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Prediction of optimal biomaterial and curing duration for self-healing concrete through designed experiments and decision tree algorithm

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ABSTRACT

Self healing concrete structures have been considered in recent decades due to their potential to repair cracks in an efficient manner. The current study considers three different biomaterials namely Bacillus subtilis, Bacillus Flexus and Bacillus Licheniformis to be mixed with concrete at fresh state to evaluate compression strength after 7, 14 and 21 days of curing in water medium. The cracked specimens are further allowed to cure in open atmosphere for 12 days to evaluate crack healing and post healed compression strength. Taguchi full factorial experimental design has been adopted for conducting experimental trials and experimental results has been analysed using signal to noise ratio method, desirability function analysis through Mini tab 17.0. In case of initial compression strength, Bacillus subtilis mixed concrete cube specimen cured for 7 days exhibited lowest value of 70 MPa and attained 260% (252 MPa) improvement when cured for 21 days, but opposite trend is observed for final compression strength. The optimum biomaterial and curing duration for pre and post compression strength has been determined using decision tree algorithm. The recommended combination of input factors and significant influencing factor identified from both the analysis methods are in good agreement.

Keywords: Biomaterial; Compression Strength; Decision Tree Algorithm; Self-Healing Concrete.

1. INTRODUCTION

Concrete structures are highly susceptible to crack formation in general when passing through ages and there pair of such cracks at early stage is a wise and economical idea to avoid disastrous outcomes. The addition of healing agents to concrete is found to be one of the highly promising methodologies to cure early stage cracks and to restrict its progression. The structure of concrete is susceptible to crack formation with repeated service loads and such cracks generally affect concrete's durability. The effective species like chlorides and sulphates can easily penetrate concrete matrix through the formation of continuously networked micro crack paths. For repairing the cracks emanated in concrete structures, concrete mix with self healing ability due to the addition of microbial induced calcium carbonate precipitation has been suggested as a viable strategy with environment friendliness. During initial stage, mixing of bacteria based healing agents in fresh concrete induces self healing characteristics. Concrete'sharsh environment affects the efficacy of bacteria added with concrete. Through optimizing the carrier material and healing agent's content, the concrete mix may be optimized to exhibit superior performance. The bacterial activity may be prolonged through appropriate selection of carrier material which generally acts as a carrier. Many Researchers around the world is showing peak interest in analyzing the effect of adding self healing agents for curing cracks formed in the concrete. WU *et al.* [1] applied bacterial spores coated within organic cementitious material to understand its effect over self healing ability of cracks. The authors have evaluated water permeability and crackhealing efficiency by studying the effectiveness of biocapsule in self crack healing. The study has concluded that a dosage of 5% biocapsule can effectively heal crack widths of 150–550 μm. The effect and mechanism of encapsulation based spores for self healing concrete at different ages has been studied by ZHENG *et al.* [2].The authors have considered parameters such as area repair ratio, water permeability, repair ratio of anti-chloride ion penetration, and ultrasonic velocity for evaluating the self-healing efficiency of cracks. Due to high alkali environment in concrete, microbial spores with better alkali resistance failed to survive and also in efficient in healing the cracks at later ages. SHAHID *et al.* [3] has reported that cracks formed in concrete can be self healed by adding bacillus strains encapsulated with sodium alginate beads.

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Other bacteria's such as Bacillus Anthracis and Bacillus Pasteurii didn't produce much considerable results, where bacillus subtilis with 2 – 3 % was found to optimum for enhancing the compressive strength of concrete.

SOUID *et al*. [4] provided the experimental data on bio self-healing concrete incubated in saturated natural soil in similar to structure ssuch as tunnels and deep foundations which are generally exposed to ground conditions. The authors have evaluated the cracks before and after incubation to understand the effect of bacillus subtilis over the healing efficiency. The SEM and EDX techniques havebeen applied for visualizing the mineral precipitations on crack surfaces. Xiaohao SUN *et al*. [5] communicated that the addition of glucose can greatly improves the bio-remediation efficiency in repairing cracks. The authors have observed that the addition of 10 g/L is the optimum dosage and it can handle irregular cracks, accelerate the bio-remediation reaction and also reduces crack repair time. LIANG *et al*. [6] discussed about controlling the calcium carbonate precipitation through Engineered Escherichia coli. The authors have conveyed that a aweak relationship exists between the urease expression and crystalsize. The crystal morphology can greatly affect the potential for controlling the biogenic CaCo3 precipitation. Jing XU *et al*. [7] employed porous ceram site particles are used as microbial carrier for microbially induced CaCo3.The authors have evaluated compressive strength regain, water up take, and visual inspection of cracks to realize the self healing efficiency of concrete. Due to heat treatment adopted for loading ceram site, the healing ratio of cracks reached 86% and 0.3 mm is the maximum crack width healed. XU andWANG [8] deployed low alkali cementious material as protective carrier for bacteria in self healing concrete. The proposed methodology is found to be novel and it can heal cracks upto 417 µm with crack closure nearing 100% in comparison with plain mortar. The study of concrete self healing properties with nano clay encapsulated bacteria is done by LUCAS *et al*. [9]. The current study has replaced aggregate with bacteria immobilized in expanded clay. The presence of calcium carbonate has contributed in the strength recovery of concrete. KHALIQ andEHSAN [10] studied the effect of adding bacteria in graphite nano platelets and light weight aggregate over the healing of cracks and compressive strength of concrete. Specimen's pre cracked at 3 and 7 days are found to have better healing when bacteria immobilized in graphite nano platelets. Similarly, bacteria immobilized in light weight aggregate performed well in pre cracked specimens at 2 and 4 weeks. SOURADEEP and KUA [11] discussed about the various encapsulation techniques for self healingof concrete by considering 8 different key factors such as robustness while mixing, curing time, probability of cracks encountered in capsules, effect of empty capsules, healing agent's controllability, healing agents' stability, self healing repeatability, recovery and sealing ability. The application of hydrogelen capsulated precipitating bacteria for attaining concrete self healing is carried out by WANG *et al*. [12] and the proposed bacteria has the ability to heal crack width of 0.5 mm and to decrease water permeability by 68%. WANG *et al*. [13] adopted silica gel or polyuerathane immobilized bacteria for self healing of concrete and they have identified that polyuerathane immobilized bacteria has more potential to serve as bacterial carrier than silica based. WIKTOR andJONKERS [14] quantified about the crack healing potential of bacteria based self healing concrete (SHC) in wet environments. The study conducted reveals the potential of bio-chemcial self healing agents in improving the durability of concrete structures in wet environments. ESPITIA-NERY*et al*. [15] reviewed about various mechanisms for encapsulation of bacteria in SHC. The authors note that by using expanded clay coated with a layer of geopolymer made of metakaolin and sodium silicate solution, maximum widths of 0.96 mm and 0.79 mm can be easily fixed.

The above cited literature survey has indicated the effectives of adding bacteria in self healing of concrete structures. The current study considers three different biomaterials such as Bacillus subtilis, Bacillus Flexus and Bacillus Licheniform is to mix with concrete at initial stage. The prepared cube specimen is allowed of cure for 7, 14 and 21 days of curing for further evaluation of compression strength. The cracked specimens are further testing for compression strength after 12 days of time and also the crack self healing. The experimental data set of initial and final compression strength has been analysed using taguchi'ssignal to noise ratio method to identify optimal factor combination for compression strength enhancement and significant factors influencing the output responses. The data is further analysed using desirability function analysis and decision tree algorithm for validation of optimum factor settings. The cracked specimens are further evaluated for crack healing and crack closure to understand the ability of different biomaterials and curing duration. Figure 1 depicts the proposed research workflow adopted in the current study.

2. MATERIALS AND METHODS

The current section highlights about the different biomaterial used in the research and also the methodology involved in conducting experimental trails.

2.1. Bacillus subtilis

A rod-shaped, catalase-positive, gram-positive bacterium called Bacillus subtilis. B. subtiliscells are typically rod-shaped, measuring 4–10 m in length, 0.25–1.0 m in diameter, and having an estimated 4.6 of stationary

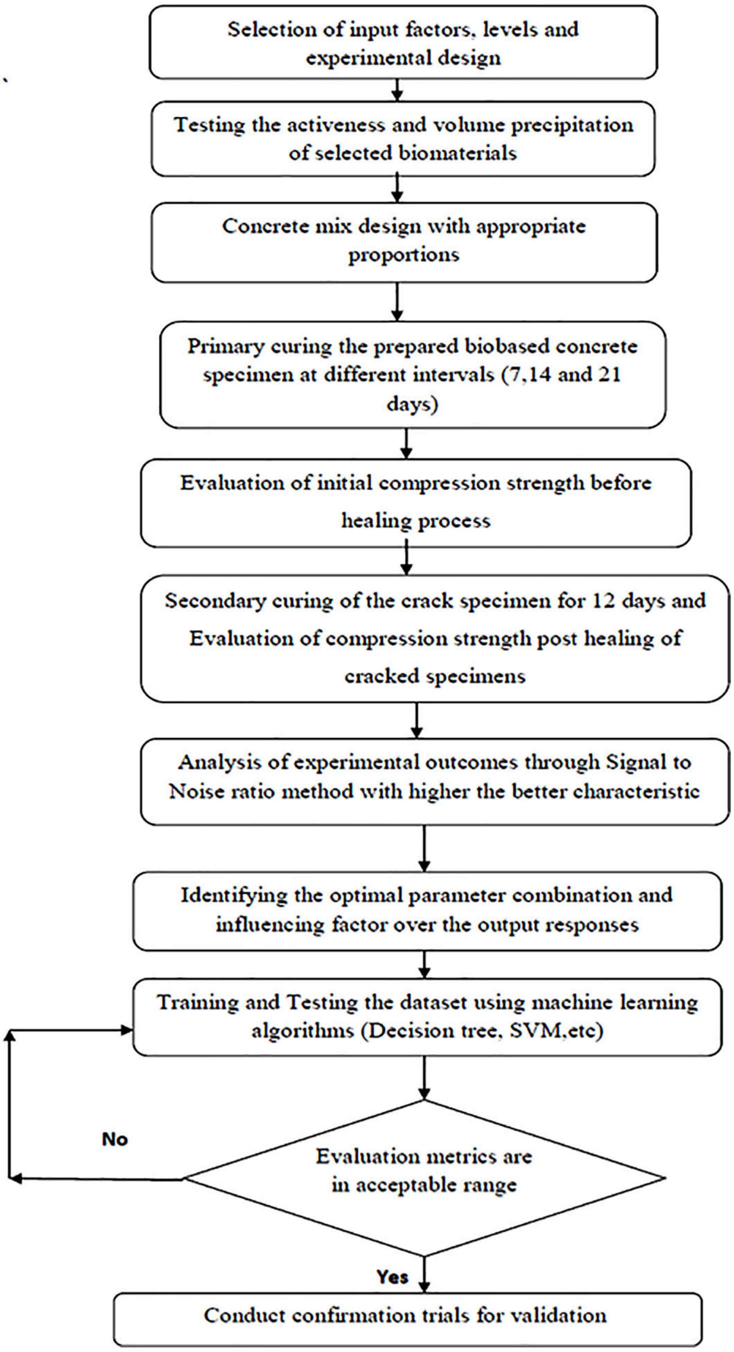

Figure 1: Proposed research workflow.

phase cell volume. To endure extremely harsh environmental circumstances of temperature and desiccation, Bacillus can develop an endospore. Prior to 1998, subtilis was thought to be an obligatory aerobe but is now known to be a facultative anaerobe. B. Subtilis can move swiftly through liquids thanks to its extensive flagellation. B. Subtilis has shown to be extremely receptive to genetic manipulation, and it has been generally accepted as a model organism for lab investigations [16].

2.2. Bacillus flexus

Bacillus flexus is an aerobic gram-variable, rodshaped, endospore forming, oxidase positive bacteria. The endospores are ellipsoidal, located in central/paracentral, un swollen sporangia. In laboratory conditions, it produces opaque, ceramic, raised margin coloniesat 30 ± 2°C when incubated at 24–72 hrs. onTryptic Soy Agar (TSA). These bacteria may be isolated from faces (poultry) and soil. Human pathogenicity has not been well described at this time [17]. This species has been recently transferred into the genus Priestia The correct nomenclature is *Priestiaflexa.*

2.3. Bacillus licheniformis

A bacteria called Bacillus licheniformis is frequently discovered in soil. It is most frequently observed on the feathers of ground-dwelling birds (like sparrows) and aquatic species (like ducks), particularly on the chest and back plumage. It is a gram-positive, mesophilic bacterium. Its optimal growth temperature is around 50°C, though it can survive at much higher temperatures [18]. The optimal temperature for enzyme secretionis 37°C. It can exist in a dormant spore form to resist harsh environments or in a vegetative state when conditions are good. The Figures 2 (a), (b) and (c) shows the images of three different bacteria's used in the current study.

2.4. Designed experiments

Designed experiments provide a greater flexibility and reduce complexity in conducting experiments for research. They generally proposeless experimental trials to understand the effect of input factors over output responses and reduce time, money and resources involved. The current study considers two different factors

Figure 2: (a) Bacillussubtilis (b) bacillus flexus (c) bacillus licheniformis.

Table 1: Input factor and levels for initial stage compression strength evaluation.

S.NO	FACTOR	NOTATION	LEVEL 1	LEVEL 2	LEVEL 3
1	Biomaterial	A	Bacillus subtilis	Bacillus flexus	Bacillus licheniformis
2	Curing duration (in days)	B	7	14	21

Table 2: Input factor and levels for final stage compression strength evaluation.

S.NO	FACTOR	NOTATION	LEVEL 1	LEVEL 2	LEVEL 3
1	Biomaterial	A	Bacillus subtilis	Bacillus flexus	Bacillus licheniformis
2	Curing duration (in days)	B	19	26	33

Table 3: Full factorial designs – experimental layout.

TRIAL NO	BIOMATERIAL	CURING DURATION (DAYS)
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

namely biomaterial type and curing duration varied in three levels (23) for evaluating the initial and final compression strength [19]. The experimental layout for the current study consists 9 experimental trials as per full factorial design. The input factors and levels for evaluation of initialand final compression strength is shown in Table 1 and 2. Table 3 shows the experimental layout as per Taguchi orthogonal array – full factorial design.

3. EXPERIMENTAL WORK

In case of experimental work, the cube specimen has to be prepared as per standard dimensions and biomaterial need to be added to the concrete at fresh stage. The prepared cube specimens are further allowed to cure for different time span and subjected to compression strength evaluation [20]. The cracked specimens are further allowed to cure for 12 days to check the potential of internally present biomaterial over curing the crack.

3.1. Sample preparation

The samples for evaluating the strength of prepared concrete cubes of 150 mm should be in accordance with BS EN 12390-2. Figure 3 Shows that the 2D and 3D view of the Concrete Cube Specimen. The size of concrete cube of size 150 mm × 150 mm × 150 mm is used in this research. The sample should be casted in a rapid manner and made to be stored for curing. The preparation of samples should be done by remixing thoroughly on a steel sampling tray or heavy plastic sheet. The mould should be very clean and oiled, filled with 50 mm layers with enough compaction using a steel tamping bar. A minimumof 25 or 35 tamps are recommended per layer for a 100 or 150 mm mould. Once tamping each layer, the mould has to be lifted slightly for closing the each layer's top surface. The last layer should over fill the mould and it has to be trowelled off to level with mould top. The prepared cubes need to be protected at 20°C until the tripping of mould to avoid the impact of environmental conditions such as high and low temperatures. The cubes has to be placed into the curing tank after tripping and if the ambient temperature is very high, it is advised to place the fresh cubes in their mould and into the curing tank [21, 22]. The cubes surface should not be disturbed by any means while removing from the mould and washing out ofthe sample should be avoided. Table 4 lists the specifics and quantity of the basic materials used to create the specimen.

Mainly two type of incubation was used. First one is when the specimen is fully submerged in water for 7,14 and 21 days and the second one is when the specimen is kept out in the room temperature for 7,14 and 21 days after initial compression strength evaluation [23]. In the current study, evaluation of compression strength of

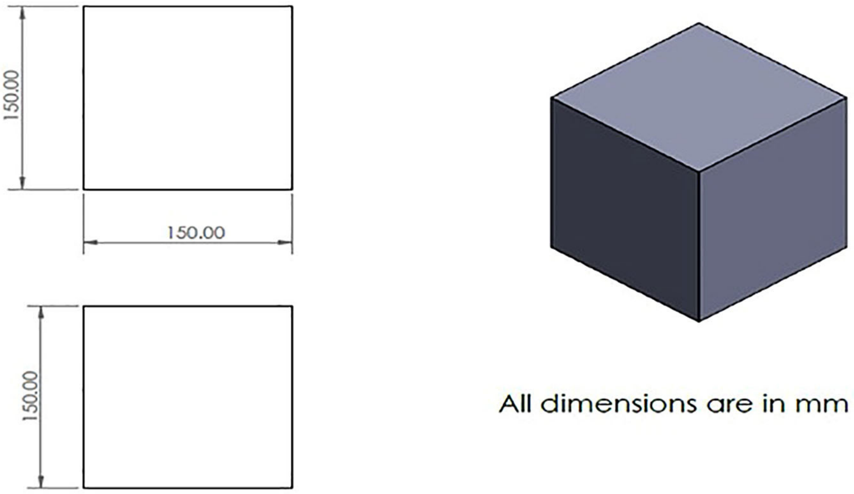

Figure 3: 2D views and 3D model of cube specimen.

Table 4: Particulars of raw material and it's quantity for specimen preparation.

S.NO	RAW MATERIAL	QUANTITY
1	Cement	24.48 kg
2	Coarse aggregate	39.546
3	Fine aggregate	85.716
4	W/C Ratio	4.07
5	Beads	6%

concrete cubes has been done in two different modes. The primary testing involves the testing of concrete with mixing of biomaterials with curing duration such as 7, 14 and 21 days. The secondary testing focus up on the increase or decrease of compression strength during the self healing period of 12 days after the initial curing duration for cracked concrete cube specimens. Figure 4 (a) shows the concrete mix and 4 (b), (c) represents the beads mixed.

The observed values of initial and final compression strength values have been tabulated for further analysis. The values are observed for its variations with respect to changes in input factors. Tables 5 and 6 shows the values of initial and final compression strength obtained. The experimental results obtained for the concrete cubes with different biomaterials at varying curing duration have been analyzed. The biomaterial Bacillus subtilis added to concrete mixture and cured for 7 days has shown compression strength of 70 MPa, but when it is allowed to cure for 14 and 21 days, the improvement in compression strength is remarkable with 100% (140 MPa) and 260% (252 MPa).The second biomaterial considered in the current study Bacillus Flexus have

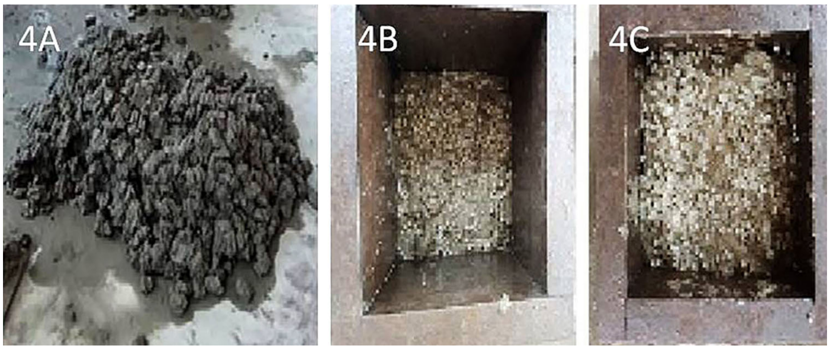

Figure 4: (a), (b) and (c) Incorporation of beads in concrete specimen.

Table 5: Initial compression strength of concrete specimens.

TRIAL NO	BIOMATERIAL	CURING DURATION (DAYS)	INITIAL CS (MPa)
1	1	1	70
2	1	2	140
3	1	3	252
4	2	1	113
5	2	2	142
6	2	3	113
7	3	1	100
8	3	2	155
9	3	3	172

Table 6: Final compression strength of cracked and self healed concrete specimens.

TRIAL NO	BIOMATERIAL	CURING DURATION (DAYS)	FINAL CS (MPa)
1	1	1	206
2	1	2	140
3	1	3	76
4	2	1	137
5	2	2	160
6	2	3	170
7	3	1	128
8	3	2	163
9	3	3	170

shown an initial compression strength of 113 MPa, which is 61.43% higher than the compression strength value obtained with Bacillus subtilis for 7 days of curing [24]. The increase in curing duration for this biomaterial have resulted with only 25.66% (142 MPa) increase in compression strength for 14 days of curing and when curing duration was extended to 21 days, the value of compression strength falls down to 113 MPa again. Tables 5 and 6 shows the values of initial and final compression strength of concrete specimen.

Bacillus Licheniformis, the third biomaterial considered in the study have shown 100 MPa compression strength at 7 days of curing which is 30% higher than Bacillus subtilis and 13% lower than Bacillus Flexus. When the curing duration is extended for 14 days and 21 days, the value of compression strength followed an increasing trend with 55% (155 MPa) and 72% (172 MPa) increase. From the critical analysis of experimental data obtained from evaluation of compression strength, the biomaterial Bacillus subtilis have shown both the lowest and highest values of compression strength when comparing to other biomaterials considered. After the cracking of specimens through compression strength test, the cube specimens have been allowed for self healing in the presence of biomaterial which has been added to concrete at initial stage [25]. The final compression strength have been evaluated to understand the potential of added biomaterial over concrete's compression strength and also its quick healing capacity after crack formation. The tabulated values show the increase or decrease in compression strength of every individual specimen. Figures 5, 6 and 7 (a), (b) shows the cracked and healed images of specimens incorporated with bacillus subtilis, bacillus flexusand bacillus licheniformis. As the

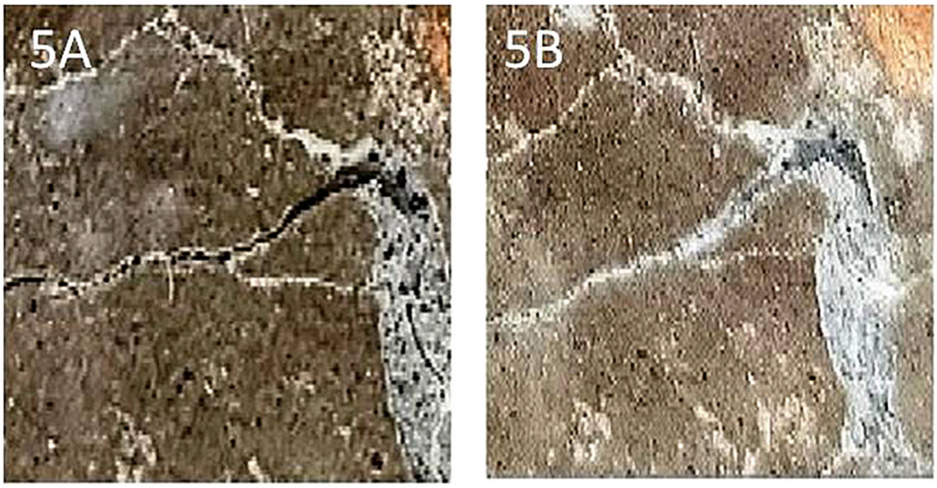

Figure 5: (a), (b) Crack image be fore and after healing of crack in specimen with bacillus subtilis.

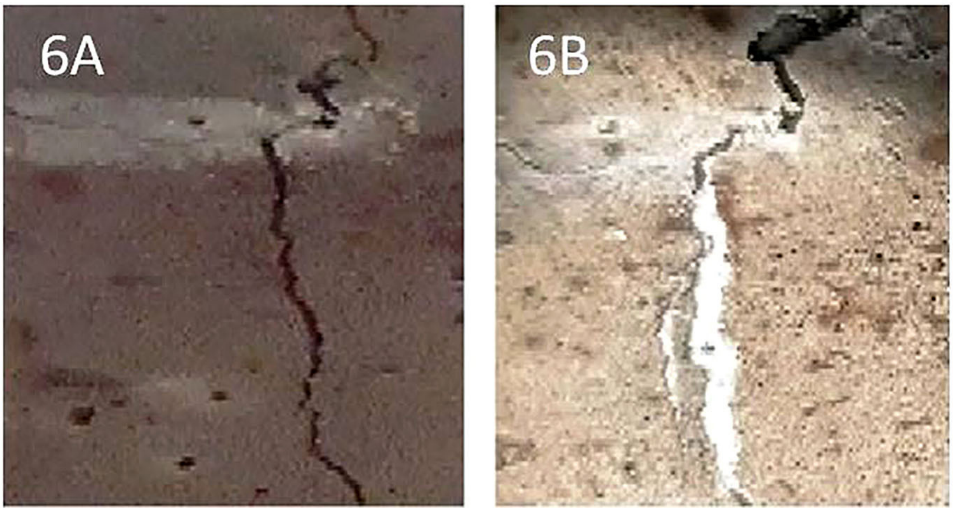

Figure 6: (a), (b) Crack image before and after healing of crack in specimen with bacillus flexus.

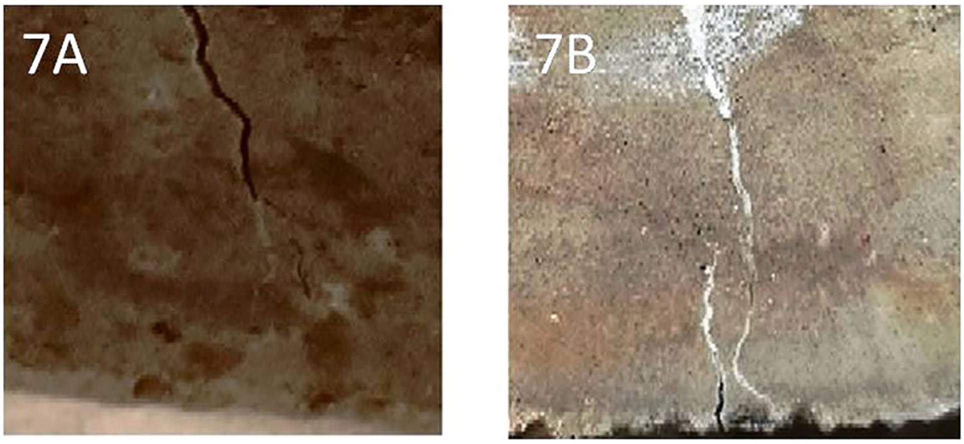

Figure 7: (a), (b) Crack image before and after healing of crack in specimen with bacillus licheniformis.

initial compressive strength decreases, there is a corresponding increase in biomaterial concentration across all three curing days, indicating a significant relationship between these variables.

Bacillus subtilis added specimen cured for 7, 14 and 21 days initially have been allowed for self healing for 12 days after compression testing. After self healing for 12 days of time, it is being observed that the specimen cured for 7 days initially have attained in compression strength of 194% (206 MPa) compared to the initial compression strength. But when the same biomaterial cured for 14 days initially has not shown any changes in value of compression strength and it remained with 140 MPa. But when the third specimen which has been cured for 21 days wastested for post compression strength, it shows a decrease of compression strength by 69.84% [26].

But for the other biomaterials considered in the study, the final compression strength was in both increasing and decreasing trend when there is an increase in curing duration. Bacillus Flexus biomaterial based concrete cube have shown an increase in compression strength by 21.23%, 12.6% and 50.44% with respect to compression strength values obtained at initial days of curing. For biomaterial Bacillus Licheniformis, the trend was both increasing and decreasing in nature [27]. The increase of compression strength was found to be 28% and 5.16% when the cube was allowed to cure for 7 days and 14 days initially. But for 21 days cured specimen, the compression test after healing period of 12 days was found to reduced by 1.16% only. Figure 8 shows the comparison of compression strength be forecracking and post healingof concrete specimen.

4.1. Signal to noise ratio – larger the better

Taguchi based experimental outcomes can be analyzed using appropriate signal to noise method to understand the combination of input factors which maximize, minimize or attain a target value of output response. The current research considers initial and final compression strength as the output response which is generally considered to be higher the better for exhibiting superior performance by concrete at diverse service conditions. Equation 1 shows the formula for finding the signal to noise ratio values for initial and final compression strength with higher the better characteristic.

$$SNR_{LargertheBetter} = -10 * \log\left(\sum(1/Y^2)/n\right) \tag{1}$$

Main effect plots (MEP) have been generated for both the output responses and also response table values high light the most influencing parameter for a particular output response. Figure 9 shows the MEP for initial compression strength.

The MEP for initial compression strength shown in figure recommends Bacillus Licheniformis with 21 days of curing (A3B3) for attaining higher initial compression strength and response table ranking indicates curing duration is the most influencing factor over initial compression strength. From experimental results for the proposed combination of input factors A3B3, the initial compression strength valueis 172 MPa which is actually higher than the average value of initial compression strength 142 MPa for Bacillus Licheniformis.The response table values and ranking of input factors for initial compression strength are shown in Table 7.

Similarly, the MEP for final compression strength suggests the combination of input factors (A2B2) Bacillus flexus with 26 days of curing and response table indicates the type of bacteria added to concrete at initial stage is the major significant factor over final compression strength than curing duration. From experimental results, the recommended combination has resulted with 160 MPa final compression strength which is actually

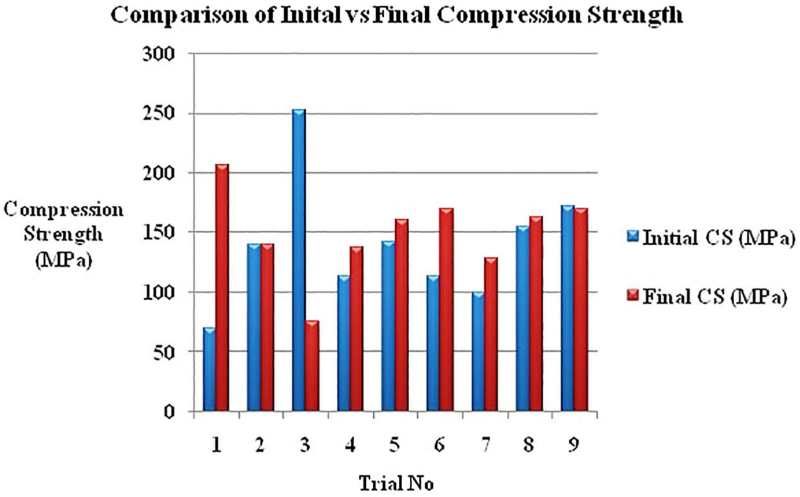

Figure 8: Comparison of compression strength after initial curing and post healing.

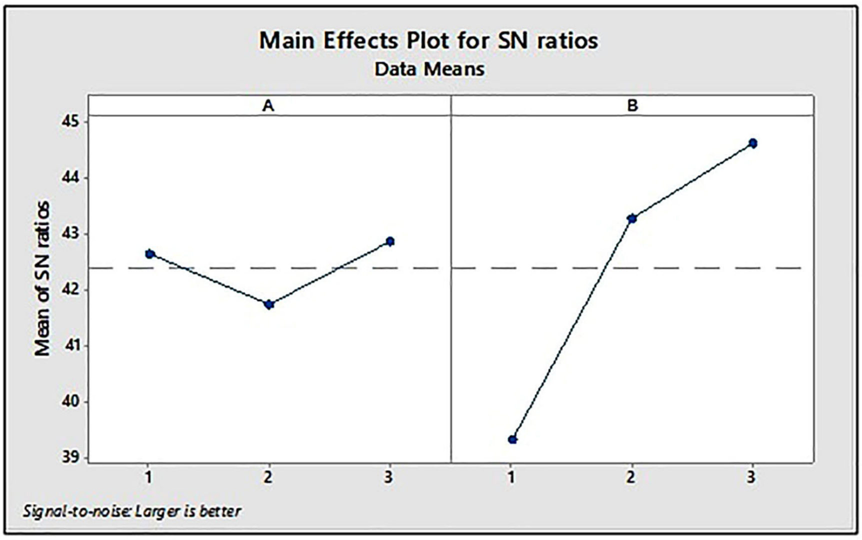

Figure 9: Main effect plot – initial compression strength.

Table 7: Response table for initial compression strength.

LEVEL	A	B
1	42.62	39.32
2	41.72	43.26
3	42.84	44.60
Delta	1.12	5.28
Rank	2	1

slightly higher than the average value of 155 MPa for bacillus flexus biomaterial. Table 8 shows the response table values and ranking of input factors for initial compression strength. The MEP for initial compression strength is shown in Figure 10.

Figure 11 and 12 represents surface plots generated for initial and final compression strength which shows the effect of input factor values over the output responses at different levels.

In addition to analyzing the experimental values through signal to noise ratio method, the output response may be targeted to a specific value through response optimizer in Mini tab 17.0. In case of initial compression strength, the average value of the experimental data set has been found as 140 MPa. By considering 140 MPa as

Table 8: Response table for final compression strength.

LEVEL	A	B
1	42.27	43.72
2	43.81	43.75
3	43.67	42.28
Delta	1.54	1.47
Rank	1	2

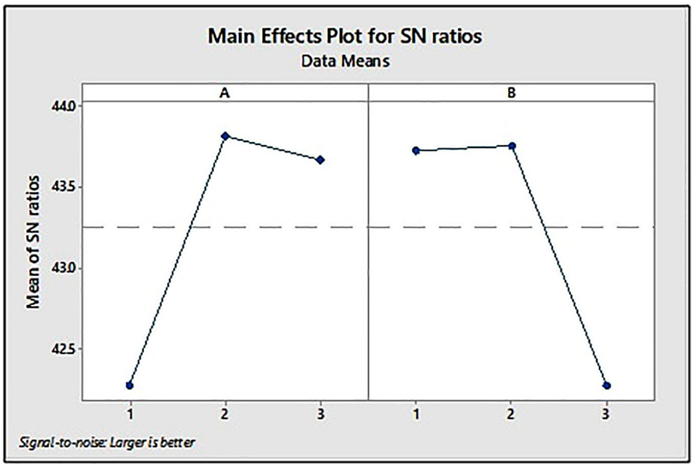

Figure 10: Main effect plot – final compression strength.

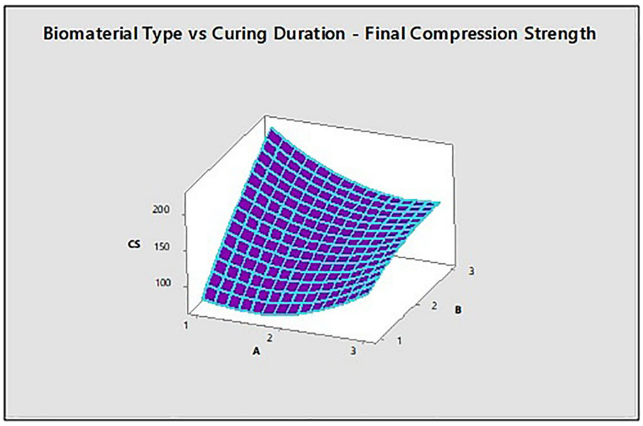

Figure 11: Surface plot for initial compression strength.

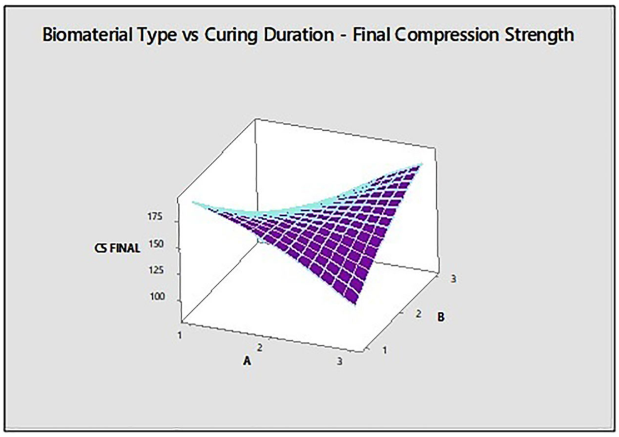

Figure 12: Surface plot for final compression strength.

initial target value with an uniform increment of 15 MPa and the maximum initial compression strength targeted is 260 MPa. Every targeted value has been verified for the factor combination, predicted value and desirability value [28]. From the analysis of targeted response, it is observed that with 155 MPa initial compression strength can be obtained with the biomaterial bacillus flexus at 19 days and 4 hours of curing duration. The predicted value for the proposed factor combination is 154.98 MPa and desirability value is 0.9998.Different target values may be fixed depending upon the functional requirement of concrete structure and predicted values may be evaluated through confirmation trials. Tables 9, 10 shows the targeted, predicted and desirability values for initial and final compression strength.

Figures 13 and 14 represent the response optimizer plot for targeted initial and final compression strength. Similarly, targeting the final compression strength with 150 MPa, it can be obtained with the biomaterial bacillus flexus at 31 days and 48 minutes of curing duration. The predicted value for the proposed factor combinationis 150.98 MPa and desirability value is 0.9985. But higher values such as 170, 180, 190, 200, 210, 220 and 230

Table 9: Targeted, predicted and desirability values for initial compression strength**.**

S.NO	A	B	INITIAL CS (MPa) TARGETED VALUES	INITIAL CS (MPa) PREDICTED VALUES	DESIRABILITY VALUE
1	2.5354	2.285	140	139.98	0.9998
2	**2**	**2.7374**	**155**	**154.98**	**0.9998**
3	1.7928	3	170	170	1.0000
4	1.5007	3	185	185	1.0000
5	1.2689	3	200	200	1.0000
6	1.0707	3	215	215	1.0000
7	1	3	230	220.83	0.9427
8	1	3	245	220.83	0.8619
9	1	3	260	220.83	0.7936

Table 10: Targeted, predicted and desirability values for final compression strength.

S.NO	A	B	FINAL CS (MPa) TARGETED VALUES	FINAL CS (MPa) PREDICTED VALUES	DESIRABILITY VALUE
1	**2**	**2.7172**	**150**	**150.08**	**0.9985**
2	1.9989	1.9989	160	160.02	0.9993
3	1.7887	1	170	170	1.0000
4	1.4563	1	180	180	1.0000
5	1.0337	1	190	190	1.0000
6	1	1	200	190.66	0.9247
7	1	1	210	190.66	0.8557
8	1	1	220	190.66	0.7963
9	1	1	230	190.66	0.7445

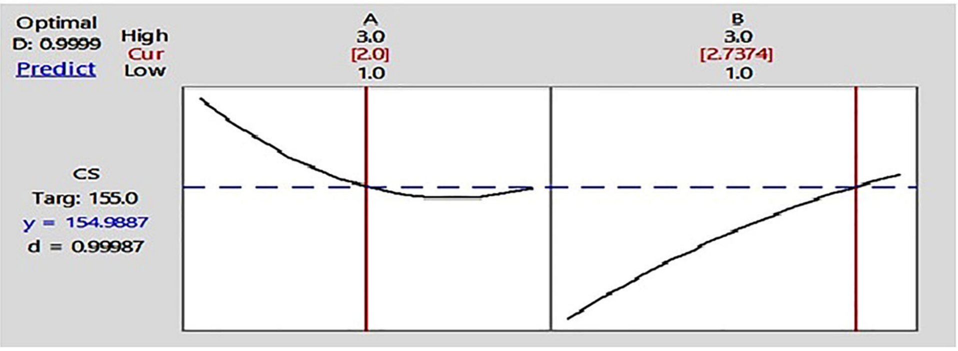

Figure 13: Response optimizer plot for targeted initial compression strength.

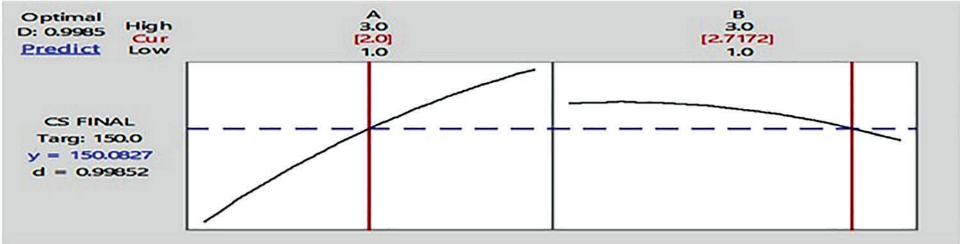

Figure 14: Response optimizer plot for targeted final compression strength.

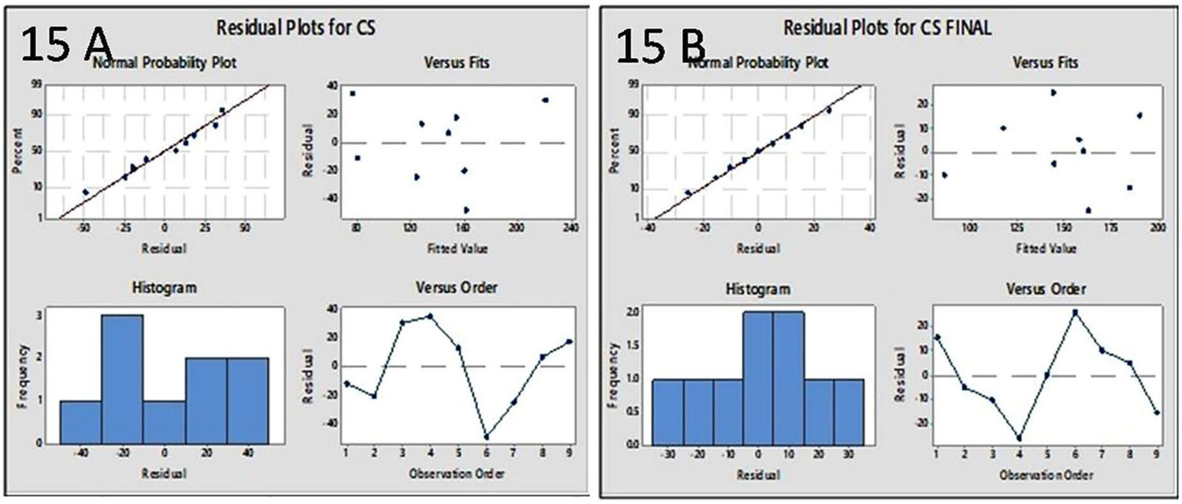

Figure 15: Residual plots for initial and final compression strength.

MPa can also be obtained at different factor combinations at standard curing duration values with different predicted and desirability values. Tables 9, 10 shows the targeted, predicted and desirability values for initial and final compression strength.

The Figure 15 (a) and (b) shows the normal probability plot for initial and final compression strength. In both the cases, the data points are very closer with regression line and outliers are very less.

5. SUPERVISED MACHINE LEARNING

A sub set of machine learning and artificial intelligence is supervised learning, commonly referred to as supervised machine learning. The current study considers classification based machine learning algorithms by labeling the experimental dataset as class 1 andclass 2. The current study considers two experimental outcomes such as initial and final compression strength, where based upon the average value of the experimental data set it has been classified. Table 11 shows the conditions for initial data set labeling.

Based upon the conditions applied over the initial data set as shown in table, initial compression strength consists of 5 class 1 labeled data and 4 class 2 labeled data from a total of 9 instances. Similarly for final compression strength, 4 class 1 labeled data and 5 class 2 labeled data is obtained from the applied conditions. The initial data set has been trained and tested using decision tree algorithm with training-testing split of 80:20 for attaining highly accurate results. Figure shows the machine learning work flow for the current research and Orange data mining software version 3.2.2 has been utilized for applying machine learning algorithm over the experimental data set. Figure 16 shows the supervised machine learning work flow in Orange software.

Decision tree algorithm is a supervised ML technique used for both classification and regression based tasks. It is predictive modeling algorithm which has a flow chart like structure to arrive decisions based upon the input data. It divides data in the form of branches and reveals the node outcomes.

Figure 17 shows the tree structure for initial compression strength which consists of 5 nodes and 3 leaves. From tree structure, it is understood that curing duration is highly significant than biomaterial type added to

Table 11: Conditions for labeling initial dataset.

S.NO	OUTPUT RESPONSE	RANGE	LABEL	NO OF INSTANCES
1	Initial Compression Strength	0–140 Mpa	Class 1	5
		141–252 Mpa	Class 2	4
2	Final Compression Strength	0–150 Mpa	Class 1	4
		151–206 Mpa	Class 2	5

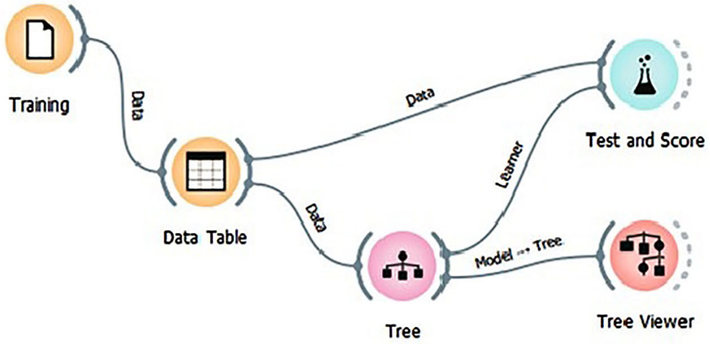

Figure 16: Supervised machine learning workflow.

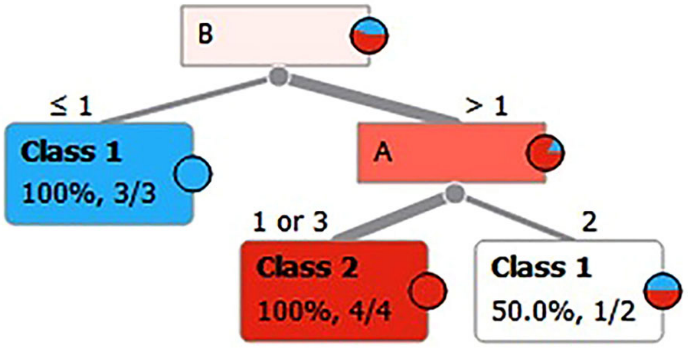

Figure 17: Decision tree structure for initial compression strength.

Table 12: Evaluation metrics for initial compression strength.

MODEL	AUC	CA	F1	PRECISION	RECALL
Tree	0.975	0.8889	0.8889	0.9111	0.8889

concrete mix. Curing duration is the root node and type of material is the decision node, this has a good correlation with the response table ranking obtained through signal to noise ratio method. On the other hand, for obtaining class 2 labelled initial compression strength values the tree structure recommends considering the curing duration higher than level 1 (i.e either 14 or 21 days) and either biomaterial Bacillus subtilis or Bacillus Licheniformis may be considered. The evaluation metric such as area under curve is 0.975 and 88.9% classification accuracy has resulted for the current analysis. Table 12 highlights the values of evaluation metrics for initial compression strength.

Similarly, Figure 18 shows the tree structure for final compression strength which also consists of 5 nodes and 3 leaves. Type of biomaterial added to concrete mix at initial stage is the highly influencing factor than curing duration as per the tree structure. Type of biomaterial is the root node and curing duration is the decision node, this also in good agreement with the response table ranking. For obtaining higher final compression

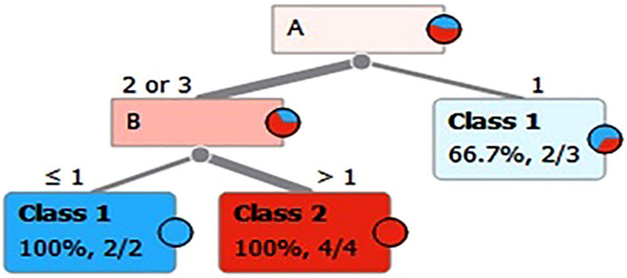

Figure 18: Decision tree structure for final compression strength.

Table 13: Evaluation metrics for final compression strength.

MODEL	AUC	CA	F1	PRECISION	RECALL
Tree	0.950	0.8889	0.8889	0.9111	0.8889

strength class 2 labeled values the tree structure recommends considering biomaterials Bacillus Flexus or Bacillus Licheniformis. In terms of curing duration after specimen cracking through compression testing, more than 19 days of curing is recommended for obtaining higher final compression strength values. The evaluation metrics such as area under curve is 0.950 and 88.9% classification accuracy has resulted for the current analysis. Table 13 highlights the values of evaluation metrics for initial compression strength

6. CONCLUSION

The current study focused upon optimizing the type of biomaterial added to concrete mix and number of curing days for enhancement of initial and final compression strength of concrete structures. The study has produced nine concrete samples by adding biomaterials such as Bacillus subtilis, Bacillus flexus and Bacillus licheniformis which are allowed to cure for 7, 14 and 21 days. The major findings of the study are highlighted below.

- Concrete cube specimen of 150 mm dimensions has been prepared with addition of biomaterials at initial stage and allowed to cure for 7, 14 and 21 days in water medium.
- The evaluation of initial compression strength for the cured cube specimen reveals the concrete mix with Bacillus subtilis with 7 days of curing exhibited low strength (70 MPa) and increased compression strength (252 MPa – 260 % increase) is attained when allowed for 21 days of curing.
- Similarly, the initial compression strength exhibited by other biomaterial ssuch as Bacillus flexus are in fluctuating manner and Bacillus licheniformis is in increasing trend.
- The determination of final compression strength after 12 days of curing the cracked specimen in open atmosphere has been carried out and it is being observed that Bacillus subtilis based specimen cured for initial 7 days have attained 206 MPa which is 194% higher than its initial value, but the final compression strength of initial 21 days cured specimen have exhibited 69.84 % lesser compression strength.
- The experimental results have been analyzed using signal to noise ratio method – higher the better characteristic. A3B3 (Bacillus licheniformis with 21 days of curing) is the recommended combination for attaining higher initial compression strength and A2B2 (Bacillus flexus with 26 days of curing) is the suggested factor combination for higher final compression strength.
- From response table rankings, curing duration is highly significant over initial compression strength and biomaterial type has high influence over final compression strength.
- From average to maximum values of both compression strength has been taken and through desirability analysis the optimum factor levels has been identified.
- For initial compression strength of 155 MPa, the biomaterial bacillus flexus at 19 days and 4 hours of curing duration will be optimum. Similarly for 150 MPa final compression strength, it can be obtained with the biomaterial bacillus flexus at 31 days and 48 minutes of curing duration.
- The initial and final compression strength values have been labeled as class1, class using their average values and analyzed using decision tree algorithm.

- The prediction of significant factor and optimal parameter combination through decision tree algorithm are in good accordance with main effect plot and response table rankings.
- SEM analysis of cracked and healed specimens will give a better insight about crack morphology.

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