

Enhancing Concrete Durability and Sustainability: Exploring the Potential of Metakaolin for Self-Healing Concrete

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ABSTRACT

Sustainable development of the construction industry requires the utilization of various new compounds. However, environmental concerns regarding harm from raw material exploitation, carbon emission, and demolishing activities associated with structure failure due to loads, serviceability, environmental exposure, and repair or maintenance have brought pressure to redesign traditional concrete. Numerous studies focus on using supplementary cementation material as a partial substitute for cement. Additionally, the self-healing technology of the concrete focusing on automatic repair features, when subjected to damage, is also developing a new trend. Metakolin, a calcined clay – Kolin, is a supplementary cementitious material used as an admixture to produce cement replacement. Open microcracks in concrete can be repaired by CaCO_3 precipitation attributable to a revolutionary method called bacterial self-healing. Hence, an attempt has been made in the present study to utilize both the pozzolanic material and developing self-healing features in the same concrete. Initially, the mix was used to find the optimum dosage of metakaolin and self-healing compound dosage individually in the concrete matrix. Later, their optimum dosages were utilized in designing Hybrid concrete. As worked out at the individual substitutions, optimum values of metakaolin replacement and self-healing compound had positive results; similarly, introducing the optimum percentage of both materials yielded fruitful results compared to traditional concrete. This investigation has shown that the metakaolin substitution and introduction of a self-healing compound in the mix can produce high-performance and smart concrete.

Keywords – Metakaolin, Self Healing, Strength, Water Absorption, Durability

1. INTRODUCTION

The construction industry has changed due to the widespread utilization of concrete. Concrete typically consists of water, fine and coarse particles, and cement as the binding agent. The binding action developed by the cement in the presence of water results in binding the aggregate, thus strengthening the matrix and contributing to the overall strength. The cement sector is expanding significantly, with the global market expected to grow from US\$340.61 billion in 2022 to US\$481.73 billion in 2029[1]. However, the increase in cement production has also increased the industrial pollution shear in the carbon dioxide emission proportionally; about 7 percent of the industrial emission is generated from the cement industry. The manufacturing process of 1 tone of cement generates 1 tone of carbon dioxide. Other dangerous gases produced during cement manufacture, such as nitrogen oxides, sulfur dioxide, carbon dioxide, and dust, can harm the environment, people's health, and flora. With the increase in cement demand, natural resources are decreasing proportionally, thus increasing greenhouse gases and contributing to rising pollution levels. In the service life of the structure, the concrete is susceptible to cracking

either due to different types of loading conditions or adverse environmental conditions. Apart from this, repair and maintenance are also a point of concern due to significantly high cost, time consumption, and alternate arrangements for serviceability. Therefore, the conventional demolition and re-building or repair of the concrete members could be more sustainable. Moreover, the traditional repair techniques have been far from the modern retrofitting methods, resulting in poor repair effects and the development of weak points apart from excessive repair costs time and again. Numerous studies focus on the use of cementitious materials as a partial alternative to cement [5]. By using less cement, carbon emissions into the atmosphere will be reduced. Additionally, recent research has begun to take shape in self-healing technology, focusing on automatic repair features when subjected to damage. In this paper, self-healing concrete was prepared using metakaolin as a partial replacement for cement. The partial substitution of metakaolin was undertaken with the binder to optimize the replacement level for the cement in the modified concrete. Concrete's compressive strength is substantially enhanced by using various extra cementitious elements as partial replacement of the cement. The early strength of cement that has minerals added to it can be improved, thereby reducing the overall amount of cement needed [2]. When a concrete member cracks, the pre-embedded self-healing components are activated when exposed to air, releasing the healing compounds that fill the cracks and heal them. This stimulates the self-healing properties [9]. This article has focused on utilizing the subsidiary cementitious element as a substitute for cement, followed by the addition of a self-healing compound to concrete, which is referred to as hybrid concrete. The hybrid concrete proposed to be developed will be environmentally friendly by reducing greenhouse gas emissions during the production of cement and by reducing the life cycle cost of the structural member in terms of maintenance and repair.

2. BACKGROUND

2.1 Metakolin

The word "kaolin," which means "high ridge," is taken from the Chinese word "Kao-ling," which refers to a hill near Jauchau Fu where this substance was long mined for use in ceramic pottery [3]. Hydrous aluminum silicate, which chemically is composed of staggered sheets of alumina octahedral and silica tetrahedral sheets, is the primary component of kaolinite. Metakaolin is a pozzolanic [6] substance manufactured by heating kaolin to temperatures between 650 and 900 °C and is non-carbon-emitting, white, and grounded. Its particle size distribution spans between 1.5 micrometers and 10 micrometers. This mineral addition's dry, dense form complies with ASTM C 618 class N pozzolana [7]. Typically, it is comprised of 40–45% Al_2O_3 and 50–55 % SiO_2 and because of its large surface area—150000–180000 cm^2/gm —it is incredibly reactive. Due to its highly controlled processing, meta-kaolinite offers good properties as an additional cementing ingredient [8]. MK powders are highly consistent in both appearance and functionality. In 1962, MK was used for the first time in concrete for the Jupia Dam in Brazil, comprising about 250,000 metric tonnes [4]. Since the mid-1990s, the commercial availability of metakaolin was made to the construction industry.

2.2 Self -Healing Concrete

Self-healing concrete is designed to be self-healing by filling in cracks and sealing them with limestone. Bacterial Self-healing concrete is a substance that, with the aid of microorganisms existing in it, biologically produces minerals like limestone, which will repair cracks that develop in the concrete. This study incorporates additional external self-healing compounds into concrete during the mixing stage to enhance performance and enable speedy concrete repair [10]. The self-healing concrete contains bacteria and a certain quantity of starch, which acts as food for the bacteria. These bacteria remain dormant in the concrete until a fracture opens and air enters. The bacteria become active as a result of this alteration and begin to consume the starch that has been introduced into concrete. The bacteria secrete calcite, a type of calcium carbonate, as they consume food, develop, and reproduce [11]. The crack is filled and sealed when the calcite bonds to the concrete.

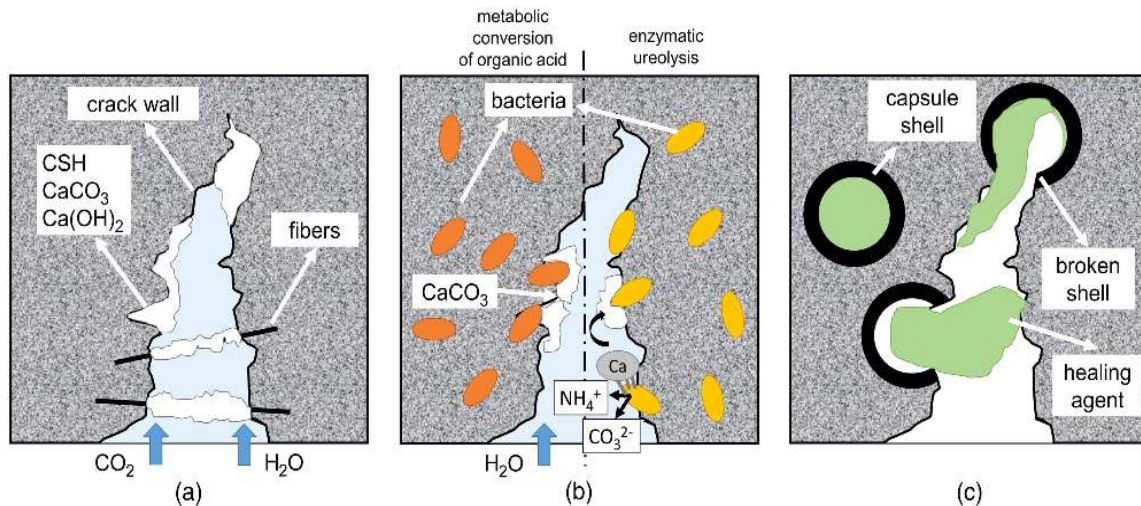


Figure 1: Self-Healing Mechanism.

3. RESEARCH SIGNIFICANCE

Concrete members (Beams, columns, etc.) in a structure, when stressed under working loads, may develop minor cracks. These cracks allow the moisture to ingress into the concrete body, thereby corroding both the reinforcements and cracked concrete surface, causing substantial degradation of concrete/reinforcement and, hence, the loss of strength. If an alternative is provided to backfill/heel these cracks themselves by concrete, it would, therefore, prevent unforeseen corrosion and, hence, loss of strength and durability of concrete. Thus inducing smart features in concrete-based structures. Self-healing concrete has the characteristic of producing calcium carbonate (Sealing compound) after the initiation of cracks and finally resulting in the healing of cracks, in a similar way as in pharmaceutical processes in the fracture of bone of a human being. This unique aspect of Self-healing concrete has inspired us to carry out an extensive research program to study the various aspects of self-healing concrete.

4. EXPERIMENTAL PROGRAMME

An extensive experimental program was launched in this research study to entail the influence of self-healing compounds (bacteria) on the mechanical and durability properties of metakaolin-based cement concrete (hybrid concrete).

- a. **Phase-I:** Pertains to the preparation of optimized metakaolin-based cement concrete.
- b. **Phase-II:** Enumerately adequate dosage of self-healing compound followed by the production of Hybrid concrete (metakaolin-based self-healing concrete) in an idealized manner.
- c. **Phase III:** Casting and testing of samples obtained from this proposed Hybrid concrete to substantiate the mechanical, durability, and self-healing properties of the proposed new concrete.

4.1 Materials

4.1.1 Cement and Aggregates

Locally available ordinary Portland cement 43 grade (Khyber Brand), confirming to IS 8112: 2013 was used in this research study. Natural river sand obtained from nearby source and meeting the requirements of grading Zone II of IS 383 has been used as fine aggregate. Crushed (angular) coarse aggregates of maximum size of 20 mm, procured from nearby crushing plant were employed in this research study. The properties of cement used have been obtained on laboratory testing and are enlisted in Table 1.

Table No. - 1, Physical Characteristics and properties of Cement

Form	Powder
Colour	Grey

Specific gravity	3.14
Consistency	29.6%
Soundness	2mm
Initial setting time (IST)	117min
Final setting time (FST)	228 min
Compressive strength 7 days	34MPa
28 days	45.2MPa

4.1.2 Water and Plasticizer

Portable drinking (tap) water was used in the preparation of concrete mixes. High range water reducing admixture Auramix – 400 from Fosroc Ltd was employed to maintain workability. Water with an average pH of 7.3 was used it was also to ensure no harmful substances like oils, acids, alkalis, salts, sugars, or organic compounds were present.

4.1.3 Metakaolin

In this research program, High Reactive Metakaolin, a natural pozzolan, was employed as a partial replacement for cement. Procured from Kaomin Industries LLP, Mujmahuda Vadodara. The physical and chemical properties of metakapol used are shown in Table 2.

Table No. – 2, Physical Characteristics and Properties of High Reactive Metakaolin

Form	Powder
Colour	off-white pink colour
Amorphous Content	70 - 90%
Avg. Particle Size	1.5 - 2.5micron
Consistency	75

4.1.4 Bacterial species

The bacterial strain was selected from Bacillus species, which has the potential to induce precipitation because it produces endospores. Bacillus subtilis, also known as the hay bacillus or grass bacillus, is a Gram-positive, catalase-positive bacterium found in soil and the gastrointestinal tract of ruminants, humans, and marine sponges. As a member of the genus Bacillus, B. Subtilis is rod-shaped and can form a tough, protective endospore allowing it to tolerate extreme environmental conditions. In this study, a direct application method for preparing bacterial concrete was used. When water comes into touch with the unhydrated calcium in the concrete, micro-organisms that function as catalysts make calcium hydroxide. This calcium hydroxide combines with the carbon dioxide in the air to produce water and limestone. The limestone then hardens and fills the cracks in the concrete. Calcite precipitating bacteria viz. B. Subtilis used in this work were procured from Varsha Biosciences, India Pvt. Ltd. Calcium lactate and yeast extract were used as nutrients for calcite-forming bacteria B. subtilis.

4.2 Test methods

The experimental setup for this investigation was carried out in three phases, viz finding the optimum percentage of metakaolin content, proper dosage of the self-healing compound, and generating the hybrid concrete using the right values from both. The design mix for the neat concrete was prepared in accordance with IS 10262 : 2009.

4.2.1 Casting and Production of Samples

Metakaolin-modified concrete was produced by mixing the constituents in accordance with the designed proportion. The fraction of metakaolin to be added was first dry mixed with cement, followed by its addition to aggregates (both coarser and finer), followed by water. Workability was maintained in the different mixes by adding the required quantity of superplasticizer. Self-healing concrete was prepared using a direct application method. Calcite precipitating bacteria viz *B.subtilis*, calcium lactate, and yeast extract were used as nutrients in this work. The bacteria, calcium lactate, and yeast powder were mixed with water, followed by their utilization in the concrete mix in accordance with the designed fraction. The optimum quantity obtained for the replacement levels of cement and dosage of self-healing compound finalized in the previous mix was utilized to design the hybrid concrete.

Table No. – 3, Design Mix Proportions

Mix	Cement (kg)	MK %	MK (kg)	Bacteria (ppm)	FA (kg)	CA (kg)	Water (kg)	Plasticizer (gms)
RC	403	0	0		738	1148	154	1410
MK6C	384.8075	6	24.18		738	1148	154	1809
MK12C	384.615	12	48.36		738	1148	154	3077
MK18C	384.4225	18	72.54		738	1148	154	3498
SH20C	403	-	-	20	738	1148	154	1410
SH40C	403	-	-	40	738	1148	154	1410
SH60C	403	-	-	60	738	1148	154	1410
SH80C	403	-	-	80	738	1148	154	1410
HBC	384.615	12	48.36	80	738	1148	154	3077

Concrete mixtures were sampled in molds of standard size along with proper compaction by vibrating the table at room temperature, followed by molding after 24 hours. The concrete was then cured to retain moisture and gain strength. The samples were then placed in the curing tank for proper curing as per IS 456-2000.

4.2.2 Production of Crack in Self Healing Concrete

The Bacterial incorporated specimens were loaded for pre-cracking at the load of 50-70% of their ultimate compressive loads and later cured using wet mats for 56 days at an ambient temperature.

5. RESULTS & DISCUSSION

5.1 Workability

The workability of concrete is determined by the fluidity of the mix. This is normally attributed to the cement-to-water ratio. The conventional slump test instrument is utilized to evaluate how easily freshly laid concrete may work. The workability of concrete was maintained by utilizing the proper quantity of superplasticizer. By adding the required percentage of superplasticizer, the true slump was maintained within a range of 25 mm to 50 mm slump values. Figure 1 depicts the demand for plasticizers in accordance with the metakaolin replacement with reference to neat concrete. However, with the addition of the Self-Healing compound mixture, no need to modify the dosage of the superplasticizer was felt.

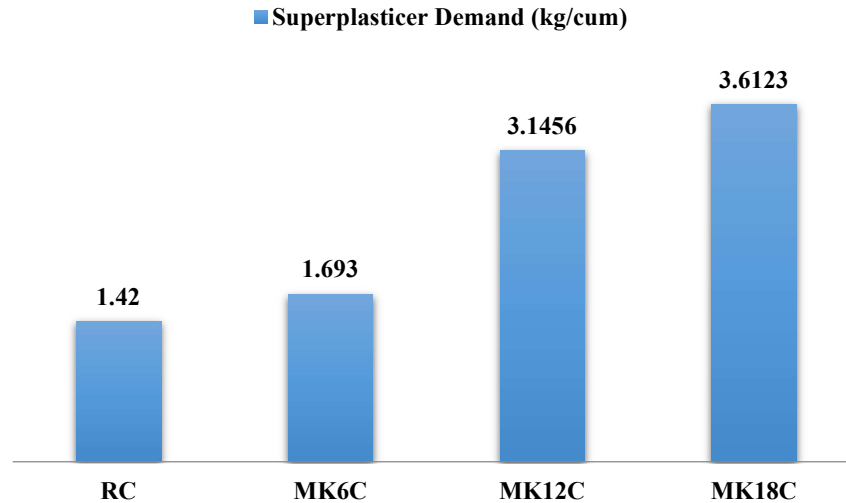


Figure 2 - Superplasticizer demand in Metakaolin replaced Concrete.

In our study, a workable slump has to be maintained by adding extra superplasticizer quantity proportionate to the decreasing slump values. As seen in Figure 2, the requirement for superplasticizers rises in direct proportion to the concentration of metakaolin. The slump value decreased as metakaolin content rose; this could possibly be explained by the metakaolin's larger surface area, which improves reactivity and speeds up heat evolution as well as the creation of hydration products.

5.2 Compressive strength

Several concrete mixes' compressive strength was tested after 7, 28, and 90 days. As can be readily observed from Figs. 3 and 4, which depict the average value of three specimens. According to the results shown in the case of MK substituted concrete, a marginal increase in compressive strength was noted, with MK12C showing a gain of 20.23 % in its compressive strength with respect to neat concrete. The graph also illustrates that with the replacement of cement, there was a marginal variation in the compressive strength, with the optimum value being at a 12% substitution level. The graph also shows the trend with the increment in the substitution level; the compressive strength increased linearly up to the optimum level, followed by a decline in the compressive strength with further enhancement in the optimum substitution level with respect to the maximum compressive strength attained. Metakaolin boosts the compressive strength of cement waste composite by filling in the interfacial transition zone between the cement waste and aggregate particles [12]. In addition to this, CH gels are quickly eliminated and actually expedite cement hydration, with cement hydrated with metakaolin. The clinker dilution effect may be the reason for the reduction in the compression strength MK18C as compared to MK12C. The diluting effect results from substituting an equivalent amount of metakaolin for the fraction of cement.

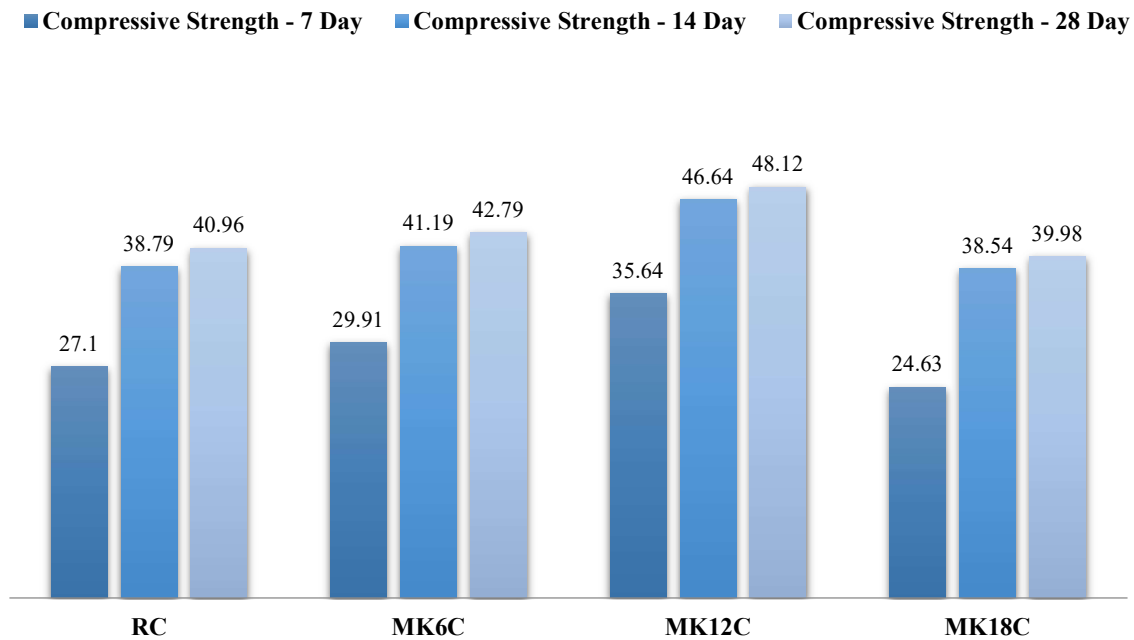


Figure 3- Compressive Strength (N/mm²) with respect to different MK replacements.

The compressive strength of cubes with a self-healing compound mixture imbibed was carried out in two stages. In the initial stage, the primary effect on concrete by direct addition of self-healing compound into the mixture was investigated, followed by developing crack patterns and then retesting after the cracks had healed up. The compressive strength of samples was measured with the addition of a bacterial mixture. Bacteria were mixed as 20ppm, 40ppm, 60ppm and 80ppm respectively. The compressive strength effect of bacterial concrete after 7, 28, and 90 days was observed and is shown in Figure 3.

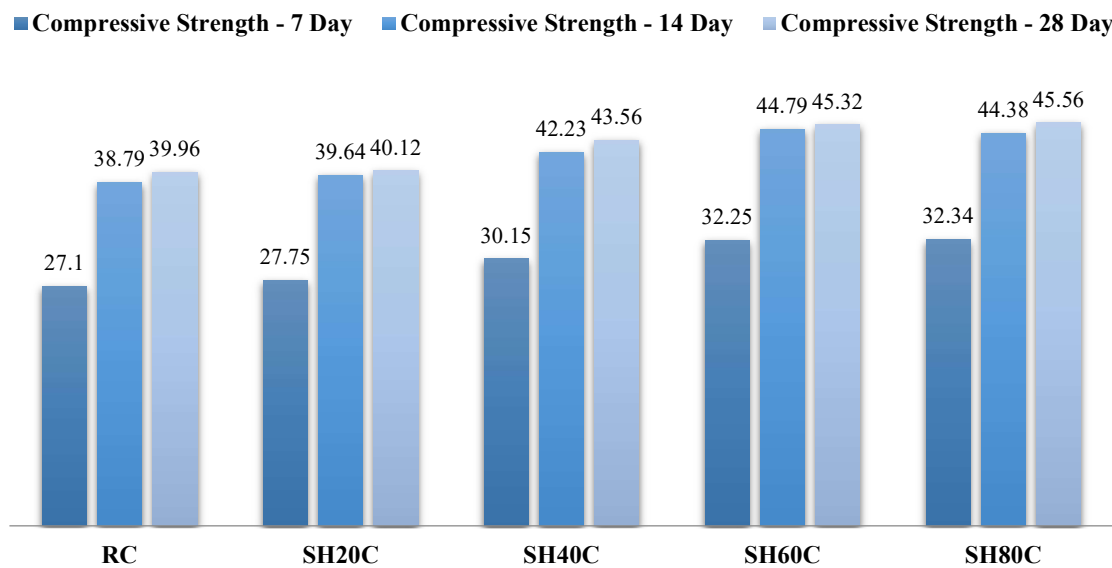


Figure 4, Compressive Strength (N/mm²) with respect to different concentration of self-healing compound.

With the increase in the concentration of bacterial mix in the concrete, the compressive strength of the cube increases and maintains a constant value from the optimum value. Hence, the optimum value is considered to be

60ppm of bacterial mix in concrete. It was observed that with the increase in the bacterial mix, the compressive strength increased; however, at 60 ppm and 80 ppm additions, a much increase in the strength was not observed. An overall 15.46% gain in strength was noted with reference to the neat concrete. After observing the failure loads, the corresponding samples were loaded to 50-70 % of the failure load values, thus developing cracks over the surface. These crack-developed samples were placed with a covering of wet jute gunny fabric, which was sprinkled with water periodically in order to maintain the moisture in and around the cracks. These cracks were periodically observed; with the aging, the cracks were seen being filled up by a white-coloured powdery substance precipitate –the calcite precipitate. After 56 days of examination, the majority of cracks had healed, followed by retesting of their compressive strengths. The results obtained are illustrated graphically below in figure 5.

The compressive strength was regained after losing through the self-imbibition of cracks, and the cracks were also healed up, as observed in Fig 5. The overall regain in strength was noted in all the concentration levels; however, the maximum results were obtained at the optimum value.

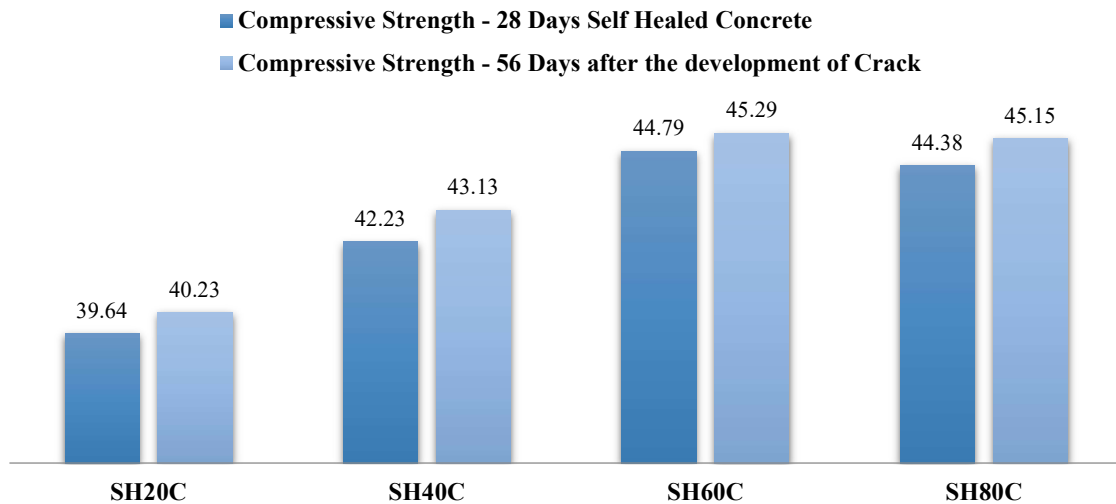


Figure 5. Compressive strength (N/mm²) recovery of cracked concrete specimens after 56-day of curing.

5.3 Water Absorption

The water absorption test was conducted after 28 days of curing for normal concrete, concrete with metakaolin as a replacement, and concrete made with bacterial contamination. The amount of water absorbed by the concrete cubes is calculated by its initial weight. The results calculated after laboratory investigations have been depicted in Figure 6.

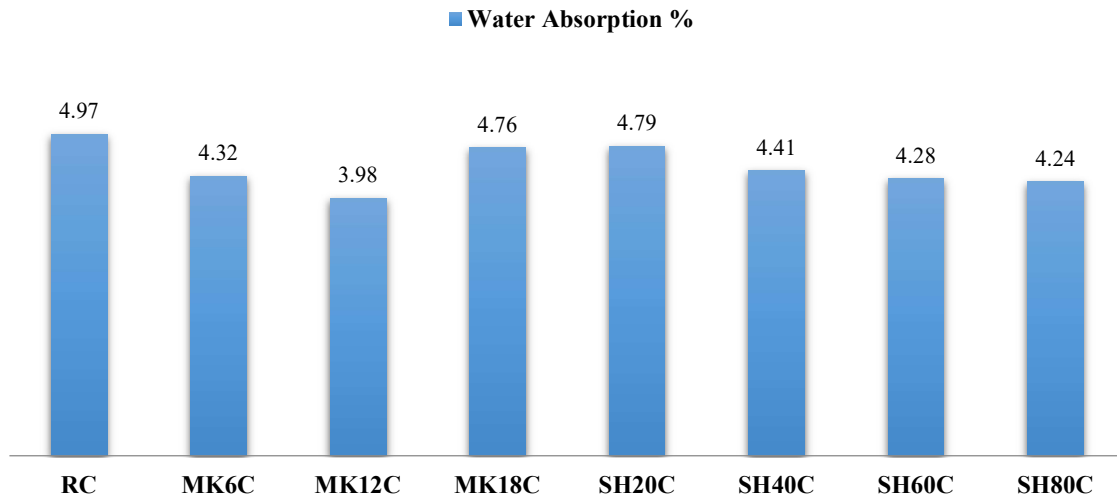


Figure 6, Water absorption of cube samples at an age of 28 days

Absorption test was done for a time period of 24 hours on the cube samples. From Fig.6, it is clearly evident that with the replacement of cement with metakaolin, the concrete water absorption ability is altered. In our work, with the increasing MK content, the ability to retain water started to decrease. Accordingly, the addition of metakaolin has a highly positive effect on the absorption of water, with a minimum retention ability of 3.98%, as shown by a substitution level of 12%. This characteristic may be attributed to the filler effect imbibed into empty pores in the concrete, thus reducing the percentage of water absorption. Similar findings were reported by Razak, H.a [13], with mortar containing 10% MTK and 5% silica fume. Additionally, bacterial concrete demonstrated a lower proportion of water absorption than conventional concrete. By introducing 60 ppm bacterial mix into the concrete, the water retention capacity was reduced to 4.28 %, almost similar to the retention capacity of 80 ppm induced concrete mix. The bacterial precipitates fill the pores and crevices in concrete, which decreases the material's capacity to retain moisture. Both these minimum values were attributed to the dense matrix formation, which was correlated with the results obtained from their respective compressive strengths.

5.4 Homogeneity

The results of homogeneity were obtained through ultra pulse velocity nondestructive test. Table 4 represents the results obtained by different concrete mixes.

Table 4 - Ultrasonic Pulse Velocity Test at 28 Days.

Mix	Pulse velocity (m/sec)	Homogeneity
RC	4788.5	Excellent
MC6C	4779.74	Excellent
MC12C	4853.24	Excellent
MC18C	4772.64	Excellent
SH20C	4782.68	Excellent
SH40C	4801.34	Excellent
SH60C	4826.66	Excellent
SH80C	4818.32	Excellent

All concrete combinations achieved pulse velocities ranging from 4772.64 to 4853.24 m/sec, demonstrating

outstanding homogeneity. It was observed that as the MK percentage increased, the UPV values also increased at 28 days of curing. A reduction in UPV values was observed after the MK content was increased beyond the 12% replacement level. In the case of self-healing concrete, there was a proportionate increase in the ultrasonic pulse velocity, along with an increase in the concentration level of our work.

5.5 Crack Healing Quantification:

Bacteria-incorporated concrete specimens were pre-cracked at 50-70% of failure load, and the surface crack developed was monitored throughout the healing stage. The white powdery substance that was formed inside and around the fissures is evidence that calcite precipitation has occurred. Higher precipitation of calcite may be caused by the autogenous healing mechanism of concrete, similar to the reports of Kalhori and Bagherpour [15]. The dimensions of the repaired cracks were measured using an optical microscope. The cracks ranging in width from 0.2mm significantly decreased in 14 days. The cracks within the width range of 0.2 and 0.3 mm healed in 34 days. The maximum width of 1.02 mm was completely healed in 56 days. The integration of bio-healing agents has been shown to significantly enhance concrete's self-healing capacity. By incorporating these biological components, researchers have observed a marked improvement in the material's ability to autonomously repair cracks, ultimately extending its lifespan and resilience in various environmental conditions. Recent studies support this advancement, highlighting how bio-healing compounds facilitate the growth of mineralized materials within the concrete matrix, effectively sealing fissures and preventing further degradation [16][17]. Such innovations in self-healing concrete technology represent a promising solution for sustainable and durable infrastructure. The difference in healing efficiency with different concentration levels was observed because there is less healing agent near the crack, and there is less sealing agent available for transfer, which lowers the amount of healing compound that can be produced to seal the fissures. Figure 6 shows the crack healing for pre-cracked specimens after 28 days of curing.

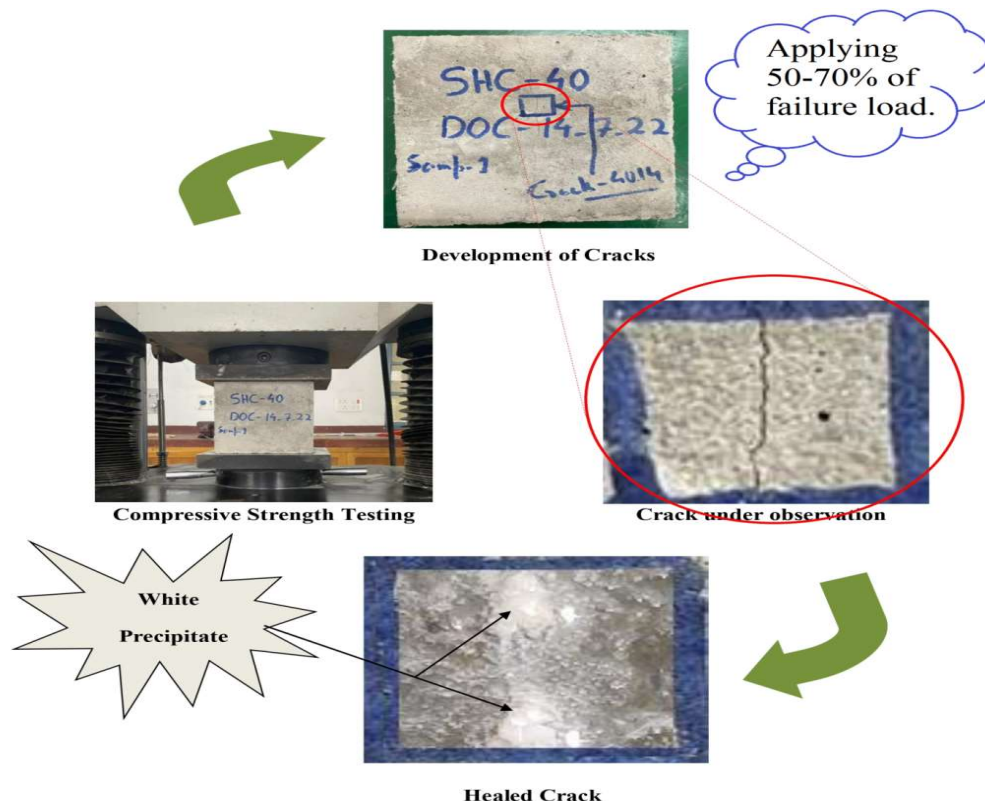


Figure 6 – Various stages involved in developing and healing of Crack

5.6 Hybrid Concrete:

After the investigations pertaining to findings related to the optimum replacement level of metakaolin and finding

the effective dosage of the self-healing compound mixture in concrete, the concrete mix with this substitution and incorporation was cast, proportioning to HBC in Table 3. Various investigations and comparisons that were made with this hybrid concrete have been represented in Figure 7 (a, b, and c).

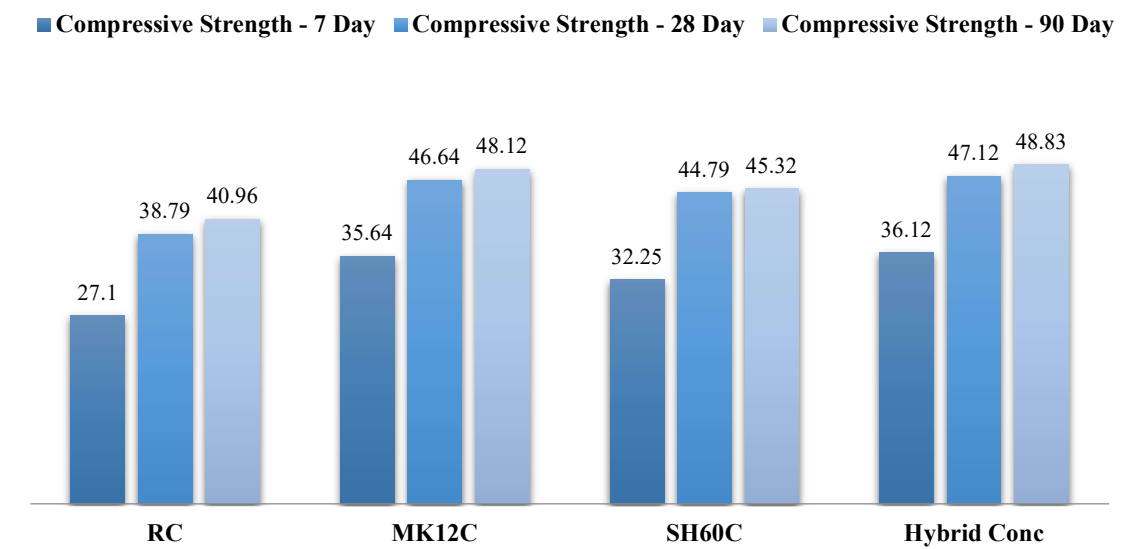


Figure 7(a) – Compressive Strength (N/mm²)

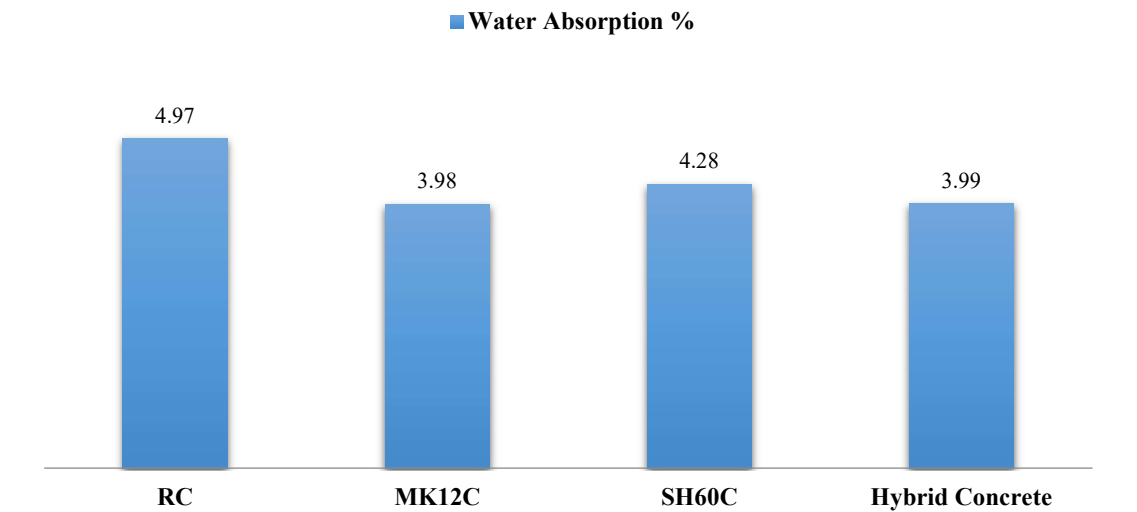


Figure 7(b) – Water Absorption

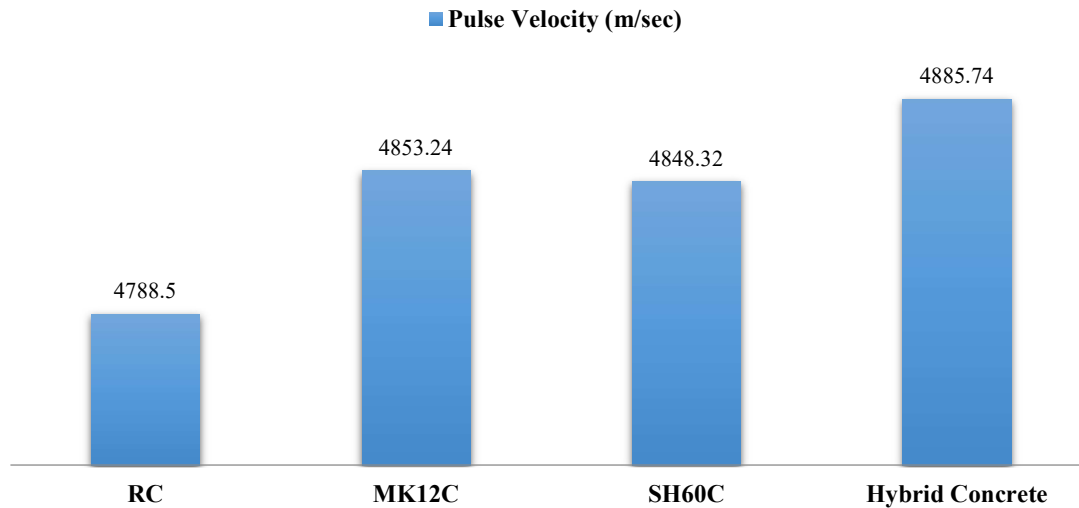


Figure 7(c) – Pulse Velocity

Figure 7, Represents the comparison between Normal Concrete, Optimum MK substituted Concrete, Self Healing Compound mixture and Hybrid Concrete with comparison in there: (a) Compressive strength, (b) Water absorption and (c) Pulse velocity

The results shown above depict that the hybrid concrete developed by incorporating the MK and self-healing compound has a positive impact on the concrete mix. The enhancement in the compressive strength was observed, which may be attributed to a reduction in micropores caused by the filler effect shown by MK reacting with calcium hydroxide, along with the calcite production by the bacterial cells, which further enhanced the compressive strength performance. In the case of the Water absorption test, the results were also favorable in the development of this hybrid composition. As evident from the laboratory investigations by the incorporation of both MK and self-healing compound, there was a marginal decrease in the water absorption levels; about 19.71% reduction in retention level was observed when a comparison was made between the normal and hybrid concrete. This may directly be associated with the result of high densification of cement matrix at the micro level caused by the high levels of calcite production and MK reacting with cement, leading to a reduction in the pore size, consequently increasing the strength along with a reduction in the water retention capacity.

The Pulse velocity generated during the Ultra Pulse velocity Test – nondestructive evaluation showed an increase in the Pulse velocity within the range of excellent homogeneity conditions. This increase in the UPV signifies better density, homogeneity, and lack of defects with concrete.

6. Conclusions

- ✓ The workability of concreting was affected largely by the replacement levels of Metakaolin, which was affected by the large surface area.
- ✓ The workability was maintained by increasing the required dosage of superplasticizer proportionally with the increase in metakaolin content.
- ✓ The surface finish of all concrete mixes is even, with the exception of the 18% metakaolin replaced by a cement-concrete mix, which looks uneven when visually observed during casting.
- ✓ There is an increase in compressive strength with the increase of replacement of Metakaolin till (M5 mix-15%), and after that increasing Metakaolin content, it starts decreasing.
- ✓ The addition of bacteria boosted the Concrete's compressive strength, which was attributed to the calcite that precipitated into the voids, increasing the Concrete's density.
- ✓ Regain in compressive strength of Self HealCompound mixed Concrete after 56-day healing.
- ✓ The pulse velocity obtained through the Ultrasonic Pulse Velocity Test indicated homogeneity in the concrete mix with variations in accordance with the metakolin substitution levels and the concentration levels of the self-healing compound.

- ✓ The velocity levels increased proportionally to 12% substitution levels in Metakaolin, which replaced Concrete, followed by a decreasing trend with incremental values beyond the 12% replacement level. The same increasing velocity was observed with the increase in concentration levels of self-healing compound mixtures to Concrete.
- ✓ Hybrid Concrete containing both Metakaolin and self-healing compound showed a marginal increase in compressive properties with reference to neat Concrete.
- ✓ Hybrid Concrete containing both the optimum content of Metakaolin and a self-healing compound mixture showed less water retention capacity in reference to reference concrete.
- ✓ The reduction in crack depth was observed in both self-healed compound mixed concrete and hybrid concrete containing both substitutions.

7. Future Scope

The future scope of this study on metakaolin-based self-healing concrete encompasses various research avenues that could strengthen its application and feasibility in civil engineering. Extended durability analysis under diverse environmental conditions, such as freeze-thaw cycles and chemical exposure, is essential to validate its effectiveness in harsh climates. Further optimization of bacterial dosage and nutrient composition can enhance calcite precipitation efficiency, with additional studies on structural integrity to assess its suitability for load-bearing and seismic applications. Economic feasibility studies, focusing on lifecycle costs and potential maintenance savings, would support large-scale implementation, while environmental impact assessments could highlight the sustainability benefits of this material. Research into high-performance applications, such as ultra-high-performance and fiber-reinforced concrete, alongside field-applicable monitoring techniques, would further bridge laboratory findings with real-world applications. Together, these research directions could propel self-healing concrete toward broader acceptance as a resilient and sustainable material in modern infrastructure.

8. Conflict of Interest

The authors declare no conflict of interest regarding the publication of this research paper. The research was conducted impartially, and the results presented reflect the authors' independent findings and interpretations. No financial, personal, or professional affiliations influenced the study, and no funding sources or sponsors were involved in the direction, interpretation, or conclusions of this work.

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