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Self-healing concrete utilizing low calcium fly ash, recycled aggregate, and macro synthetic fibers: autogenous behavior and properties

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Abstract. This study aims to develop a self-healing concrete solution that addresses the issues of high maintenance and repair costs, limited durability, and reduced service life of concrete structures. To achieve this, low calcium Fly Ash and partially replaced recycled aggregate were utilized, resulting in decreased concrete strength. To counteract this issue, macro synthetic fibers were introduced at 0.5 % and 1 %. The samples were then cracked and left to self-heal over a five-week period. The outcomes indicated that incorporating 60 % Fly Ash was the most effective method of healing cracks within the given timeframe. Moreover, the addition of 0.5 % macro synthetic fibers showed substantial enhancement in mechanical properties without compromising workability. This study highlights the potential of self-healing concrete as a sustainable and cost-effective solution to enhance the performance and durability of concrete structures.

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1. Introduction

Concrete is a widely used construction material that can be designed to have a service life of several decades [1–4]. It is a crucial component in the construction of many infrastructures, and its annual global production in 2011 was estimated at 3.5 billion tons, which highlights the significant demand for cement [5]. Emerging markets are investing in new infrastructure to sustain their rapid economic development and growing populations, and it is projected that emerging Asian markets will require $776 billion in annual investments between 2010 and 2020 to meet the increasing infrastructure demand [6]. Due to its moldable nature, concrete is a versatile construction material that can be cast into any shape within a proper framework, and its physical attributes can be utilized in various structural applications. However, concrete's highly brittle behavior makes it vulnerable to cracking, which reduces its lifespan and sustainability. Extreme loading, earthquakes, and adverse environmental factors are the leading causes of cracks in concrete, weakening its strength, exposing it to harsh environmental agents, and decreasing its service life. These cracks result in higher maintenance and repair costs and reduced strength and service life of concrete structures [1–4].

The occurrence of cracking-related issues increases the maintenance and repair costs of civil infrastructure and reduces its service life, rendering concrete infrastructure unsustainable. Consequently, research and development have shifted towards developing new technologies that can enhance the material properties of concrete and construct new infrastructure that can withstand multiple hazards [7]. The development of concrete that can recover from any performance loss caused by cracking is highly desirable. The hydration of concrete has been shown in several research studies and practical experiences to repair its structural cracks on its own. This has led material scientists to explore the concept of "self-healing," which was inspired by biomimicry, such as the natural healing of broken bones or blood coagulation. However, applying this idea to industrial materials was challenging due to the complexities involved in the healing process. Nonetheless, this concept has proven to be a revolutionary approach to the maintenance and repair of concrete.

The self-healing capability of concrete was first identified by Abrams in 1925 [8]. In his study, concrete samples that had cracks after a compression test were repaired when left outdoors for eight days, and their compressive strength was twice as high as that in 28 days. Further research has revealed that freeze-thaw damage to concrete samples can also self-heal after curing. Ettringite crystals and calcium hydroxide crystals were found in the cracks, and parts of the resonant frequencies were restarted [9]. Subsequent studies on crack healing in concrete can be classified into two self-healing techniques: intrinsic healing and extrinsic healing. Intrinsic healing can occur through several mechanisms, including carbonation of $Ca(OH)_2$ to generate $CaCO_3$ precipitation, further hydration of un-hydrated cementitious particles, closing cracks caused by water impurities or loosened concrete particles, and matrix swelling (Calcium Silicate Hydration) products (C-S-H). The formation of calcium carbonate $CaCO_3$ precipitates has been identified as the main cause of autogenous self-healing [10]. The second self-healing approach is subdivided into vascular and capsule-based healing methods, which rely on incorporating adhesive reserves inside the matrix to detect deterioration with or without human involvement [11, 12]. However, technical flaws emerged when the chemical substances were not simultaneously present at the affected locations, leading to long-lasting voids inside the concrete and a decline in durability. Among all potential strategies, only intrinsic healing investigations have resulted in a considerable reduction in fracture width, less water permeability, and improved or recovered mechanical characteristics [13–16].

Autogenous self-healing is the ability of concrete to repair itself using its own matrix potential. This phenomenon is common in water-retaining structures, culverts, and pipelines and has been extensively studied since it was first identified by the French Academy of Science in 1836, particularly in relation to water-retaining structures. To promote autogenous self-healing in concrete, mineral admixtures such as Fly Ash and Blast Furnace Slag, expansive minerals, and crystalline admixtures can be used. High-activity mineral admixtures, such as Fly Ash and slag, can improve the mechanical properties of concrete by enhancing pore structure, compactness, and durability, and also reduce cement consumption and lower the temperature rise during hydration. This can have a positive impact on the environment by reducing carbon dioxide production from cement production [17, 18].

Recycling and processing concrete waste into new aggregates can enhance the geotechnical and chemical properties of concrete, and recycled aggregates can also improve soil characteristics [19]. In a recent study, Fly Ash was added as a mineral admixture at different volumes to induce autogenous self-healing in concrete, while recycled aggregates were used to partially replace natural aggregates and make the concrete more environmentally friendly and improve its mechanical properties. Furthermore, 0.5 % of macro synthetic fibers were added to the concrete matrix to further enhance its durability and mechanical properties [20].

To enhance the self-healing capability of cement-based materials, fibers are typically used in combination with clinker substitutes such as Fly Ash and silica fume, as well as with crystalline admixtures [21]. The ultimate aim of this research is to develop new techniques that can promote self-healing capabilities in concrete using Fly Ash as a cement autogenous self-healing addition. This method has the potential to revolutionize the concrete industry by creating more durable, sustainable, and long-lasting structures while significantly reducing repair and maintenance costs [20].

2. Materials and Methods

2.1. Materials

The focus of this study is on the utilization of Class F Fly Ash, a supplementary cementing material, in concrete to explore its self-healing capabilities when combined with recycled aggregate and macro fibers.

In this research, Ordinary Portland cement grade 53 was employed, with a claimed fineness of about 301 m^2/kg and a specific gravity of 3.15 g/cm^3. The chemical composition of the cement used in the investigation is presented in Table 1.

Table 1. Chemical composition of cement.

Chemical composition (% by weight)	
SiO_2	21.24
Al_2O_3	5.56
Fe_2O_3	3.24
CaO	63.53
MgO	0.93
Na_2O	0.13
K_2O	0.62
SO_3	2.55
Free lime	0.55
Insoluble residue	0.64
Loss on ignition	1.24

2.1.1. Concrete

Mix design is a critical step in concrete research, involving the determination of the appropriate proportions of cement, aggregates, water, and additives to achieve desired properties. The outcome of the mixed design process directly affects the performance of the concrete, including its strength, durability, and workability. Thus, a well-designed concrete mix is essential for the success of any substantial research project. For the preparation of M30 concrete, various quantities of cement aggregates and water content were evaluated.

In the present study, a cubic (6in*6in) concrete of 30 MPa strength was designed as a control group, as shown in Table 2.

Table 2. Mix design of control group.

Description	Cement, (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Water Content (kg)
Ratio	1	1.725	2.416	0.46
Per Cube (6in × 6in)	1.60	3.17	3.7	0.784
Per m^3	420.23	724.92	1015.11	193.3

2.1.2. Fly Ash

Fly Ash is a residual substance that is generated during the combustion of coal in industrial settings. It comprises fine particles carried away by the exhaust gases, with those that do not ascend being referred to as base ashes. The composition of Fly Ash is heterogeneous and typically consists of Silicon dioxide (SiO_2), Aluminum oxide (Al_2O_3), Ferric oxide (Fe_2O_3), Calcium oxide (CaO), and Magnesium oxide (MgO).

Fly Ash is a versatile material offering substantial performance benefits in concrete and non-concrete applications. When treated with sodium hydroxide in high-temperature pyrolysis, it can act as a catalyst for converting polyethylene into a substance similar to crude oil. Due to the hardening of Fly Ash particles during their suspension in exhaust gases, they tend to have a round shape and range in size from 0.5 to 300 micrometers.

In the construction industry, Fly Ash is classified as a supplementary cementitious material (SCM) and can replace binders in cement. The use of SCMs in concrete provides several environmental benefits, as waste materials are used to reduce the amount of cement required, which is a significant source of carbon emissions that contribute to global warming.

Figure 1. Fly Ash.

Moreover, modern research has shown that SCMs like Fly Ash can induce self-healing of cracks when exposed to moisture, making them increasingly sought after. When combined with lime in concrete, Fly Ash enhances its strength, with a typical usage rate of 15–35 % by weight of cement in structural concrete and up to 70 % in mass concrete for dam construction, roller-compacted concrete pavements, parking lots, and low-strength concrete applications. The chemical composition of Class F Fly Ash used in this research is detailed in Table 3.

Table 3. The chemical Composition of Class F Fly Ash.

Analysis	Result
	II
Loss on ignition (LOI) (%)	1.53
Chloride (as Cl) (%)	0.011
Sulphate (as SOs) (%)	0.51
Free CaO (%)	Nil
Reactive CaO (%)	4.06
Total CaO (%)	4.42
SiO_2 (%)	51.55
Al_2O_3 (%)	33.32
Fe_2O_3 (%)	3.34
SiO_2+ Al_2O_3+ Fe_2O_3 (%)	88.21
Na_2O (%)	0.51
MgO (%)	0.75
Phosphate (as P_2O_5) mg/kg	6.22

2.1.3. Macro Synthetic Fibres

Macro synthetic fibers, referred to as "structural" synthetic fibers, are composed of a blend of polymers and were originally developed to serve as a substitute for steel fibers in specific applications. These fibers are preferred over steel fibers due to their lightweight nature, resulting in less dense concrete when used in reinforced concrete. While initially investigated as a potential replacement for steel fibers in shotcrete, subsequent research and development has demonstrated their effectiveness in the design and construction of ground-supported slabs and various other applications. Macro synthetic fibers have multiple important uses and are characterized by their embossed structure and length of approximately 3 inches.

Figure 2. Macro Synthetic Fibers.

The physical properties of embossed macro synthetic fibers used for this project are explained in Table 4.

Table 4. Physical properties of MSF.

Characteristic	Property
Material	100% virgin polypropylene
Surface Texture	Continuously Embossed
Appearance	White
Water Absorbency	Nil
Tensile Strength	500-700Mpa
Elastic Modulus	>9000Mpa
Length	55mm
Density	0.91 g/cm^3
Melting Point	160–170°C
Resistance to Acid & Alkali	Excellent

2.1.4. Recycled Aggregate

Cement recycling is a straightforward process that involves breaking down, removing, and crushing existing cement to create a particular size and quality material. Recycled aggregate is produced by crushing concrete and, in some cases, asphalt, to recover the aggregate. This research collected large lumps of recycled concrete aggregate (RCA) from a demolished site in Mirpur Abbottabad. These large lumps were then crushed into smaller sizes of 4.75 mm – 19 mm using an aggregate crusher machine.

Figure 3. Recycled coarse aggregate.

2.2. Methods and Mixing design

The methodology for this study involved a three-stage process. In the first stage, control samples of mixed design were prepared and tested for strength to establish a baseline. In the second stage, various modifications were made to the concrete mix, including replacing 50 % of the coarse aggregate with recycled aggregate, replacing 60 % of the cement with Fly Ash, and adding macro synthetic fibers at volumes of 0.5 % and 1 % individually, with a specific focus on the effects of the 0.5 % volume addition of macro synthetic fibers. Finally, in the third stage, the results of the final concrete samples were analyzed, which included the replacement of cement with Fly Ash, replacing 50 % of the coarse aggregate with recycled aggregate, and adding macro synthetic fibers at a volume of 0.5 %.

3. Results and Discussion

3.1. Compressive Strength of Natural Concrete

The compressive strength of the reference concrete samples was obtained using a compression testing machine after 7, 14, and 28 days respectively. The compressive strength values post-testing are given in Table 5.

Table 5. Compressive strength of the reference concrete.

SAMPLE	7 DAYS (N/mm^2)	14 DAYS, (N/mm^2)	28 DAYS (N/mm^2)
NC 1	19.01	23.13	29.17
NC2	18.65	22.56	28.84
NC3	17.94	21.92	28.65

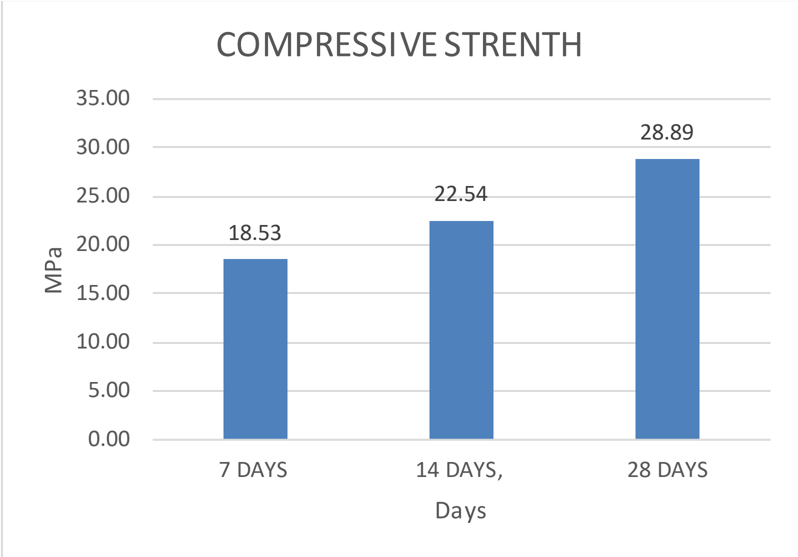

Figure 4. Average values of '7,14- and 28-days' compressive strength reference concrete.

3.2. Replacement of Coarse Aggregate with 50 % RCA

The coarse aggregate in the concrete mixture was partially substituted with recycled aggregate, representing 50 % of the total coarse aggregate used. The recycled aggregate was obtained by crushing large lumps of recycled concrete and producing 19 mm down recycled aggregate. The recycled aggregate was incorporated as a partial replacement for the natural aggregate in the concrete mixture. Compression tests were conducted on the concrete specimens using a testing machine after 28 days to determine their strength. The outcomes of the compression tests are presented in Table 6.

Table 6. Compressive strength of 50%RCA replaced concrete after 28 days.

SAMPLES	28 DAYS
RA1	20.83
RA2	20.68
RA3	23.49

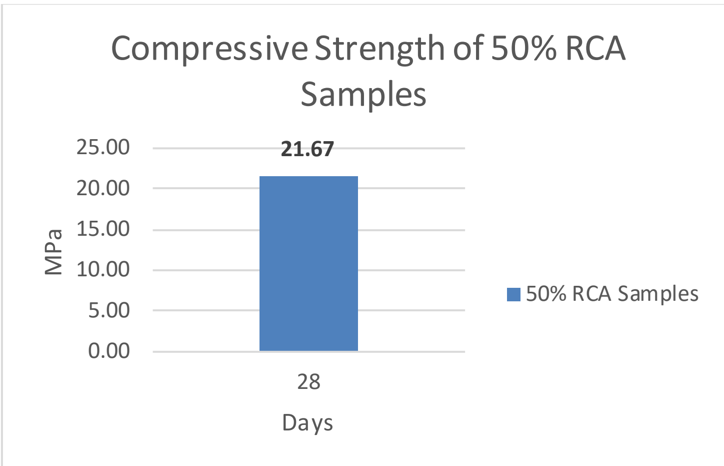

Figure 5. Average compressive strength of 50 % RCA samples at 28 days.

3.3. Addition of Macro Synthetic Fibers (0.5 % & 1 %)

As part of the research, we used macro synthetic fibers to increase the mechanical properties of concrete as we lost strength due to the usage of Fly Ash and recycled aggregate. The volume used macro synthetic fibers on two percentages, 0.5 %, and 1 %, respectively.

Compressive strength of 28 days was obtained using a compression testing machine, the values of which are presented in Table 7.

Table 7. Compressive strength of concrete with fibres at 1 % and 0.5 %.

SAMPLE	50%RA+ 0.5% FIBERS (N/mni²)	50% RA + 1 % FIBERS (N/mm²)
1	21.41	23.13
2	23.5	23.92
3	21.87	24.09

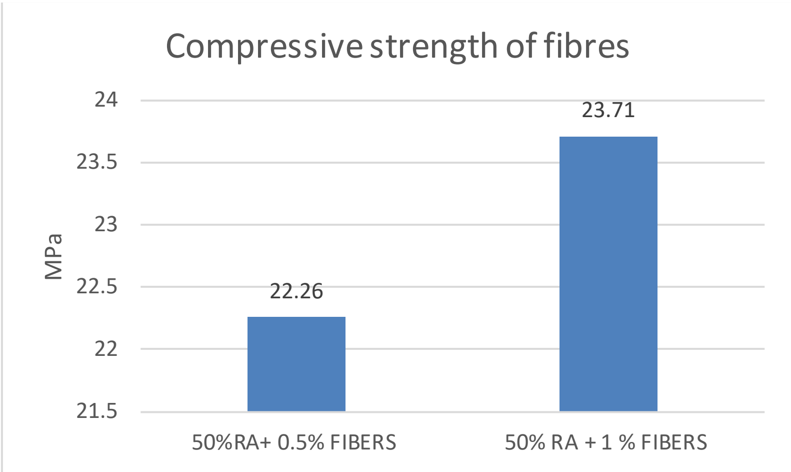

Figure 6. Compressive strength of fibres with concrete at 28 days.

3.4. Replacement of Fly Ash + RCA & addition of MSF in Concrete

Following the successful autogenous self-healing in Fly Ash based RCA concrete, the next objective was to enhance the mechanical properties of concrete by incorporating macro synthetic fibers, as a decrease in the strength was observed due to the use of Class F Fly Ash and 50 % replaced recycled aggregate. For this purpose, concrete samples were prepared by replacing 50 % of the coarse aggregate with recycled aggregate and utilizing Fly Ash at a proportion of 60 %. Macro synthetic fibers were then added to these samples at a volume percentage of 0.5 %. These samples were subsequently cured for 28 days and subjected to various loading conditions to induce cracking. The resulting crack widths under each loading condition are presented in Table 9.

Table 9. Different cracking loads for Fly Ash, RCA, and MSF concrete.

SAMPLE	FA %age + 50% RCA+0.5% Fibres	PEAK (KN)
1	60%	147.7
2	60%	164.0
3	60%	152.8

Following the induction of cracks in the concrete samples, they were subjected to autogenous self-healing by being submerged in water. The initial observation was made after three weeks, and the second and final observations were made after five weeks, so cracking widths and details are in Table 10.

Table 10. Cracking details with healing behavior of Fly Ash, RCA, and MSF concrete after 3 and 5 weeks, respectively.

Concrete samples	Crack width (mm)	Healing status (after three weeks)	Healing status (after five weeks)
SAMPLE (60% FLY ASH + 50% RA + 0.5% FIBERS)			
C11	0.6	Completely healed	
C12	0.63	Completely healed	
C2I	0.57	Completely healed	
C31	0.48	Completely healed	

3.5. The healing in the concrete of 60% Fly Ash + 50% RA + 0.5% Fibers

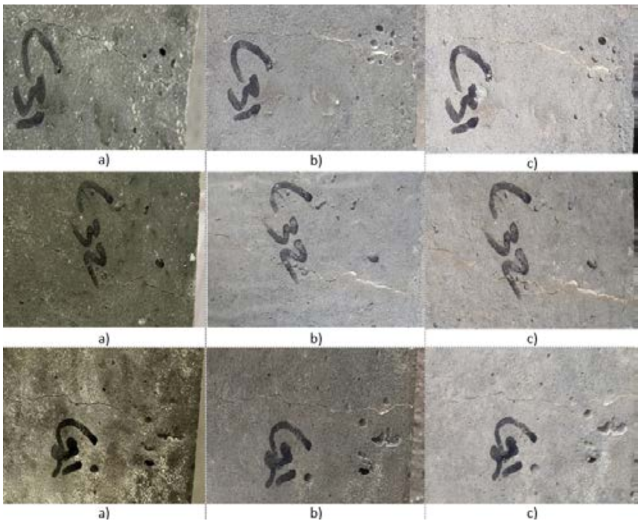

Figure 8: Healing in concrete having 60% Fly Ash + 50% RA + 0.5% fibres.
a) initial, b) after three weeks, c) after five weeks.

After observing successful healing in the samples, their compressive strength was evaluated using a compression testing machine. The resultant values are presented in Table 11.

Table 11. Compressive strength of samples of FA+50%RCA+fibres after healing

SAMPLE	FA %age+50% RA+ 0.5% Fibers	STRENGTH(N/mm^2)
1	60%	14.8
2	60%	15.91
3	60%	14.36

4. Conclusions

This study investigated the autogenous self-healing properties of concrete containing varying volumes of low calcium Class F Fly Ash with partially replaced recycled aggregate and the incorporation of macro synthetic fibers to improve mechanical properties. The following conclusions can be drawn from this investigation:

1. The use of recycled aggregate and fibers in concrete reduced the workability of concrete, which was rectified by using a higher water-cement ratio.

2. The use of partially replaced recycled aggregate resulted in a decrease in the strength of concrete. However, the incorporation of macro synthetic fibers led to an increase in the mechanical properties of the concrete.

3. The self-healing behavior of Fly Ash was observed to be significant within the first two weeks after the cracking of 28-day strength samples.

4. The self-healing behavior of concrete generally increased with the increasing volume of Fly Ash up to 60 percent replacement, beyond which a decrease in self-healing ability was observed.

5. Future recommendation

Based on the results of this study investigating the self-healing behavior of concrete with partially replaced recycled aggregate and the addition of macro synthetic fibers, the following recommendations can be made:

1. The use of calcium-treated Class F Fly Ash with $CaCl_2$ could potentially enhance the healing ability of concrete and should be further explored to heal larger crack widths.

2. Increasing the volume of replaced recycled aggregate to 75 % and 100 % may provide a more economical solution for the production of self-healing concrete, and this possibility warrants further investigation.

3. Other supplementary cementitious materials (SCMs), such as blast furnace slag, could be combined with recycled aggregate to enhance the autogenous self-healing of concrete and should be considered in future research.

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