracks, which may later propagate into macro-cracks [Shah and Choi (1999) & Zhong and Yao, (2008)].

Fiber addition has been proved to be a competent way in improving the mechanical properties as well as the shrinkage control of fragile mortars and concretes based on alkaline-cements by break capturing. Moreover, it is well known that the fracture toughness given by fiber bridging

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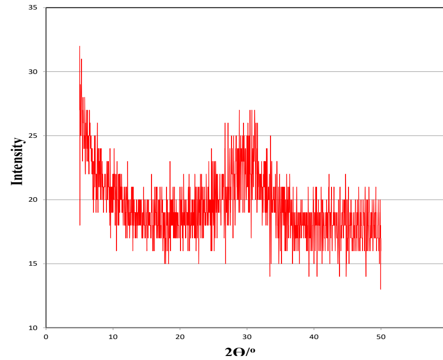
on cracks before their propagation. Debonding, sliding and pulling-out of the fibers are the main components that control the bridging activity [Silva and Thaumaturgo (2003a,b)& Penteado and Thaumaturgo (2005)]. At the starting of macro-cracking, the opening and cracks' development is controlled by the bridging activity of fibers, which leads to an increase in the required energy for crack propagation .The linear elastic performance of the binder may not be influenced essentially by low content of fibers. Whilst, post cracking conduct can be significantly altered, with increments of strength, toughness as well as materials' durability [Penteado and Thaumaturgo (2005)]. The enormous existence of micro crack in alkali activated slag's framework causes a preterm failure, large interfacial zone, high permeability, and low durability. Crack healing is an interesting concept that received much attention in recent years [He et al. (2011)], prominently using self-healing material [Li, et al. (2018) & Yıldırım and Şahmaran (2018)]. Based on previous investigations, there were many self-healing materials accessible for micro-crack refinement target. Several works were performed by utilizing microbes or polymer to fill the voids within the microstructure of concrete [Dong et al .(2015)& Snoeck et al. (2014)] either utilizing outside mediation or self-healing strategies. The process concerned with the releasing of self-healing particles into cracks when the inserted microcapsule split by crack formation. The purpose of this research focus on the formation alkali activated slag materials that exposed to artificial cracking then immersed in water, saturated lime, and using steel fiber as well as basalt fiber to examine their capability in healing the produced cracks. The sequence of crack healing is characterized petrographic examination; also ultrasonic pulse velocity as well as compressive strength will be studied.

2 Material and Methods

2.1 Materials

Blast furnace slag (BFS) was used as raw materials for alkaline activation process [Iron and Steel Factory- Helwan, Egypt]. Steel fiber and basalt fiber were used as healing agents. Sodium hydroxide was used as an alkaline activator for the reaction [99 %, Sigma Aldrich], while calcium hydroxide [99 %, Sigma Aldrich] was used for the preparation of saturated lime solution for immersion of geopolymer. The used steel fiber was of length 5 mm and diameter 0.2 mm with aspect ratio of 25. The complete compositions of the used materials are given in Fig. (1), as well as their mineralogical properties; where its mineralogical composition reflects its high amorphous structure as a results of fast quenching process, while the chemical composition depicts that it has mainly SiO2, CaO, and Al2O3 as major constituents.



Material	Water – Cooled Slag (GGBFS)
SiO_2	36.67
Al_2O_3	10.31
Fe_2O_3	0.50
CaO	38.82
MgO	1.70
SO_3	2.17
K_2O	1.03
Na_2O	0.48
TiO_2	0.57
MnO_2	4.04
P_2O_5	0.04
Cl^-	0.05
L.O.I.	0.12
SrO	0.18
BaO	3.28
Total	99.96

Fig (1): Chemical and mineralogical properties of blast furnace slag

2.2 Alkali Materials Preparation and Curing

Binders activation were done using 6 wt., % NaOH from the total dry mixes, whereas their water content was 23 % as indicated in the table (1). The dried binder was stirred mechanically for 2 min followed by another 5 min with activator solution, then were poured in 10 cm length cylindrical shaped mold with diameter of 5 cm. The cast binders were vibrated followed by sealing with plastic sheet for preventing water evaporation. The molded blends were cured at 23oC (r.t.) for 24 hrs, followed by curing at 40°C under 100 % relative humidity (R.H.) up to 28 days. In order to stimuli cracking for the samples, they were exposed to strength equal 0.2 of the 28 days compressive strength of the control paste [Shim et al. (2015)].

Table (1) : Composition of the geoplymer mixes.(Mass, %)

Mix no.	Water cooled slag(WCS), %	Steel fiber, %	Basalt fiber, %	NaOH, %	Water immersion	Saturated lime immersion	Water/ binder, %
A0	100	--	--	6	√	×	0.23
A1	100	--	--	6	×	√	0.23
S	100	0.50	--	6	√	×	0.23
B	100	--	0.50	6	√	×	0.23

In order propagate a crack with a width between 0.1 and 0.3 mm. After that the samples were treated using different healing conditions as in Table (1). During immersion, at specified time all samples were tested using ultrasonic pulse velocity to attain the healing efficiency of the used agent. At the end of immersion time, the samples were tested mechanically for compressive strength, and the crushed specimens were then exposed to stopping of further hydration using acetone solution for 24 hrs at 60 ºC [Ke et al. (2014)]. All samples were tested visually as well as using petrographic microscopic imaging.

2.3 Methods of Investigation

Chemical examination of the raw materials using XRF-Axios (PW4400) WD-XRF Sequential Spectrometer, while mineralogical characterization done by XRD-Philips PW 3050/60 Diffractometer with a Cu-Kα source. Compressive strength determined using five tones German Brüf machine with rate of 100 MPa/s [ASTM(2016)]. Petrographic inspection was done on fluorescent dyed alkaline samples using a stereo-microscope (Olympus Gx70) equipped with a blue filter (BG-12) and under magnification 50×. Flat polished section was and lapped by using a series of silicon carbide grit followed by polishing using diamond paste, until a smooth surface is obtained [Khater and Ezzat (2018)]. For nondestructive in-situ testing for concrete, ultrasonic pulse velocity (UPV) test is the most promising technique for checking the quality of the cement binders using Proceq's Tico instrument, by measuring the velocity of an ultrasonic pulse passing through a hardened binder structure, in addition it can be helpful in quantifying the damage of the hardened binder [Qasrawi, and Marie(2003) & Zhong and Yao (2008)] according to the following equation:

UPV=L/T……………………………（1)

Where (T) is the elapsed time and L is the distance of the ultrasonic propagation through the concrete matrix, whereas UPV readings were taken in accordance with **ASTM C597 (2016)**.

3 Results and Discussion

Ultrasonic concrete tester is shown in Figure (2) of alkali activated slag treated using various healing parameters. As known, the main principle of this test consists of measuring the time of ultrasonic pulse travel passing through the tested samples. Relatively, as the specimen quality is good in terms of density, uniformity, homogeneity, etc., the higher the velocity is obtained. From the figure we can deduce that tap water as well as saturated lime solution immersed samples possess high UPV values and increases with time up to more than 100 % from its original value giving an indication about the continuous healing of the precracked samples with time. On the other hand, samples incorporating basalt fiber as well as steel fiber have lower UPV readings by about 50 % from the previous two groups as well as from their original readings; in spite their readings increase with time reflecting also the continuous healing of the precracked hardened samples. One can classify the resulting data according to ASTM C597 (2016), where UPV more than 4.5 resulting in formation of excellent binder quality, while reading below 3; results in doubtful quality of the formed binder. This means that the immersion in tap water as well as in saturated lime solution has good potential in formation of excellent quality binder (UPV more than 5) rather than fiber incorporated sample (UPV less than 3).

UPV results indicate that the damaged hardened paste mended entirely during consequent storage in tap water as well as saturated lime solution medium, whereas the UPV's recovery has many factors affecting on it as damage degree etc. Lastly, any increase in mortar moisture content causes an increase in UPV which negatively affect compressive strength; where any discontinuity as a crack in the wave path, results in reflection of part of the energy from the flaw surface.

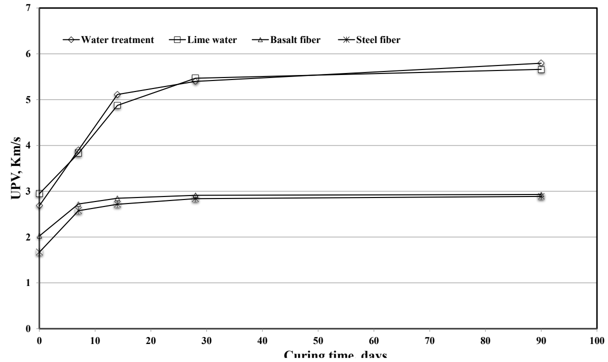


Fig. (2): UPV of alkali activated slag treated with various healing parameters

Concurring to consider of other analysts [Suaris and Fernado (1987)], the UPV diminish to an extreme degree depending on the secant modulus diminishment within uniaxial compressive testing, So Zhong and Yao (2008) defined a damage degree as:

Damage efficiency D= 1-(v/v0)…………………（2)

Where D is the harm degree of concrete, v is the UPV prior to self-loading and v0 is the UPV prior to loading. So the microstructure changes in concrete can be induced from the diminish of UPV by D.

From Figure (3) we can conclude that all damage data is in the negative zone which reflects the increased UPV of the healed specimens as compared with the control unhealed one at all studied healing parameters.

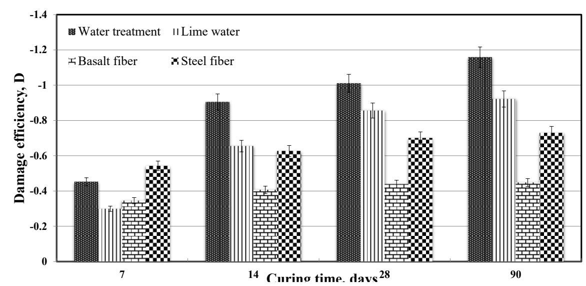


Fig. (3): Damage efficiency of 90 days alkali activated slag treated with various healing parameters.

The figure shows also the highest negative values for tap water, followed by saturated lime solution and then steel fiber mixes. This indicates that those mixes can retain their original uniformity steadily with time resulting in uniform compact structure as well be emphasized later by petrographic examination. The result of damage degree illustrates the increased UPV after healing as compared with control reading as reflected on the negative reading of the damage degree for all samples. However, tap water as well as saturated lime solution followed by steel fiber treated samples have lowest D values which confirmed by highest healing efficiency for those treatments. Samples treated with basalt fiber has highest D values as compared with other treatments which reflected negatively on the healing efficiency of this treatment.

Fig.4 and Fig.5 shows the strength and K value of hardened geopolymer exposed to various healing parameters. It seems that the compressive strength results of all blends is in the range 300 to 480 kg/cm2, where mixes immersed in saturated lime solution acquires high strength retain followed by basalt fiber and tap water mixes It can be clearly found the binders strengthened by steel fibers have lower impact on the self-healing compared with those strengthened by other parameters. In order to characterize the self-healing capability, self-healing proportion was presented and marked as K, which referred to the proportion of the compression quality after self-healing (P0) to the first compression (P) of UHPCC.

K=P/P0……………………………（3)

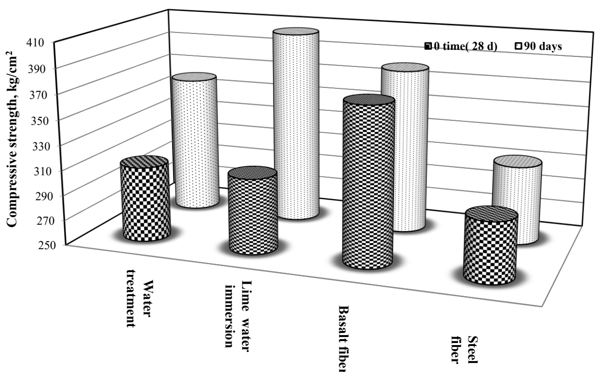


Fig. (4): Compressive strength of alkali activated slag treated with various healing parameters for zero and 90

The self-healing ratio K of alkali activated slag treated with various healing parameters (Fig.5) of both tap water and saturated lime approaches 1.2 and the self-healing ratio K of both basalt fiber and steel fiber approaches to one. The blends incorporated steel fibers appears superior mechanical property, but the self-healing proportion is lower than that of blends treated with other factors. Zhong and Yao (2008) found that there is a damage threshold degree on concrete, which in case it is lower than this limit, the self-healing proportion of the concrete will increment with damage degree increment. So we know, the damage degree may impact the self-healing implementation of the concrete, but it isn't the only factor. In tap water as well as saturated lime solution environment, the unhydrated cement particles re-hydrate, and the fine splits are bridged and contracted steadily. In case of too low damage degree, the contact number of unhydrated cement particles is little and it isn't accommodating for re-hydration. On the other hand, in case of too high damage degree over threshold, the new hydrated materials are not capable of crack bridging and so K values reduced.

Figure (6) illustrates the visual as well as petrographic examination of 90 days precracked alkali activated hardened specimens**.** One can depict from the visual patterns that the micro cracks almost healed under the studied healed parameters, which emphasized by their petrographic images where a few re-hydration items agglomerates along the cracks 'edges of and may be seen in micro cracks clearly through the petrographic examination, and the rehydration materials filled within the center portion were less thick than those along the edges, as well as the width of cracks contracted [Stefan, et al. (1995)].

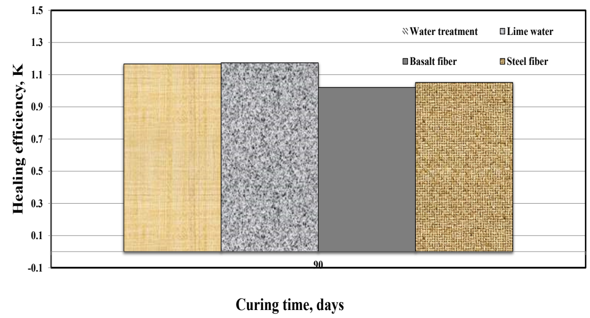


Fig. (5): Healing efficiency of 90 days alkali activated slag treated with various healing parameters.

From the figure we can deduce also that microcrakcs in tap water is the most filled one followed by basalt fiber and saturated lime solution and finally steel fiber samples. The sequence of crack repairing can be seen visually in Figure (7), where the cracks were completely healed after 3 months of treatment.

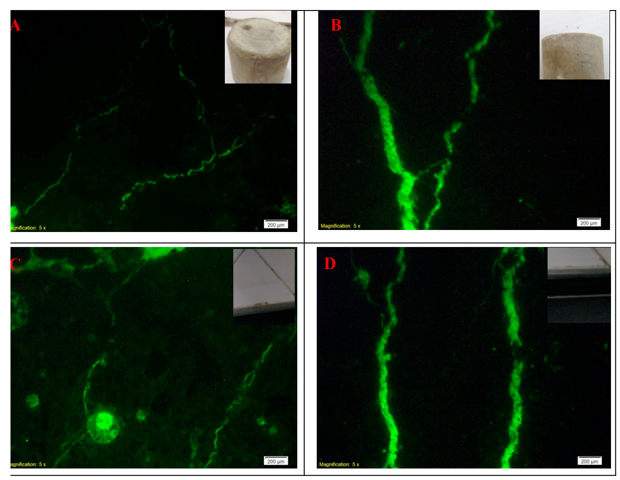


Fig. (6): Fluorescent images of 90 days alkali activated slag treated with various healing parameters; A) water immersion, B) saturated lime immersion, C)steel fiber in water, D) basalt fiber in water.

4 Conclusions

Self-healing of alkali activated slag is markedly affected by the treatment methods as well as the materials used for promoting their healing efficiency. The current work has some main findings:

1- Damage degree of all treatments was very low but mixes immersed in tap water as well as saturated lime solution has the lowest damage degree. Where the damage degree affected markedly by ultrasonic pulse velocity reading.

2- The mechanical and ultrasonic data show that the self-healing ratio of alkali activated slag increases with the decreasing of damage degree depending on the ways of treatment.

3- Precracked hardened alkali activated samples in both tap water as well as saturated lime solution exhibit higher self-healing performance with high UPV that increased to about 100 % of its original value indicating high retention of structure with time. Also, they acquire high healing efficiency more than 1.2.

4- Basalt fiber as well as steel fiber has lower UPV values while improved with the increasing of curing ages, whereas their healing efficiency reached to about one. After self-healing treatment, UPV has been recovered to a large extent and the damage degree could be deduced from the UPV increase.

***Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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