Self-Healing of Concrete using Bio-Influenced Techniques

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***Abstract* - For the long service life of concrete structures, durability of concrete is very important. But this durability is greatly influenced (reduced) by the small cracks produced in concrete. Water penetrates from these cracks causing degradation of matrix and corrodes the steel embedded in concrete. So it is very important that these cracks should be filled as they appear. A phenomenon that can fill these cracks automatically is called self-healing in concrete. For this purpose, spore forming bacteria with calcium lactate are introduced in concrete which precipitates CaCO3 and heal the cracks. Experiments show that Bacillus Subtilis can be used for this type of precipitation. This study will investigate and quantify best crack healing technique through changing the quantities of bacteria and carrier compound. This study will also investigate the effect of bacteria on compressive strength as well as strength regain of concrete specimen.**

Keywords-self-healing, Bacillus subtilis, Bacterial concrete

1. INTRODUCTION

Concrete is a major material used in the construction field, from the foundation of a building to the structures of bridges and dams. Several construction techniques without incorporating concrete has been developed by concrete still continues to be the most important building material for infrastructure. The major shortcoming of concrete is that it tends to crack when subjected to tension. Tiny cracks formed on the surface of the concrete make the whole structure vulnerable due to seepage of water into the concrete, promoting corrosion of the steel reinforcement, thus reducing the life span of the structure. Self-healing concrete is a solution to this problem of durability of concrete structures and has also received increasing attention as a smart material with interesting potential applications in civil infrastructure. Self-healing material used in such type of concrete have the ability to heal the damage inflicted on the concrete partially or completely, thereby restoring the original functionality of concrete. Self-healing system can achieve a tremendous cost reduction in terms of health monitoring, damage detection and maintenance of concrete structures, assuring a safe service life of the structure.

2. TYPES OF SELF-HEALING MECHANISM

2.1 Autogenic Self-Healing Mechanism

To create a material where the self-healing does not require human intervention, the focus is on autogenic self-healing. In order to initiate self-healing process in concrete, certain preconditions have to be fulfilled, i.e. availability of sufficient unhydrated cement in the matrix, a small crack width, and sufficient water for hydration. Concrete can now be engineered to have a small and stable crack width, combined with a sufficient amount of unhydrated cement. These factors will support self-healing only if water is available. To ensure this water is available inside the crack after cracking of the matrix, water should be encapsulated with a sealing material and embedded inside the matrix.

2.2 Fiber Reinforced Self-Healing

The presence of water and small crack width are the two most important factors for autogenic self-healing. Water is required for autogenic self-healing because the matrix cannot react chemically without water self-healing products build up on cracks faces, if the cracks are too large than the crack won't close completely. As the concrete itself cannot control the expansion of cracks because of its brittle nature so it cannot heal by itself.

In order to achieve complete healing (crack closure) the crack widths are to be restricted. For this Fiber reinforced strain hardening engineered cementitious composite (ECC) can be introduced in the concrete to restricts the crack width. Poly vinyl alcohol (PVA) fibers are generally used because of its unique crack pattern and its high ductility. PVA results in multiple small cracks instead of one single large crack. When PVA is introduced in the matrix it restricts the maximum crack width to or below 60 µm. PVA fibers have hydroxyl groups attached on their fiber structure which attracts calcium ions and enhances autogenic healing by helping in the deposition of crystallization products. PVA fibers having embedded brittle tubes can also be used for autogenic healing by putting the repair agent in these tubes. The fluid repair agent form crystals in the concrete matrix by reacting with silica particles chemically. The fibers are required to be pulled out sufficiently or the tube do not break, which is generally possible for crack width greater than 200 µm. Healing is more efficient when cracks are large enough to break the tubes thus silica material is not available to block the crack.

2.3 Capsule Based Self-Healing

Capsules can be used for self-healing, having a healing agent inside the capsules. When the capsules are ruptured, the self-healing agent comes in direct contact with concrete and in order to obtain crack closure, the release results in reaction of the healing agent in the region of damage. Many capsule based agents react upon contact with water or air or when they are heated or when they come in contact with the cementitious matrix itself while the rest of the agents react when they come in contact with a second component which is either present in the matrix or is additionally added via capsules. Capsules generally have a spherical or cylindrical shape. The capsules should be uniformly distributed in matrix else, there might not be healing agent available for healing where crack is developed in the concrete.

2.4 Bacteria Based Self-Healing

Although the idea to use bacteria and integrate them in the concrete may seem odd at first, it is not from a microbiological viewpoint. Bacteria naturally occur virtually everywhere on earth, not only on its surface but also deep within. Various species of extremophile bacteria, i.e. bacteria that love the extreme, are found in highly dried environments such as deserts, but also inside rocks and even in ultra-basic environments which can be considered homologous to the internal concrete environment. These type of bacteria have the ability to form endospores. These specialized cells are able to resist high mechanically- and chemically induced stresses and are viable for periods of up to 200 years.

In some previously published studies the application of bacteria for cleaning of concrete surfaces and strength improvement of cement-sand mortar was reported. Although promising results were reported, the major drawback of these studies was that the bacteria and compounds needed for mineral precipitation could only be applied externally on the surface of the structures after crack formation had occurred. This methodological necessity was mainly due to the limited life-time (hours to a few days) of the (urease-based) viability of the applied bacterial species.

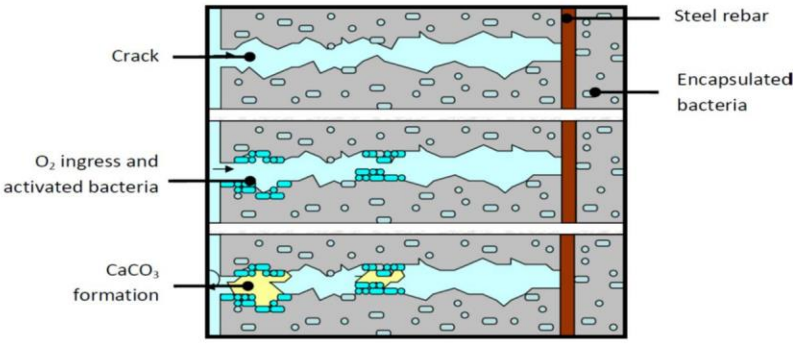

Figure 5 Schematic representation of self-healing by bacteria.

The goal is to create a concrete mix that contains bacteria packed in microcapsules that will activate if water enters through a crack. The bacteria will multiply, as a result produce limestone and seal the crack before the water can do any harm. Including bacteria in concrete not only block the crack in the concrete but also offers a double layer of protection in preventing steel from the oxygen which is present due to crack formation by using it in the reaction.

Bacteria-based self-healing concrete is generated by adding two-component biochemical self-healing agent to the concrete mixture during mixing. The first component is spores of bacteria and second component is the biochemical healing agent that is added in the concrete during the mixing of concrete. This two-component biochemical self-healing agent is opened when cracks are developed in the concrete system after the final setting of concrete. And when water came into contact with this agent then it forms compound CaCO3 and fill the cracks and no further cracks are developed and hence steel is prevented from corrosion.

3. TYPE OF BACTERIA USED

Bacteria used for self-healing is Bacillus subtilis, a spore forming bacteria which can form an endospore, to survive extreme environmental conditions of temperature and desiccation Bacillus subtilis, as with many in the Bacillus genus, is an extremely common bacterium. It can divide symmetrically to make two daughter cells (binary fission), or asymmetrically, producing a single endospore that can remain viable for decades and is resistant to unfavorable environmental conditions such as drought, salinity, extreme pH, radiation, and solvents. The endospore is formed at times of nutritional stress, allowing the organism to persist in the environment until conditions become favorable. Under stressful conditions, such as nutrient deprivation, B. subtilis undergoes the process of sporulation to ensure the survival of the species. This makes them excellent for use in our project.

4. HEALING MECHANISM

When a concrete structure is cracked and water starts to percolate in that crack, the spores of the bacteria germinate after coming in contact with the water and precursor

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compound. After the activation, bacteria start to feed on the calcium lactate. As the bacteria feeds, oxygen is consumed and the soluble calcium lactate is converted to insoluble limestone (CaCO3). The limestone solidifies over that cracked surface and seals it up. The bio-chemical reaction in bacterial concrete is much more efficient due to the active metabolic conversion of calcium lactate by the present bacteria

$$Ca\,(C_3H_5O_2)_2 + 7O_2 \longrightarrow CaCO_3 + 5CO_2 + 5H_2O$$

Another advantage of this reaction is the production of CO2 with the CaCO3, latter this CO2 react with the portlandite still present at the cracked surface and produce additional CaCO3.

The consumption of oxygen during the bacterial conversion of calcium lactate to limestone has an additional advantage. Oxygen is an essential element in the process of corrosion of steel and when the bacterial activity has consumed it all it increases the durability of steel reinforced concrete constructions.

5. CASTING

There were two types of samples.

5.1. Controlled samples

The controlled samples are conventional concrete samples with the same mix design as other samples which will be casted in order to compare the effects of bacteria on different properties of concrete such as strength and healing capacity. The strength regain will also be found out by comparing the strength of controlled samples to the samples which are healed after crack development.

5.2. Bacteria Samples

Three different amounts of bacteria will be used in order to determine the effective quantity of bacteria for providing adequate healing capability to concrete. These include

Bacteria Quantity A = $1.6x10^{10}$ Spores

Bacteria Quantity B = $2.4x10^{10}$ Spores

Bacteria Quantity C = $3.2x10^{10}$ Spores

6. SIZES OF SAMPLES

Two different size of cylinders 6″x12″ and 6″x4″ were used for checking of healing capacity and strength regain . The cylinder of size 6″x12″ were used for checking both the healing capacity and strength regain while the cylinders of size 6″x4″ were used for checking of healing capacity only. The cylinder size of6″x12″ was selected keeping in view the ASTM standard C 39/C 39M –03 for checking the compressive strength of concrete.

7. MIX DESIGN

The mix was designed according to ACI Recommended Practice 211.1.

TYPE	Controlled	Bacteria Amount A	Bacteria Amount B	Bacteria Amount C
Cement	6.5	6.5	6.5	6.5
Coarse Aggregate(kg)	13	13	13	13
Fine Aggregate(kg)	26	26	26	26
Water (kg)	2.6	2.6	2.6	2.6
Light Weight Aggregate (gm)	_	230	350	460

8. CRACK INTRODUCTION

Cracks were developed using compression testing machine. Sample was placed in compression machine and loading rate was decreased to 0.08 KN/sec. The loading rate was reduced to ensure that no abrupt change in the crack development process takes place and the loading process can be stopped as the cracks appear in the concrete.

Crack introduction using compression testing machine

9. CRACK READING

The samples cracked in compression testing machine were kept under observation for crack measurement. Width of the cracks were noted after marking the cracks under study and cracked cylinders were placed again in curing tank. Cracks of width less than 0.2 mm were studied.

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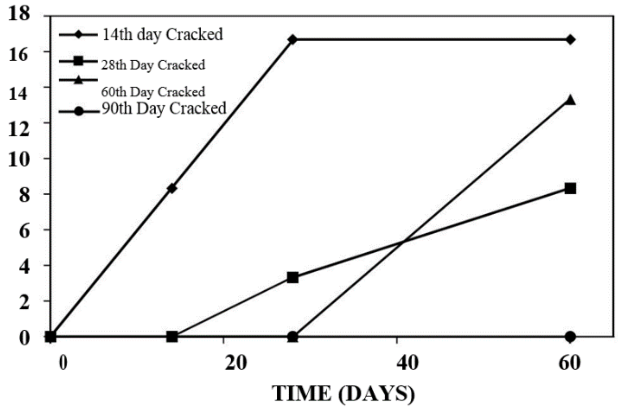
10. HEALING MEASUREMENT

Healing phenomenon was measured in terms of crack width. Cracks were developed at different days after casting and then measuring those cracks at regular intervals to see how much cracks are filled. These values are noted and given at the appendix section of this report. Mean value of three samples is used for each entity and plotted on graph in the form of percentage of original crack width



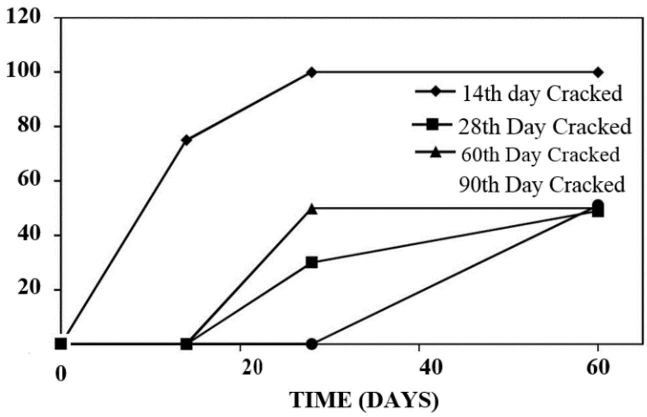
Self-healing in different days cracked control samples

This graph gives the information of healing phenomenon in control samples. It also shows the comparison of crack healing capacity of samples which were cracked at different time (days). Cracks were developed in control samples at 14th, 28th, 60th and 90th day of curing.

Graph shows that specimens cracked at 14 days have maximum possible healing (17%) capacity and start the healing process very quickly. This is due to the fact that after 14 days' hydration process is not completed and un-hydrated cement particles are present in the concrete matrix. So when crack is developed and water infiltrates through these cracks then these un-hydrated cement particles react with water and make the hydrated products. Therefore, cracks developed after 14 days of curing have some capacity to heal themselves, but this healing capacity is very less. While 28th and 60th day cracked samples healed only 8% and 13% of the cracked width respectively. 90th day cracked samples didn't heal cracks as most of the hydration process is completed and there are no un-hydrated cement particles.

Graph lines show that 14th day cracked samples start the healing very early and healing rate is also higher as compared to 28th and 60th day cracked samples. 28th and 60th day cracked samples start healing with delay of 14 and 28 days respectively.

So we can say the cracks that are developed in the early ages of concrete, they have small capacity or capability to heal the cracks automatically but with the passage of time this healing capacity of cracks also vanishes.



Self-healing in different days cracked bacterial samples of quantity A

The above graph shows the healing capacity of bacterial specimen, sample A. Graph shows that bacterial specimens which were cracked at 14th day of curing, healed the crack width 75% and 100% after 14 and 28 days respectively. Crack was completely filled with CACO3 precipitation after 28 days. This was result of dual healing mechanisms, one (as described earlier) due to continuous hydration of cement particles while other due to added bacteria. While 28th day cracked samples healed 0%, 30% and 50% after 14, 28 and 60 days respectively. 60th day cracked samples healing was 0% and 50% after 14 and 28 days respectively. 90th day cracked samples healing of crack was 0%, 0% and 50% after 14, 28 and 60 days respectively.

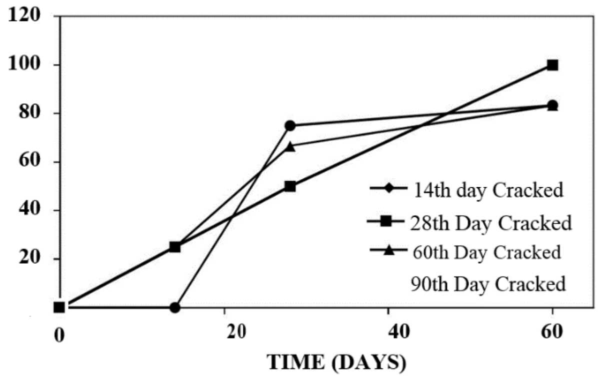
In 14th day cracked samples healing started quickly, bacteria started precipitation of $CaCO_3$ to fill the cracks, and this process goes on for 28 days until complete crack was filled. Samples cracked on 28th and 60th day delayed the healing to

14 days and then started healing, reached to 50% after 60 days of cracking. Samples cracked on 90th day also delayed the healing for 30 days after that healing started and filled the crack width up to 50% after 60 days of cracking.

From graph it is clear that for 28th, 60th and 90th day cracked samples, rate of healing in almost equal, means they get their absolute healing capacity with the same rate, irrespective of when healing process starts.

From the above discussion about graphs we can say that samples cracked at 14th day have more healing capacity, less delayed of initiation of process, and have greater rate of healing as compared to those samples that were cracked at 28th, 60th and 90th day of curing.

So sample A is only suitable for those cracks which are developed in the early ages of concrete, but the for the cracks developed in older ages of concrete, quantity of bacteria in sample A doesn't give satisfactory results of healing.



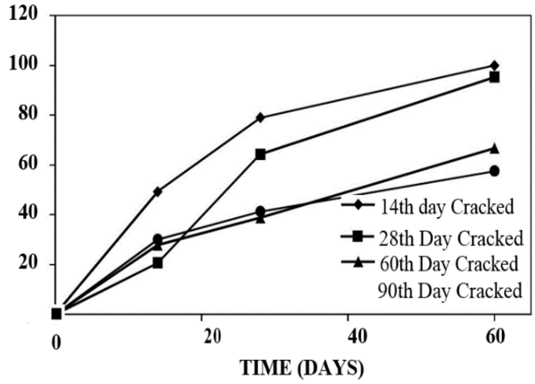
Self-healing in different days cracked bacterial samples of quantity B

The above graph shows the healing of bacterial specimen, sample B. Graph shows that specimens which were cracked at 14th and 28th day of curing, healed the crack width of 25%, 50% and 100% after 14,28 and 60 days respectively. Crack was completely filled with CaCO3 precipitation after 60 days. For 60th day cracked samples, healing was 25%, 65% and 85% after 14, 28 and 60 days respectively. While 90th day cracked samples healing of crack was 0%, 75% and 85% after 14, 28 and 60 days respectively.

In 14th and 28th day cracked samples, healing started quickly, bacteria started precipitation of CaCO3 to fill the cracks, and this process goes on for 60 days until complete crack was filled. Samples cracked on 60th day have no delay in the healing process and fill the cracks up to 85% after 60 days of cracking. Samples cracked on 90th day delayed the healing for 14 days after that healing started and filled the crack width up to 85% on 60 day after cracking.

From graph it is clear that for 14th and 28th day cracked samples rate of healing is equal. For 60th and 90th day cracked samples, rate of healing in almost equal, means they get their absolute healing capacity with the same rate, irrespective of when healing process starts.

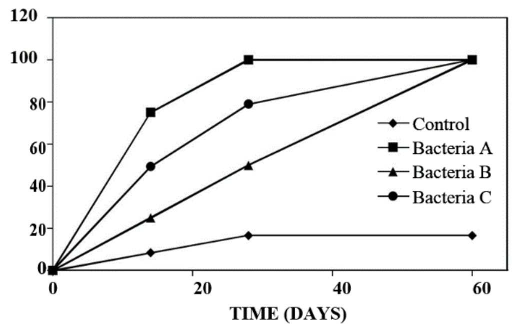
From the above discussion of graph behavior of samples cracked at different age we can say that B samples cracked at 14th and 28th day have more healing capacity, no delayed of initiation of process, and have greater rate of healing as compared to those samples that were cracked at 60th and 90th day.



Self-healing in different days cracked bacterial samples of quantity C

The above graph shows the healing of bacterial specimen, sample C. Graph shows that specimens which were cracked at 14th day of curing, healed the crack width 50%, 80% and 100% after 14, 28 and 60 days respectively. Crack was completely filled with CaCO3 precipitation after 60 days. 28th day cracked samples were healed 20%, 65% and 95% after 14, 28 and 60 days respectively. 60th day cracked samples were healed 30%, 40% and 65% after 14, 28 and 60 days respectively. 90th day cracked samples were healed 30%, 45% and 60% after 14, 28 and 60 days respectively.

From graph it is clear that for rate of healing for 14th and 28th day cracked samples is equal and greater than 60th and 90th day samples. For 60th and 90th day cracked samples, rate of healing in almost equal and less than 14th and 28th day cracked samples. Healing started quickly in all samples, bacteria started precipitation of CaCO3 to fill the cracks, and this process goes on for 60 days until complete crack was filled. No delay was observed in any sample.



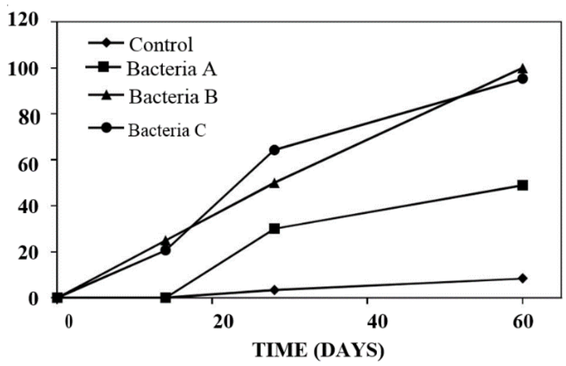
Self-healing on 14th day cracked samples for different quantities of bacteria

The above graph gives the information of healing for sample cracked after 14 days of curing. Specific cracks were measured with the help of microscope before putting the samples into curing tank. Cracks having width of less than 0.20mm were observed for healing process. The crack healing was measured after 14, 28 and 60 day of curing of cracked sample. It also shows the comparison between the healing potentials of different quantities of bacteria and the rate of healing of cracks that were developed after 14 days of curing.

The Curve of control samples, in which no bacteria were added, shows very less capacity to healing. Although, control samples start healing due to un-hydrated cement particles but they have no such healing capability that can fill the cracks completely. So control samples heal the cracks only up to 17% of crack width.

Similarly, after 14 days of cracking there was 75%, 25% and 50% healing in sample A, B and C respectively. On 28th day, sample A healed 100% i.e. crack was filled completely while 50% and 80% healing was observed in sample B and Sample C respectively. After 60 days of cracking sample B and C were healed completely.

There is no delay in healing process for sample A. For sample B, healing starts quickly as in case of sample A. There was also no delay in healing process and it healed the cracks in 60 days after the crack was developed. Similarly, for sample C, graph shows the similar behavior. Crack healing process starts with no delay and filled the crack in 60 days. But in sample C, rate of healing is less than sample A and greater than sample B.



Self-healing on 28th day cracked samples for different quantities of bacteria

The above graph gives the information of healing for sample cracked after 28 days of curing. The same procedure was followed for crack healing observation as in the previous case of 14 days' crack developed. The crack healing was measured after 14, 28 and 60 day of curing of cracked sample. It also shows the comparison between the healing potentials of different quantities of bacteria and the rate of healing of cracks that were developed after 28 days of curing.

The Curve of control samples, shows very less capacity to healing. After 14 days of cracked developed no healing was observed in control samples. On 28th day and 60th day observation only 4% and 8% healing was observed respectively.

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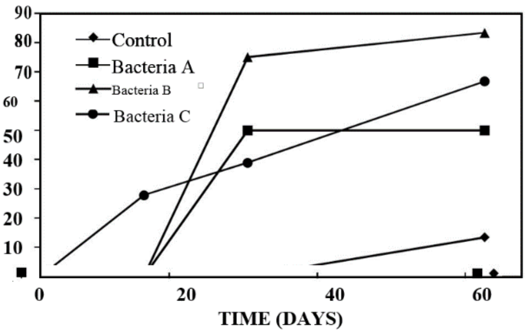
Similarly, on 14th day after cracking there was no healing observed in sample A, but sample B and C were healed 25% and 20% respectively. On 28th day, sample A, B and C were healed 30%, 50% and 65% respectively. On 60th day observation sample B crack was completely filled while 48% and 95% healing was observed in sample A and C respectively.

As the graph show there is delay in healing process for sample A. For sample B, healing starts quickly and it healed the cracks in 60 days after the crack was developed. Similarly, for sample C, graph shows the similar behavior. Crack healing process starts with no delay and filled the crack in 60 days. From graph it is also clear that rate of healing is very much greater than quantity A and also constant. In sample C, rate of healing is less than B samples in early ages then it gets greater speed than B sample up to 50 days, then again it slows down.



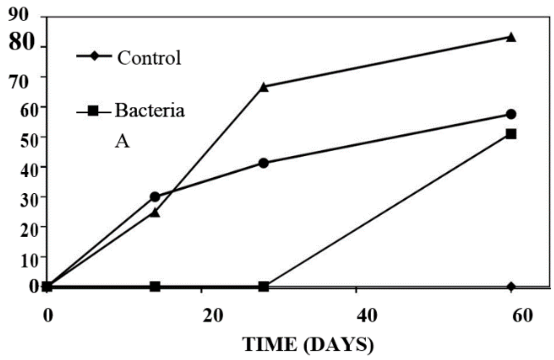
Self-healing on 60th day cracked samples for different quantities of bacteria

The above graph gives the information of healing for sample cracked after 60 days of curing. The same procedure was followed for crack healing observation as in the previous case of 14 and 28 days' crack developed. The crack healing was measured after 14, 28 and 60 day of curing of cracked sample.

The Curve of control samples, shows very less capacity to healing. On 14th and 28th day of observation no healing was observed in control samples. On 60th day only 14% healing was observed respectively.

Similarly, on 14th day after cracking there was no healing observed in sample A and B while C was healed 28%. On 28th day, sample A, B and C were healed 50%, 75% and 40% respectively. On 60th day observation sample B crack was completely filled while 50% and 65% healing was observed in sample A and C respectively.

There is delay of 14 days in healing process for sample A and B, but healing starts quickly as in case of sample C. From graph it is clear that rate of healing in sample B is greater than sample A and C.



Self-healing on 90th day cracked samples for different quantities of bacteria

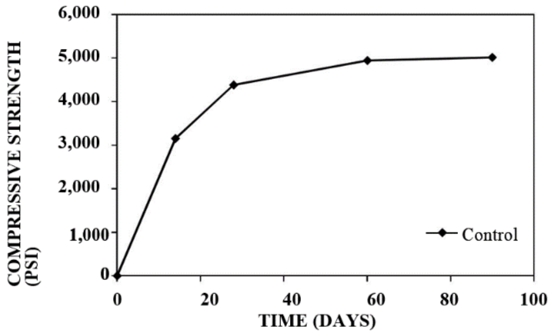
The above graph gives the information of healing for sample cracked after 90 days of curing. The same procedure was followed for crack healing observation as in the previous case of 14 and 28 days' crack developed. The crack healing was measured after 14, 28 and 60 day of curing of cracked sample.

Control samples did not show any sign of healing. Similarly, on 14th and 28th day after cracking there was no healing observed in sample A. While sample B was healed 25% and 66% after 14 and 28 days respectively. Sample C was healed 30% and 41% after 14 and 28 days respectively. On 60th day of observation, cracks were filled 85% in sample B while 50% and 65% healing was observed in sample A and C respectively.

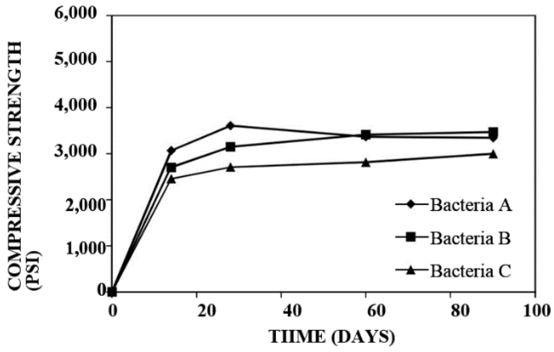
There is delay of 28 days in healing process for sample A, but healing starts quickly as in case of sample B and C. From graph it is clear that rate of healing in sample B is greater than sample A and C

11. STRENGTH TEST

Strength test or Compressive strength test is very vital to analyze the concrete performance and usability. Strength test is conducted using Compression testing machine. Compressive strength tests of both control and bacterial specimens with different quantities of bacteria is conducted. Results of these tests are given in appendix section at the end of this report.



Compressive strength for different days of control specimen



Compressive strength for different days of bacterial specimen

Standard procedure for this test was adopted. Key points are given below:

Remove the specimen from water after specified curing time and wipe out excess water from the surface. Apply plaster of paris on the opposing surfaces which are to be touched by machine plates to avoid non uniform load application.

Place the specimen in the machine in such a manner that the load shall be uniformly applied to the opposite sides of the cylinder cast. Apply the load gradually without shock and continuously at the rate of 140kg/cm2/minute till the specimen fails. Record the maximum load and note any unusual features in the type of failure.

12. STRENGTH REGAIN

Strength regain is an important phenomenon in self-healing concrete research. This test shows how much strength a specimen has regained after the cracks are developed due to the healing phenomenon. Normally it is considered that when cracks are appeared and sample does not take further any load then its strength is reduced to zero. Same approach is used in this research while conducting tests for strength regain. Procedure for this test is same as the normal compressive strength test. Specimen which are used for healing observation at 14, 28 and 60 days after cracking are used for strength regain

Specimen lose their strength when cracked for the purpose of healing observations. But once healing starts in the samples, precipitation of calcite occurs in the sample due to the chemical reaction of bacteria and calcium lactate. This precipitation of calcite increases the bonding in the concrete between crack surfaces. This results into some regain in specimen strength. Since average strength of samples is known (shown in section 3.5.1) therefor we compared the results with the original strength values to find how much strength has been regained due to healing.

The strength regain of all the four types of samples was checked. Sample's strength was found at 14th, 28th, 60th and 90th day of curing. After examining the cracks for healing along with curing the samples for 60 days, regain strength was found using the compression testing machine in accordance with ASTM standard C39. The strength regain was plotted against the average strength of same type of samples with same curing duration.

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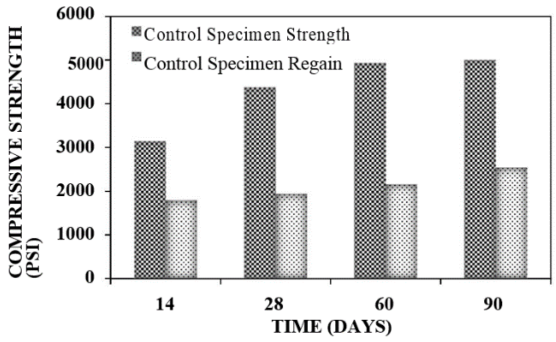
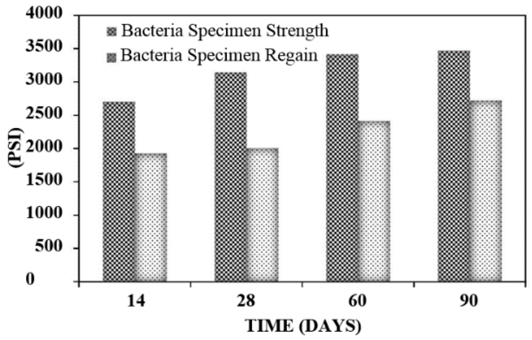


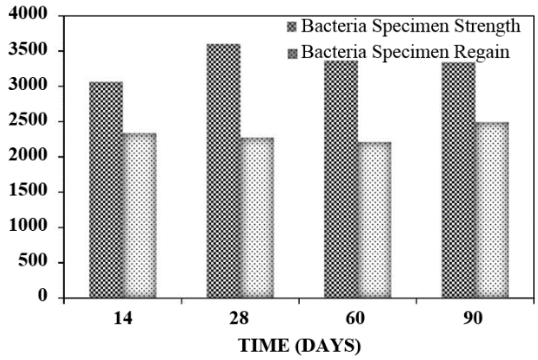
Strength regain for different days cracked control specimen

Strength regain for controlled samples cracked on 14th day was 57%. The strength regains for 28th, 60th, and 90th day of cracking the regain was 44%, 43% and 50% respectively. The maximum regain was for the samples cracked on 14th day because



Strength regain for different days cracked bacterial specimen with quantity A

hydration process was still in progress due to presence of un-hydrated cement, thus allowing development of more strength.



Strength regain for different days cracked bacterial specimen with quantity B

Strength regain for sample A cracked on 14th day was 76%. The strength regains for 28th, 60th, and 90th day of cracking the regain was 63%, 65% and 74% respectively. The high value of regain for samples regain can be accredited to the hydration of the unhydrated cement along with the reason that these samples had a healing of 100%.

Strength regain for sample B cracked on 14th day was 71%. The strength regains for 28th, 60th, and 90th day of cracking the regain was 63%, 70% and 78% respectively. Strength regain for sample C cracked on 14th day was 69%. The strength regains for 28th, 60th, and 90th day of cracking the regain was 67%, 71% and 58% respectively.

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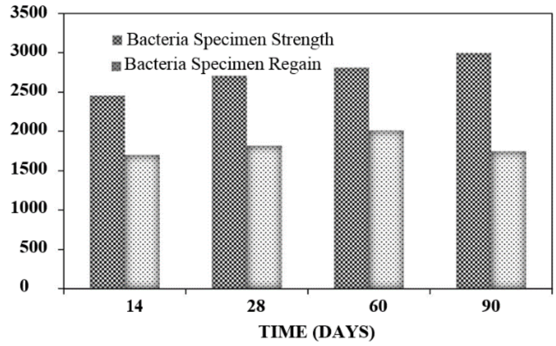

Strength regain for different days cracked bacterial specimen with quantity C

From the above values of regain we can conclude that the regain value of control samples is lower than the bacteria samples as it has a very low healing capability. The average regain for control samples is 49%, whereas for sample type A, Band C it is 70%, 71% and 66% respectively. The regain for all the bacteria type samples is close to each other. Thus by applying bio influenced techniques for self-healing of concrete the regain capacity of concrete can be enhanced by 20%.

CONCLUSION AND RECOMMENDADTION

After conducting thorough study of effect of different quantities of bacteria on healing in concrete matrix, we can conclude that:

The earlier age cracks of concrete were healed by all the quantities of bacteria under study. So if the objective is to counter the shrinkage cracks than we should opt for Quantity A of bacteria as it has the least negative effect on the strength of concrete and is the most economical

When cracks were developed at older age of concrete the cracks didn't heal completely for bacteria quantity A and B however the samples having quantity C healed. However, it was observed that with the increase of bacterial quantity more quantity of light weight aggregate was required which reduced the compressive strength of concrete, so the optimum quantity of bacteria would depend upon requirements of the particular structure and the cracks that are likely to occur in life time of structure, the need is to balance the strength requirement and optimum crack restriction for a particular structure.

After evaluating the regain of concrete we can conclude that use of bio influenced techniques in self-healing enables the concrete to have a higher value of regain as compared to conventional concrete.

The reduction of compressive strength can be reduced by using a light weight aggregate with high absorption capacity. As light weight aggregate with high absorption capacity can absorb more bacteria spore thus increasing the influence area of the bacteria

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Compressive strength of controlled specimens

Days	Sample 1 (Psi)	Sample 2 (Psi)	Sample 3 (Psi)	Average (Psi)
14	3142	3423	2900	3149
28	4698	4200	4258	4385
60	4945	4875	5003	4981
90	4956	5421	4652	5009.66667

Compressive strength of Bacterial specimens with Quantity A

Days	Sample 1 (Psi)	Sample 3 (Psi)	Sample 3 (Psi)	Average (Psi)
14	3277	2850	3075	3067.3333
28	3408	3611	3795	3604.6667
60	2740	3826	3540	3368.6667
90	3726	2248	4060	3344.6667

Compressive strength of Bacterial specimens with Quantity B

Days	Sample 1 (Psi)	Sample 3 (Psi)	Sample 3 (Psi)	Average (Psi)
14	2320	2755	3045	2706.6667
28	2977	3129	3340	3148.66667
60	3470	2828	3955	3417.6667
90	3165	3846	3408	3473

Compressive strength of Bacterial specimens with Quantity C

Days	Sample 1 (Psi)	Sample 3 (Psi)	Sample 3 (Psi)	Average (Psi)
14	2175	2560	2639	2458
28	2365	2620	3145	2710
60	2552	2824	3065	2813.6667
90	2567	2965	3470	3000.6667

Strength regain of control specimens

Days	Sample 1 (Psi)	Sample 3 (Psi)	Sample 3 (Psi)	Average (Psi)
14	1720	1760	1920	1800
28	1980	2225	1630	1945
60	1523	2620	2340	2160
90	2346	2843	2465	2551.33

Strength regain of Bacterial Sample with Quantity A

Days	Sample 1 (Psi)	Sample 3 (Psi)	Sample 3 (Psi)	Average (Psi)
14	2239	2294	2485	2339.33
28	2726	1015	3089	2276.67
60	1479	2496	2670	2215
90	2712	2668	2115	2498.33

Strength regain of Bacterial Sample with Quantity B

Days	Sample 1 (Psi)	Sample 3 (Psi)	Sample 3 (Psi)	Average (Psi)
14	1760	1880	2150	1930
28	1923	1843	2260	2009.33
60	2477	2163	2614	2418
90	2208	3145	2812	2721.67

Strength regain of Bacterial Sample with Quantity C

Days	Sample 1 (Psi)	Sample 3 (Psi)	Sample 3 (Psi)	Average (Psi)
14	1866	1740	1504	1703.33
28	1769	1719	1973	1820.33
60	2871	1537	1640	2016
90	2741	1812	696	1749.67

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