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EXPERIMENTAL STUDY ON REPAIRING CONCRETE CRACKS USING BIO-INFLUENCED SELF-HEALING TECHNIQUES

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Abstract: Cracks in the concrete are repaired using chemicals, bacteria, and resins that are mixed into the self-healing concrete during the mixing step. This allows the concrete to mend itself. Bioconcrete, also known as bio-influenced self-healing concrete, is a product that has the capacity to mend fractures in concrete by creating chemical compounds from micro-organisms that have been purposefully introduced into the concrete. During the mixing process of this particular kind of concrete, microorganisms as well as a precursor component are distributed throughout the concrete. The formation of cracks allows water to flow into the crevices, which wakes up any microorganisms that were previously latent in the area. These microorganisms will eventually generate minerals that will cover the fissures, which will prevent the concrete from losing its strength and will increase its longevity.

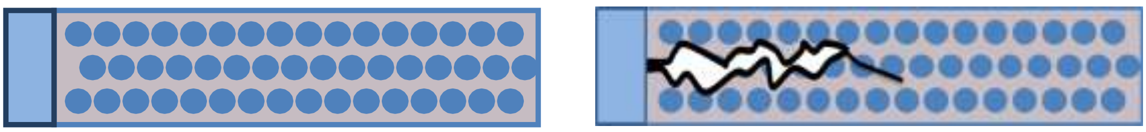
An experimental programme was carried out in order to investigate the self-healing process of concrete under a variety of different circumstances. Different methods, such as directly integrating bacteria into the mix, immobilising bacteria in lightweight aggregate, and combining bacteria with graphite nanoplatelets, were used in order to get bacteria into the concrete. Calcium lactate was used as an organic precursor in all of the processes, and it replaced about 5% of the cement. In order to evaluate the degree to which each mixture underwent a change in compressive strength, specimens of each mixture were prepared. In addition to that, concrete specimens were pre-cracked at 3, 7, 14, and 28 days to measure the crack healing effectiveness of each mix. This was done by cracking the specimens with a hammer.

Keyword: Bio-influenced Self-healing concrete, Bacteria with Graphite nanoplatelets, Calcium lactate, Compressive strength, Pre-cracked, Crack healing

1. INTRODUCTIONS

Self-healing concrete is a product that has the capability to fix gaps by manufacturing chemical products from bacteria, chemicals, or resins that have been purposely added into the mix. These chemical products have the ability to heal the concrete. This enables the concrete to mend and strengthen itself. One of these methods of self-healing is known as bio-influenced self-healing concrete, which is also known as bio concrete. In this procedure, microorganisms that are already present in the concrete are used to create new minerals via a process known as mineral synthesis. Bio-concrete is a material that, when put to use, has the potential to mend the cracks that are caused in it by producing the necessary mineral compounds to fill the voids created by the usage of the material. In previous studies, a procedure that included spraying a bacterial solution over cracks that had occurred in a structure was utilised. This approach was less effective and less feasible than others. In contrast, during the mixing process of concrete in recent years, microorganisms and an organic mineral precursor component have been introduced. These additions have occurred in recent years.

Concrete is the engineering material that is used in the construction business the most frequently because of its strength, durability, and relative cost in contrast to other building materials. Additionally, concrete is the material that is most often used in the construction sector. Nevertheless, one should be aware of a couple of the drawbacks associated with it. One of the most major drawbacks that concrete has is that it has poor tensile strength. As a direct result of this, the material is predisposed to the formation and coalescence of microcracks, which eventually leads to the material's inability to maintain its strength and durability over time. These tensile stresses might have been caused by a number of factors, including tensile loading, plastic shrinkage, or expansive reactions (Mehta and Monteiro, 2006).



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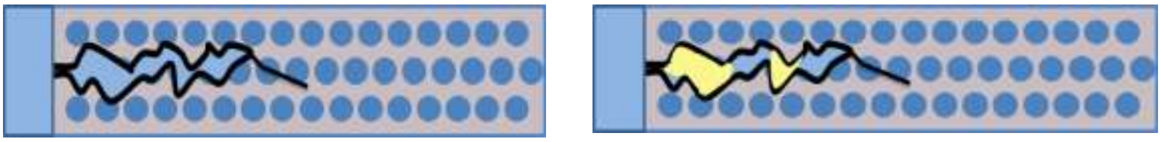

Bacteria incorporated in concrete mix Crack produced in concrete due to tensile stresses

Water is deliberately entered in the cracks $CaCO_3$ is produced which heals the cracks

Figure 1: Process of self-healing of crack through bacteria

These shortcomings encouraged scientists and researchers to hunt for an ideal method to strengthen the durability of concrete by identifying a technique to counteract the spread of fractures in concrete. The best solution was found. To be more specific, scientists and researchers sought a remedy that would stop fractures from developing in concrete. Epoxy systems, acrylic resins, and silicone-based polymers are only some of the materials that researchers have tried in their attempts to bring this problem under control. Other materials, such as silicone-based polymers and epoxy resins, have also been used. On the other hand, it was discovered that the great majority of these materials were not compatible with concrete, that they were harmful to the environment, and that they were expensive (Vekariya and Pitroda, 2013).

2. MATERIALS AND METHODS

2.1 Materials

Cement: In order to accomplish the goals of this study, KCP Cement Company's OPC 53 grade cement served as the material of choice. Building and manufacturing are two industries that make frequent use of this particular kind of cement. The chemical parameters of the cement are outlined in Table 4.1(a), which was given by the supplier and may be accessed at this location. The pycnometer and the equipment owned by Vicat were utilised to carry out tests on the cement in accordance with IS 12269:1987 (which was reaffirmed in 2004), and Table 1 presents the findings of those tests. In order to determine the cement's physical properties, it was put through a series of tests (b)

Table 1: Physical properties of OPC 53 grade

1.	Specific Gravity	2.91
2.	Standard consistency	32%
3.	Setting time	
	(i) Initial setting time	90 mts
	(ii) Final setting time	210 mts
4.	Fineness	2.5%

Coarse Aggregate: When producing high-performance concrete, the aggregate must be chosen with careful attention paid to the material's dimensions, shape, surface roughness, mineralogy, and level of cleanliness, among other factors. Aggregates of a coarser size must be machine-crushed stone made of black trap or any similar black hard stone. This optimal size of aggregate can be found by dividing the total volume of aggregate by the total volume of cement. The compressive strength of concrete made using crushed stone aggregates is much higher than the compressive strength of concrete made with gravel aggregates. Crushed aggregate with a size of 20 millimetres and an angular shape is being used for the objectives of this inquiry.

Table 2: Properties of the Coarse Aggregate

Specific gravity	2.68
Density	1567 kg/m^3
Fineness modulus	7.682

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Impact value	22.12% < 45%
Crushing value	24.44% < 45%

Fine Aggregate: In addition to this, they need to be chemically inert, clean, and sturdy, and they need to conform to the criteria that are defined in Indian Standard 383:1970. Analysis of the fine aggregate was carried out in order to ensure compliance with the requirements outlined in International Standard 2386 (Part-3):1963. This research shows fine aggregate with a fineness modulus of 2.46 and it complies with zone 2 and sieve analysis for sand.

Table 3: Properties of Fine Aggregate

Specific gravity	2.54
Fineness modulus	2.46
Bulk density	1.65 kg/m^3
Type of sand	Medium sand (zone 2)

Micro-organism: The integration of these bacteria into concrete may be accomplished by a number of different processes, the most common of which is the use of bacterial solutions, also called bacteria in nutrient bath. In a carefully monitored and managed microbiology facility, this bacterial solution has been created and processed in the correct manner to assure the formation of spores. In order to accomplish this goal, First, 0.5 ml of blank solution was put into the spectrophotometer, and the 600 nm wavelength was selected. This was done so that the readings would be accurate. After the reading for the blank solution was finished, 0.5 millilitres of the bacterial solution was injected into the spectrophotometer, and a wavelength of 600 nanometers was selected for the optical density test. This was done so that the test would be accurate. On the basis of the results of this experiment, the concentration of bacteria that were found in the solution was calculated using the equation Y = 8.59 x 107 x 1.362 (Ramachandran et al., 2001). Where Y is the bacterial concentration expressed in millilitres and X is the measurement taken with an optical density of 600. It was determined by the use of a spectrophotometer that the bacterial concentration was 2.8 x 108 cells per millilitre.

Graphite nano platelets: The basic purpose of this study is to examine the impact that graphite nanoplatelets (GNP) have as a carrier material and to measure its performance in comparison to that of other carrier compounds at the same time. Taking this into consideration, it is of the utmost need to conduct research into the characteristics of GNP. As may be seen in Figure 3.2, the GNP is shown in the physiological manifestation that it has.

Table 4: Properties of GNP

Properties of GNP	
Grade	Nano 25
Primary particle size	≤ 100nm
Composition	99 % carbon
Surface Area	180 m^2/g
Lamella thickness index (LTI)	14-15

Light weight aggregate: In order to determine which approach is the most effective in terms of transporting bacteria inside the mixture, research was conducted as well as a comparison made between the employment of GNP and the use of lightweight aggregates (LWA) as a carrier material. This experiment was conducted with the intention of integrating bacterial spores, provides a visual depiction of the LWA that was used for this aim.

Mix proportions: In this experiment, we employed a variety of different kinds of combinations in order to carry out the tasks that needed to be done. The quantities of fine aggregate, coarse aggregate, and ordinary portland cement (OPC)

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type I conforming to IS that were used were as follows: fine aggregate at 662 kg/m3, coarse aggregate at 1107 kg/m3, and ordinary Portland cement (OPC) type I at 372 kg/m3. At a rate of 18 kg/m3, the calcium lactate was used in the experiment. The ratio of water to cement was kept constant at 0.4 in each and every one of the concrete mixtures.

Table 5: Mix design of different sets of specimens

Specimens		**Mix 1**	**Mix 2**	**Mix 3**	**Mix 4**
Cement	kg/m^3	372	372	372	372
Fine Aggregate	kg/m^3	662	662	662	662
Coarse Aggregate	kg/m^3	1107	1107	1107	1107
Water cement Ratio		0.5	0.5	0.5	0.5
Super Plasticizer	(%)	1	1	1	1
Calcium Lactate	kg/m^3	18	18	18	18
Bacteria with Spore concentration (2.8 x 10^8 cells/ml)	liter/m^3	0	6.33	6.33	6.33
Bacteria incorporation technique		None	Direct	By LWA	By GNP

3. RESULTS AND DISCUSSIONS

In this part, we will present and talk about the outcomes of the tests that were mentioned in the previous section in order to determine how efficient the self-healing mechanism of each combination is. These findings include crack width measurements and visual inspection of cracks, as well as the compressive strength of self-healing concrete samples; scanning electron microscopy microstructural study; and X-ray powder diffraction analysis of the mineral composition of healing compounds.

3.1 Self-healing analysis

Pre-cracked specimens were inspected using a crack measuring microscope at predefined time intervals of 3, 7, 14, and 28 days in order to assess the efficacy of the self-healing process. This was done in order to ascertain whether or not the technique was successful. These fractures showed significant signs of self-healing, especially in specimens of Mix 2, Mix 3, and Mix 4, in that order. These fissures were responsible for the creation of a substantial number of calcium carbonate crystals. (CaCO3). The healing chemical known as CaCO3 crystals was the predominant contributor to the reduction in the size of the cracks that was seen in the specimens that included bacteria.

Table 6: Crack healing in specimens pre-cracked at 3 days

Healing Time (Days)	**Mix 1 (mm)**	**Mix 2 (mm)**	**Mix 3 (mm)**	**Mix 4 (mm)**
3	0.03	0.07	0.06	0.17
7	0.08	0.11	0.14	0.34
14	0.10	0.19	0.53	0.66
28	0.12	0.37	0.64	0.83

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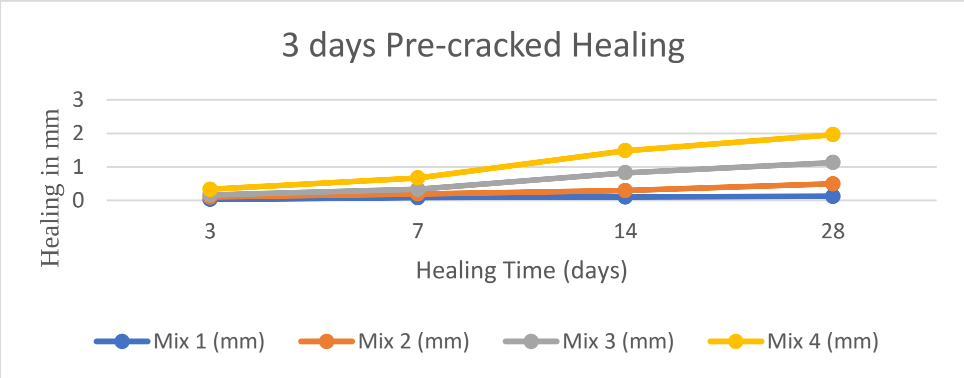

Figure 2: Crack healing in specimens pre-cracked at 3 days

Crack healing in specimens that were pre-cracked and then cured for 7 days showed a tendency that was comparable to the trend shown in Fig. 2 for specimens that were pre-cracked after 3 days. A significant amount of additional healing can be seen in the mixed 4 specimens thanks to the presence of GNP as the carrier component, as can be seen in Figure. This effective behaviour of GNP may be attributed to its tiny size, which, as was mentioned in the introduction, promotes a thorough and equal dispersion of bacteria-carrying particles throughout the mixture. Because of their tiny size, GNP particles are able to penetrate the inter-particle gaps and make it possible for bacteria to be present, which in turn facilitates the process of self-healing. Because of its larger size in comparison to GNP, LWA is unable to enter the micro-sized holes in the concrete matrix.

Table 7: Crack healing in specimens pre-cracked at 7 days

Healing Time (days)	Mix 1 (mm)	Mix 2 (mm)	Mix 3 (mm)	Mix 4 (mm)
3	0.02	0.05	0.05	0.16
7	0.06	0.08	0.16	0.26
14	0.08	0.17	0.43	0.64
28	0.10	0.37	0.61	0.81

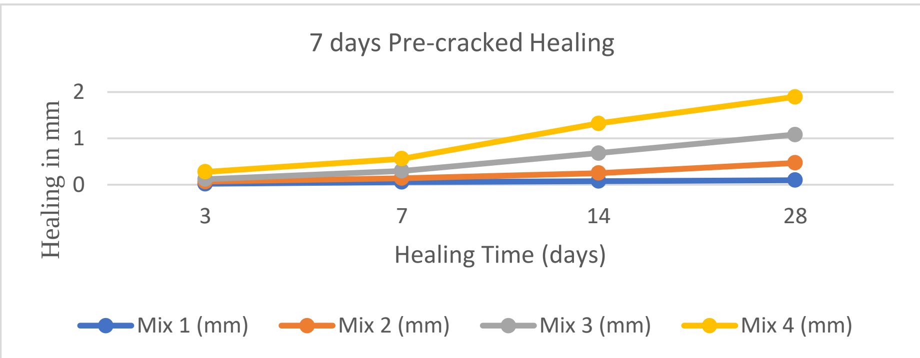

Figure 3: Crack healing in specimens pre-cracked at 7 days

The results that are shown in Figure 4.4 provide an illustration of the healing process that occurred in pre-cracked specimens after being cured for a total of fourteen days. After a treatment period of 14 days, the mix-3 specimens exhibit the highest degree of healing compared to other pre-cracked samples. Mix 4, which demonstrated optimum healing in samples pre-cracked after 3 and 7 days of curing, was found to be less effective than Mix 3 when samples were pre-cracked after 14 days of curing. This was the case despite the fact that Mix 4 demonstrated maximum healing in samples pre-cracked after 3 and 7 days of curing. Following the realisation that Mix 4 had shown maximum healing in samples that had been pre-cracked after curing for 3 and 7 days, this finding was made.

Table 8: Crack healing in specimens pre-cracked at 14 days

Healing Time (days)	Mix 1 (mm)	Mix 2 (mm)	Mix 3 (mm)	Mix 4 (mm)
3	0.01	0.04	0.05	0.05
7	0.03	0.05	0.14	0.13
14	0.06	0.16	0.40	0.37
28	0.07	0.21	0.60	0.42

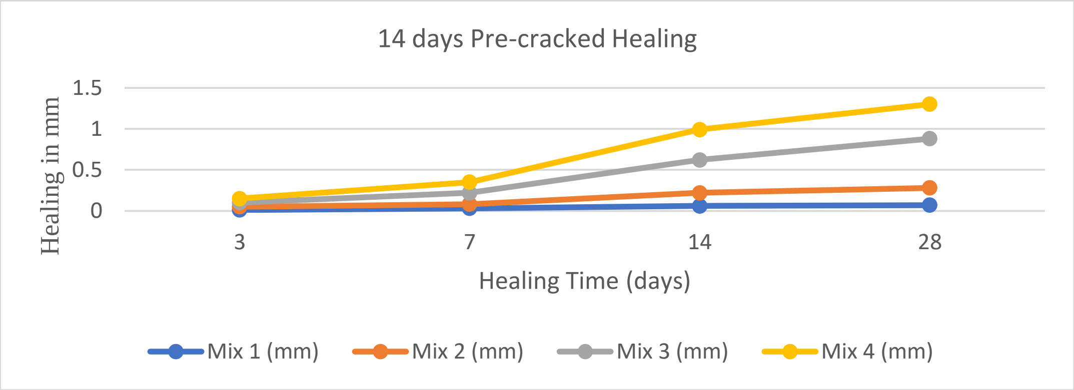

Figure 4: Crack healing in specimens pre-cracked at 14 days

The findings of the measures of self-healing in materials that were pre-cracked and then cured for a period of 28 days. These results were acquired by testing the materials after they had been cracked. These results are based on the measurements that were taken of the self-healing properties of several materials. Mix 3, which includes LWA, is exhibiting the greatest amount of healing, measuring 0.52 millimetres, which is more than any of the other mixes. There is a possibility that this may be detected. When specimen mix 4 is coupled with GNP, the pace at which it heals is much slower than what it was on days 3 and 7 prior to the pre-cracking stage. This is because the rate at which it heals is significantly affected by the GNP. The rate of healing that was displayed by the Mix 4 specimens was 0.38 mm, which is significantly higher than the rate of healing that was displayed by the Mix 2 specimens, which was 0.15 mm. The rate of healing that was displayed by the Mix 4 specimens was much higher than the rate that was displayed by the Mix 2 specimens.

Table 9: Crack healing in specimens pre-cracked at 28 days

Healing Time (days)	Mix 1 (mm)	Mix 2 (mm)	Mix 3 (mm)	Mix 4 (mm)
3	0.00	0.03	0.05	0.03
7	0.00	0.04	0.10	0.08
14	0.02	0.13	0.36	0.32
28	0.05	0.15	0.52	0.38

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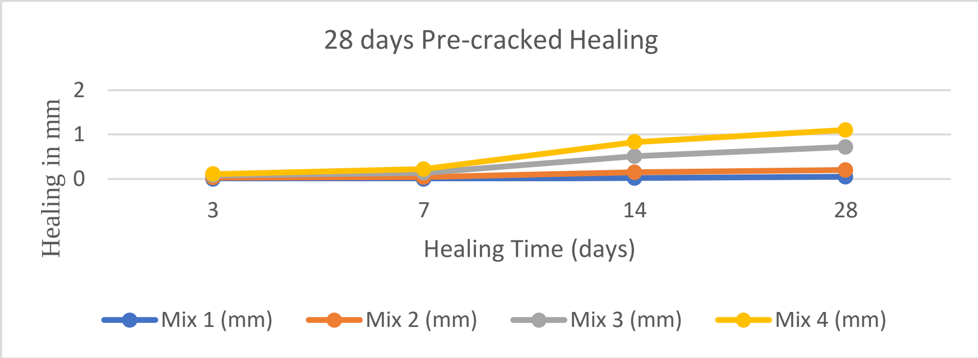

Figure 5: Crack healing in specimens pre-cracked at 28 days

This reveals that Mix 4, which contains GNP-containing bacteria, nevertheless provides a significant advantage in healing, despite the fact that this increase in healing is smaller than what was seen with Mix 3. This reduction in healing of Mix 4 specimens at 28 days of pre-cracking can again be thought to be due to the dense microstructure formed in the concrete after 28 days of curing, which is comparable to samples pre-cracked at 14 days of curing. This reduction in healing was observed when the concrete had been cured for a total of 28 days. This slowing down of the healing process was discovered after the concrete had been hardened for a total of 28 days.

3.2 Microstructure analysis

In addition to the findings that were discovered by visually examining concrete specimens, specimens of each of the four mixes were analysed by scanning electron microscopy (SEM) in a bid to investigate the ways in which self-healing could perhaps impact the underlying microstructure of the concrete. This was done in order to determine the ways in which self-healing might affect the underlying microstructure of the concrete. This was done in order to get insight into the potential effects that self-healing may have on the concrete. The scanning electron microscopy (SEM) examination was conducted both seven days and twenty-eight days into the process of self-healing so that a comparison can be made between the two different time periods.

The production of calcium carbonate-based crystals was the primary focus of this experiment. This is due to the fact that the number of crystals created is a reliable predictor of the effectiveness of a crack healing combination. Calcium carbonate crystals have the capacity to crystallise into one of three distinct forms, which are respectively known as calcite, aragonite, and vaterite (Rao et al., 2013). Because of the crystal structure of calcite, it is known as "calcite," and it is the form of calcium carbonate that is considered to be the most stable.

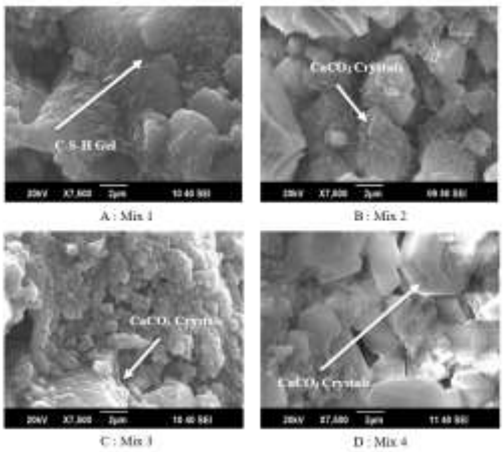

Figure 6: Scanning electron microscope analysis of 7 days pre-cracked samples

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The results of a scanning electron microscopy (SEM) examination that was performed on specimens that were obtained 28 days previous to the cracking incidence are shown in Figure 4.7. The examination was carried out on the specimens. Due to the fact that the experiment was carried out over a period of 28 days, it is noticeable that Mix 3 produces a much higher quantity of calcium carbonate crystal formation in specimens that were pre-cracked in contrast to Mix 2. The analysis of the crystals that were discovered in the combination was the means by which this information was able to be unearthed. When the amounts that were produced in samples that were pre-cracked after seven days of curing are compared to the quantities that were discovered to be present in Mix 2, it appears that the quantity of $CaCO_3$ that was discovered to be present in Mix 2 is even smaller than what was produced in those samples. This is because Mix 2 was found to contain a lower concentration of $CaCO_3$ than the samples that were manufactured.

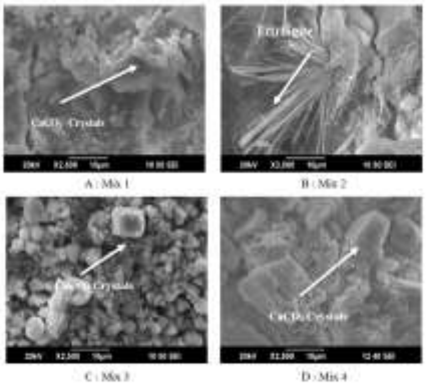

Figure 7: Scanning electron microscope (SEM) analysis of 28 days pre-cracked samples

GNP is not particularly great at having this property. Reading the article that was published was the means by which this information was received; it was the source of this knowledge. Because of this, the ability of the Mix 4 samples to assist the healing of wounds diminishes as the percentage of the hydration process that has been completed increases and as the pore size drops. This is a direct result of the fact that the Mix 4 samples have a smaller particle size. With LWA, on the other hand, the spores that are present in the samples are safeguarded while the samples are being mixed together. Having this information helps to ensure that the results are accurate.

3.3 X- Ray diffraction analysis

In order to gain a better understanding of the self-healing mechanism and to validate the production of calcium carbonate in the samples, XRD analysis was performed on the healing compounds that had evolved in the fractures. This was done in order to validate the production of calcium carbonate in the samples. This was done so that the findings of the study could be used to support the hypothesis that the samples contained calcium carbonate. The hypothesis was based on the fact that the samples contained calcium carbonate.

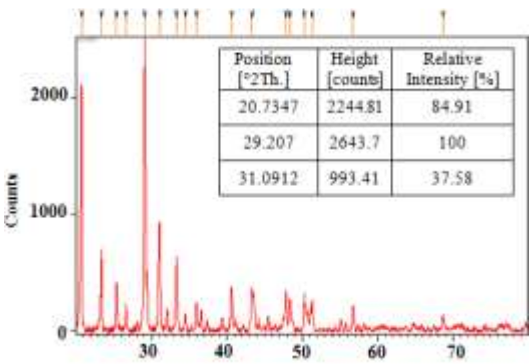

Figure 8: XRD analysis of healing compound produced in the cracks.

Because Bacillus Subtilis is a kind of bacteria that is capable of producing calcite, the findings of the XRD were analysed and compared to calcite reference cards (Rao et al., 2013). The largest peak was found at a 2theta (2) value of

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29.2070 degrees, which is fairly near to the 2theta (2) value of 29.455 degrees seen in pure calcite as demonstrated by. [Citation needed] (Herrington, 1927).

3.4 Compressive strength analysis

The measured compressive strength of self-healing specimens. It has been shown that using any approach of bacterial integration will result in an increase in the compressive strength of the mixture. This is the case regardless of the method used.

Table 10: Compressive strength development with different bacteria incorporation techniques

Curing Time (days)	Mix 1 (MPa)	Mix 2 (MPa)	Mix 3 (MPa)	Mix 4 (MPa)
3	12.5	13.0	14.2	13.8
7	18.3	19.8	20.1	20.5
14	22.3	22.8	24.2	23.9
28	25.8	27.2	29.0	28.4

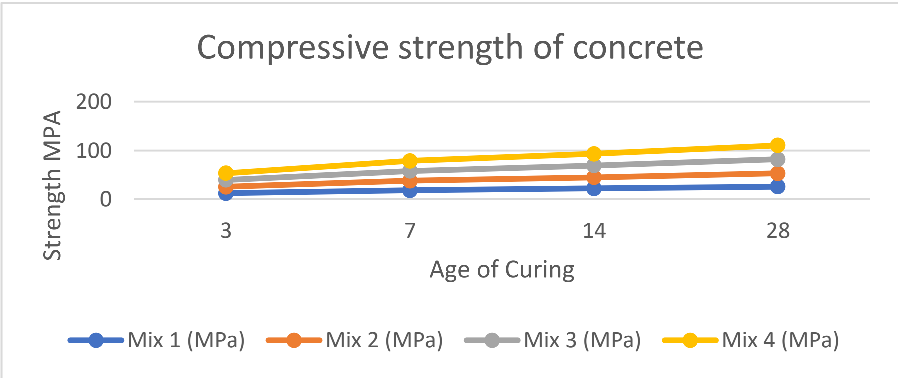

Figure 9: Compressive strength development with different bacteria incorporation techniques

When compared to controlled concrete specimens, test samples that included LWA as a carrier chemical for the integration of bacteria indicated a maximum strength of 29.43 MPa. When compared to controlled concrete specimens, this represents a 12% increase in compressive strength. The results of the study on self-healing that Sierra-Beltran and Jonkers (2012) carried out are compatible with the findings that were discovered in the increase in compressive strength. Sierra-Beltran and Jonkers (2012) This implies that self-healing is a cause of the increase in compressive strength, which implies that self-healing is a cause of the rise in compressive strength. This improvement in compressive strength may be ascribed to the smaller size of LWA as compared to normally sized coarse aggregates. This comparison was made in order to establish a cause and effect relationship. This comparison was intended to highlight the progress. This comparison was presented to demonstrate one way in which the topic may be comprehended. As a direct result of this, the concrete matrix that was surrounding the specimens was able to be packed and compacted more effectively, which resulted in a much greater strength when compared to the controlled specimens.

4. CONCLUSIONS

This study aims to analyse and compare the efficacy of various self-healing therapies with regard to their capacity to repair cracks. Specifically, the research will focus on the different treatments. An investigation was conducted to determine the efficacy of these techniques by analysing the effects they had on compressive strength, microstructure, the production of calcium carbonate, and the healing of fractures. A scanning electron microscopy (SEM) investigation was carried out in order to assess the alterations in the microstructure that took place as a consequence of the use of various techniques. Additionally, the healing component that was found in the specimens was placed through X-ray diffraction (XRD) in order to determine the chemical composition of the compound. This was done in order to determine their composition. The findings that were essential from the experimental work were the ones that were used in order to construct the correlations between the observed crack healing and the compressive strength via the utilisation of bacteria inclusion techniques. Specimens that have been combined with graphite nanoplatelets (GNP) as a carrier component demonstrated uniformly distributed bacteria as well as protection against bacteria in specimens that have been pre-cracked at an early age of 3 and 7 days, which resulted in optimal crack healing effectiveness. Graphite nanoplatelets were used as a carrier component. On the other hand, when the same specimens were subjected to pre-cracking at later dates, the pace at which cracks healed was significantly slowed down. Although lightweight aggregate (LWA) as the carrier compound was not as effective as GNP in early age pre-cracked specimens, it showed consistency in crack healing efficiency in pre-cracked specimens at later days. This was the case even though they were not as effective as GNP. Despite the fact that they were not as effective as GNP, this was the situation all the same.There was no evidence that the specimens that were directly coupled with the bacteria had any influence on the fracture healing process of the concrete. The patterns of compressive strength exhibited across all mixtures indicate that the addition of the bacteria "Bacillus Subtilis" resulted in a slight increase in compressive strength. This was shown by the trends in compressive strength. This was the case regardless of the method that was used to include the information. Nevertheless, the LWA strategy led to a significant increase in quality.

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