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Mathematical Model for Predicting Stress-Strain Behaviour of Bacterial Concrete

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Abstract:- Bacillus subtilus, a mineral precipitating microorganism, when introduced into concrete produces calcium carbonate crystals which seals the micro cracks and pores in the concrete. This process imparts high strength and durability to bacteria treated concrete along with enhancement in other mechanical properties. In order to study one such mechanical property, the stress-strain behavior of bacterial concrete, appropriate analytic stress-strain model is established that capture the real (observable) behavior. In this paper, an attempt is made to develop a mathematical model for predicting the stress-strain behaviour of bacteria induced high strength concrete. This research mainly aims at utilizing the best attributes of earlier models and proposes a new stress-strain model that can well represent the overall stress-strain behavior of high strength bacterial concrete mixes. After obtaining the stress-strain behavior of controlled and bacterial concrete experimentally, empirical equations are developed to represent uni-axial stress-strain behavior of controlled and bacterial concrete mixes. From these empirical equations, theoretical stresses for controlled and bacterial concrete are calculated and compared with experimental values. The proposed equations have shown good correlation with experimental values validating the mathematical model developed. The proposed empirical equations can be used as stress block in analyzing the flexural behavior of controlled and bacterial concrete.

Keywords:-Bacterial concrete, stress-strain curves, Saenz model, Bacillus subtilus, toughness.

I. INTRODUCTION

For decades, many researchers developed empirical and semi-empirical stress-strain relationships to describe the behavior of concrete in compression. The better the stress-strain model, the more reliable is the estimate of strength and deformation behavior of concrete structural members. The compressive stress-strain behavior of concrete is a significant issue in the flexural analysis of reinforced concrete beams and columns. The stress-strain curve of concrete is also useful for investigating the ductility of concrete. Moreover, the total area under the stress-strain curve can represent the amount of energy absorbed by the specimen under loading. A stress - strain curve is a graph obtained by plotting the values of stresses and strains obtained by testing cylinders of standard size made with concrete under uni-axial compression. It is observed from the stress-strain plots that, no portion of the curves is in the form of a straight line even though the stress strain relation for cement paste and aggregate when tested individually is practically linear. In concrete the rate of increase of stress is less than that of increase in strain because of the formation of micro cracks, between the interfaces of the aggregate and the cement paste. Thus the stress strain curve is not linear. In controlled concrete, the value of stress is maximum corresponding to a strain of about 0.002 and further goes on decreasing with the increasing strain, giving a dropping curve till it terminates at ultimate crushing strain. After obtaining the stress-strain behavior of controlled and bacterial concrete mixes experimentally, an attempt is made by validating it against the analytical stress-strain curves for controlled and bacterial concrete mixes.

II. EXPERIMENTAL PROGRAMME

In this paper, Stress-Strain behavior of controlled and bacterial concrete of high strength grades (M60 and M80) are studied. The test is carried out on cylindrical specimens of diameter 150 mm and height 300 mm. Total 12 cylinders of standard size are cast with the specified controlled and bacterial concrete mixes and tested in axial compression under strain control and stress-strain behavior is observed by plotting stresses against strains.

III. TEST PROCEDURE

The capped cylindrical specimen is attached with setup having two dial gauges and is placed on the movable cross head of the testing machine and centered correctly. The dial gauges having least count of 0.02mm is used. The specimen is placed in a computer controlled universal testing machine (UTM) of 3000 kN capacity. For satisfactory recording of strain, the cross head movement of 0.02 mm per second is suggested by the previous researchers. The specimens are tested under strain control under uni-axial compression as per IS : 516-1999 to get the stress-strain characteristics.

IV. MATHEMATICAL MODELING FOR STRESS-STRAIN BEHAVIOUR

A. Mathematical Models available for Stress-Strain behaviour of Concrete

Many models were developed for the Stress-Strain behaviour prediction of concrete by many researchers. Some models are considered below.

1) **Desayi's and Krishnan's model(1964)**

This model is a derivation from Saenz's original equation.

For normal strength concrete, stress-strain relationship is given by

$$f = \frac{Ax}{1+Bx^2}$$

where f = The Normalized stress (f / f_o) ; x = Normalized strain ($\in / \in_o$) and

A, B are the constants and they can be found out by using boundary conditions. This model is valid only to ascending portion of stress-strain curve.

2) **Modified Saenz Model (1964)**

Considering the limitation of analytical equation proposed by Desayi et al, Saenz proposed a model by taking into

account both the ascending and descending portions of the stress-strain curve. This model is in the form of

$$y = \frac{Ax}{1+Bx+Cx^2}$$

Where $y = \sigma / \sigma_u$ and $x = \in / \in_u$

3) **Hognestad Model (1955)**

For Normal strength concrete up to ascending portion:

The stress-strain model is $f_c = f_c' \left\{ 2(\in / \in_o) - (\in / \in_o)^2 \right\}$

f_c' = compressive strength ; $\in_o$ = strain at peak stress = 0.0078 (f_c') $^{1/4}$

4) **Wang *et al*, Model (1978)**

The model used by Wang *et al*. is in the form of

$$f_c = f_c' \left\{ \frac{A(\in / \in_o) + B(\in / \in_o)^2}{1 + C(\in / \in_o) + D(\in / \in_o)^2} \right\}$$

However instead of using one set of the coefficients A, B, C, and D to generate the complete curve, Wang *et al*, used two sets of coefficients – one for the ascending branch and the other to the descending branch. The respective coefficients being obtained from the relevant boundary conditions assigned to each part of the curve.

5) **Carriera and Chu Model (1985)**

This model is in the form of

$$f_c = f_c' \left\{ \frac{\beta(\in / \in_o)}{\beta - 1 + (\in / \in_o)^{\beta}} \right\}$$

In which $\beta = 1 - \left(f_c' / \in_o E_{it} \right)$

where f_c'= cylinder ultimate compressive strength and

$\in_o$ = strain at ultimate stress; E_{it} = Initial tangent modulus

B. Proposed Model for Stress-Strain behavior of bacterial concrete

Of all the above stress-strain models, simplified and the modified single variable polynomial equations based on modified Saenz's model that fits with developed normalized stress-strain curves seems to be valid for both ascending and descending portions of the curve. The developed equations for ascending and descending portions of analytical stress-strain curve are in the form of

$$y = \frac{Ax}{1 + Bx + Cx^2} \quad \text{and} \quad y = \frac{Dx}{1 + Ex + Fx^2}$$

where y is the stress at any level ; x is the corresponding strain at that level; A, B, C are the constants for ascending portion and D, E, F are the constants for descending portion of analytical stress-strain curve. Similarly, the equations for ascending and descending portions of non-dimensional stress-strain curve are in the form of

$$f / f_o = A^1(\in / \in_o) \ / (1+ B^1(\in / \in_o) + C^1 (\in / \in_o)^2) \ \text{and}$$

$$f / f_o = D^1 (\in / \in_o) + / (1+ E^1 (\in / \in_o) + F^1(\in / \in_o)^2)$$

A^1, B^1, C^1 are the constants for ascending portion and D^1, E^1, F^1 are the constants for descending portion of non-dimensional stress-strain curve. f / f_o is normalized stress(stress ratio) and $\in / \in_o$ is the normalized strain (strain ratio).Constants are evaluated based on the boundary conditions of normalized stress-strain curves for both controlled and bacterial concrete.

Boundary conditions for ascending and descending portions of stress-strain curves are,

(1) At the origin the ratio of stresses and strains are zero

i.*e.* at $(\in / \in_o)= 0,(f / f_o) = 0$

(2) The strain ratio $(\in / \in_o)$ and stress ratio at the peak of the non-dimensional stress-strain curve is unity.

i.*e* at $(\in / \in_o)= 1$, $(f / f_o) = 1$

(3) The slope of non-dimensional stress-strain curve at the peak is zero

i.*e* at $(\in / \in_o)=1.0$, $d(f / f_o) / d(\in / \in_o)= 0$

(4) At 85% stress ratio, the corresponding values of strain ratio is recorded

i.*e* at $(f / f_o) = 0.85$, $(\in / \in_o)$=strain ratio corresponding to 0.85 stress ratio

where f_o - peak stress and $\in_o$ - strain at peak stress ; f and $\in$ corresponds to stress and strain values at any other point.Boundary conditions (1), (2) and (3) are for determining the constants A^1, B^1, C^1 in the ascending portion of the normalized stress-strain curve and (2), (3) and (4) are for determining the constants D^1, E^1, F^1in the descending portion of the curve.. Corresponding A, B, **C** constants for ascending portion and D, E, F constants for descending portion of analytical stress-strain curve are then evaluated using equations

$$A= A^1 (f_o \ / \in_o), \ B= B^1(1/ \in_o) \ \text{and} \ C= C^1 (1/ \in_o)^2$$

$$D= D^1 (f_o \ / \in_o), \ E= E^1(1/ \in_o) \ \text{and} \ F= F^1 (1/ \in_o)^2$$

Ultimately analytical equations giving the complete stress-strain behavior are developed for high strength grades of controlled and bacterial concretes.

C. Development of Analytical equations

Table 1: Constants for ascending and descending portions of non-dimensional stress-strain curve

Grade of Concrete	Controlled Concrete						Bacterial Concrete					
	Ascending portion Constants			Descending portion constants			Ascending portion Constants			Descending portion constants		
	A^1	B^1	C^1	D^1	E^1	F^1	A^1	B^1	C^1	D^1	E^1	F^1
M60	1.20	-0.80	1	1.87	-0.13	1	0.56	-1.44	1	1.25	-0.75	1
M80	0.60	-1.40	1	1.87	-0.13	1	0.63	-1.37	1	1.51	-0.49	1

Table 2: Analytical equations for non-dimensional stress-strain curve

Grade of Concrete	Controlled Concrete		Bacterial Concrete	
	Ascending portion	Descending portion	Ascending portion	Descending portion
M60	$y = \frac{1.20x}{1 - 0.80x + x^2}$	$y = \frac{1.87x}{1 - 0.13x + x^2}$	$y = \frac{0.56x}{1 - 1.44x + x^2}$	$y = \frac{1.25x}{1 - 0.75x + x^2}$
M80	$y = \frac{0.6x}{1 - 1.4x + x^2}$	$y = \frac{1.87x}{1 - 0.13x + x^2}$	$y = \frac{0.63x}{1 - 1.37x + x^2}$	$y = \frac{1.51x}{1 - 0.49x + x^2}$

Table 3: Peak stress values and their corresponding strains

Grade of Concrete	Controlled Concrete		Bacterial Concrete	
	Peak Stress	Corresponding	Peak Stress	Corresponding

	f_o	strain at peak stress $\in_o$	f_o	strain at peak stress $\in_o$
M60	72.61	0.0023	94.21	0.0023
M80	98.50	0.0020	113.00	0.0024

Table 4: Constants for ascending and descending portions of theoretical stress-strain curve

Grade of Concrete	Controlled Concrete					
	Ascending portion Constants			Descending portion constants		
	A	B	C	D	E	F
M60	37832	-326	189036	59096	-230	189036
M80	29998	-700	250000	92545	-65	250000
	Bacterial Concrete					
M60	23007	-539	189036	51057	-317	189036
M80	29693	-745	250000	71227	-365	250000

D. Calculation of Theoretical Stresses using proposed Analytical Equations

Theoretical stresses have been calculated using proposed empirical equations for controlled and bacterial concrete which are derived from modified Saenz's model in the form of

$$y = \frac{Ax}{1 + Bx + Cx^2}$$

Where y is the stress at any level ; x is the corresponding strain at that level

After developing empirical equations for stress-strain curves of controlled and bacterial concrete, theoretical values of stresses are calculated at different values of strains in concrete based on the developed empirical equations. These theoretical stress-strain curves are compared with experimental stress-strain curves and found that, theoretical stress-strain curves have shown good correlation with experimental stress-strain curves for all grades of controlled and bacterial concrete mixes.

E. Modulus of Toughness and Elasticity

Toughness is the ability of a material to counteract crack propagation by dissipating deformation energy. Toughness can be determined by measuring the area (i.e., by taking the integral) underneath the stress-strain curve. The area covered under stress strain curve is called toughness. The area up to the yield point is termed the modulus of resilience, and the total area up to fracture is termed the modulus of toughness. The modulus of resilience is then the quantity of energy the material can absorb without suffering damage. Similarly, the modulus of toughness is the energy needed to completely fracture the material. Materials showing good impact resistance are generally those with high moduli of toughness. The slope of the stress-strain curves gives the modulus of elasticity.

Table 5: Modulus of Toughness and Elasticity

Grade of Concrete	Modulus of Toughness (MPa) (from Stress-Strain curves)		Modulus of Elasticity (GPa)	
	Controlled Concrete	Bacterial Concrete	Controlled Concrete	Bacterial Concrete
M60	0.136	0.165	38.7	44.1
M80	0.182	0.215	43.6	50.9

V. TEST RESULTS

Table 6: Experimental Stress - Strain values of High strength grade concrete (M60)

Controlled Concrete				Bacterial Concrete			
Strain	Stress, MPa	Normalized Strain	Normalized Stress	Strain	Stress, MPa	Normalized Strain	Normalized Stress
0	0	0.00	0.00	0	0	0.00	0.00
0.0001	3.27	0.04	0.05	0.0001	2.83	0.04	0.03
0.0002	6.41	0.09	0.09	0.0001	5.66	0.04	0.06
0.0003	9.01	0.13	0.12	0.0002	8.49	0.09	0.09
0.0004	12.98	0.17	0.18	0.0003	11.32	0.13	0.12
0.0005	15.32	0.22	0.21	0.0003	14.15	0.13	0.15

0.0006	18.65	0.26	0.26	0.0004	16.99	0.17	0.18
0.0007	21.10	0.30	0.29	0.0004	19.82	0.17	0.21
0.0008	24.55	0.35	0.34	0.0005	23.20	0.22	0.25
0.0009	28.56	0.39	0.39	0.0006	25.70	0.26	0.27
0.0010	36.00	0.43	0.50	0.0007	31.00	0.30	0.33
0.0011	38.80	0.48	0.53	0.0008	34.60	0.35	0.37
0.0012	42.30	0.52	0.58	0.0010	40.00	0.43	0.42
0.0014	47.60	0.61	0.66	0.0011	46.70	0.48	0.50
0.0016	61.00	0.70	0.84	0.0012	54.90	0.52	0.58
0.0023	72.61	1.00	1.00	0.0014	61.00	0.61	0.65
0.0027	65.70	1.17	0.90	0.0015	82.40	0.65	0.87
0.0033	36.80	1.43	0.51	0.0023	94.21	1.00	1.00
0.0034	30.30	1.48	0.42	0.0033	51.00	1.43	0.54
0.0035	29.15	1.52	0.40	0.0035	36.08	1.52	0.38

Table 7: Experimental Stress - Strain values of High strength grade concrete (M80)

Controlled Concrete				Bacterial Concrete			
Strain	Stress, MPa	Normalized Strain	Normalized Stress	Strain	Stress, MPa	Normalized Strain	Normalized Stress
0	0	0	0	0	0	0	0
0.0001	2.54	0.05	0.03	0.0001	2.11	0.04	0.02
0.0003	6.13	0.15	0.06	0.0001	3.06	0.04	0.03
0.0003	11.20	0.15	0.11	0.0002	4.50	0.08	0.04
0.0005	14.69	0.25	0.15	0.0003	7.11	0.13	0.06
0.0006	18.91	0.30	0.19	0.0003	9.08	0.13	0.08
0.0006	21.63	0.30	0.22	0.0004	13.33	0.17	0.12
0.0007	25.44	0.35	0.26	0.0004	18.64	0.17	0.16
0.0008	32.59	0.40	0.33	0.0005	25.54	0.21	0.23
0.0009	36.33	0.45	0.37	0.0006	36.11	0.25	0.32
0.0009	41.25	0.45	0.42	0.0007	40.99	0.29	0.36
0.0010	48.99	0.50	0.50	0.0008	53.28	0.33	0.47
0.0011	55.09	0.55	0.56	0.0010	61.01	0.42	0.54
0.0012	67.32	0.60	0.68	0.0014	81.30	0.58	0.72
0.0016	85.40	0.80	0.87	0.0016	94.10	0.67	0.83
0.0020	98.50	1.00	1.00	0.0018	104.40	0.75	0.92
0.0033	70.30	1.65	0.71	0.0022	107.40	0.92	0.95
0.0036	36.80	1.80	0.37	0.0024	113.00	1.00	1.00
0.0034	30.30	1.70	0.31	0.0036	41.60	1.50	0.37
0.0037	29.15	1.85	0.30	0.0038	20.20	1.58	0.18

Table 8: Experimental and Theoretical non-dimensional Stress - Strain values of High strength grade concrete (M60)

Controlled Concrete			Bacterial Concrete		
Normalized Strain	Experimental Normalized Stress	Theoretical Normalized Stress	Normalized Strain	Experimental Normalized Stress	Theoretical Normalized Stress
0.00	0.00	0.00	0.00	0.00	0.00
0.04	0.05	0.05	0.04	0.03	0.03
0.09	0.09	0.12	0.04	0.06	0.03
0.13	0.12	0.14	0.09	0.09	0.08
0.17	0.18	0.14	0.13	0.12	0.12
0.22	0.21	0.27	0.13	0.15	0.12
0.26	0.26	0.27	0.17	0.18	0.16
0.30	0.29	0.33	0.17	0.21	0.16
0.35	0.34	0.41	0.22	0.25	0.22
0.39	0.39	0.37	0.26	0.27	0.27

0.43	0.50	0.52	0.30	0.33	0.32
0.48	0.53	0.59	0.35	0.37	0.39
0.52	0.58	0.64	0.43	0.42	0.50
0.61	0.66	0.73	0.48	0.50	0.57
0.70	0.84	0.91	0.52	0.58	0.63
1.00	1.00	1.00	0.61	0.65	0.75
1.17	0.90	0.85	0.65	0.87	0.80
1.43	0.51	0.55	1.00	1.00	1.00
1.48	0.42	0.40	1.43	0.54	0.55
1.52	0.40	0.38	1.52	0.38	0.31
0.00	0.00	0.00	0.00	0.00	0.00

Table 9: Experimental and Theoretical non-dimensional Stress - Strain valuesof High strength grade concrete (M80)

Controlled Concrete			Bacterial Concrete		
Normalized Strain	Experimental Normalized Stress	Theoretical Normalized Stress	Normalized Strain	Experimental Normalized Stress	Theoretical Normalized Stress
0	0	0.00	0	0	0.00
0.05	0.03	0.03	0.04	0.02	0.02
0.15	0.06	0.11	0.04	0.03	0.02
0.15	0.11	0.11	0.08	0.04	0.05
0.25	0.15	0.21	0.13	0.06	0.08
0.30	0.19	0.27	0.13	0.08	0.08
0.30	0.22	0.27	0.17	0.12	0.11
0.35	0.26	0.33	0.17	0.16	0.11
0.40	0.33	0.40	0.21	0.23	0.15
0.45	0.37	0.47	0.25	0.32	0.18
0.45	0.42	0.47	0.29	0.36	0.23
0.50	0.50	0.55	0.33	0.47	0.27
0.55	0.56	0.62	0.42	0.54	0.39
0.60	0.68	0.69	0.58	0.72	0.63
0.80	0.87	0.92	0.67	0.83	0.76
1.00	1.00	1.00	0.75	0.92	0.86
1.65	0.71	0.77	0.92	0.95	0.99
1.70	0.37	0.40	1.00	1.00	1.00
1.70	0.31	0.32	1.50	0.37	0.33
1.85	0.30	0.33	1.58	0.18	0.17

Table 10: Experimental and Theoretical Stress - Strain values of High strength grade concrete (M60)

Controlled Concrete			Bacterial Concrete		
Strain	Experimental Stress, MPa	Theoretical Stress, MPa	Strain	Experimental Stress, MPa	Theoretical Stress, MPa
0	0	0	0	0	0
0.0001	3.27	3.91	0.0001	2.83	2.53
0.0002	6.41	8.02	0.0001	5.66	5.53
0.0003	9.01	12.29	0.0002	8.49	8.32
0.0004	12.98	16.66	0.0003	11.32	10.36
0.0005	15.32	21.06	0.0003	14.15	12.36
0.0006	18.65	25.41	0.0004	16.99	16.64
0.0007	21.1	29.65	0.0004	19.82	21.64
0.0008	24.55	33.7	0.0005	23.2	25.13
0.0009	28.56	37.5	0.0006	25.7	28.78
0.001	36	41	0.0007	31	32.54
0.0011	38.8	44.15	0.0008	34.6	36.34
0.0012	42.3	46.92	0.001	40	43.75

0.00134	47.6	51.31	0.0011	46.7	47.19
0.0016	61	59.5	0.0012	54.9	50.37
0.0023	72.61	69.6	0.0014	65.6	64.7
0.0027	65.7	65.3	0.00161	82.4	80.3
0.0033	36.8	47.24	0.0023	94.21	92.4
0.0034	30.3	42.3	0.0033	51	53.5
0.0035	29.15	34.4	0.0035	36.08	38.59

Table 11: Experimental and Theoretical Stress - Strain values of High strength grade concrete (M80)

Controlled Concrete			Bacterial Concrete		
Strain	Experimental Stress, MPa	Theoretical Stress, MPa	Strain	Experimental Stress, MPa	Theoretical Stress, MPa
0	0	0	0	0	0
0.0001	2.54	3.17	0.0001	2.11	2.53
0.0003	6.13	10.91	0.0001	3.06	5.53
0.0003	11.2	10.91	0.0002	4.5	7.32
0.0005	14.69	20.74	0.0003	7.11	10.36
0.0006	18.91	26.46	0.0003	9.08	11.36
0.0006	21.63	26.46	0.0004	13.33	14.64
0.0007	25.44	32.7	0.0004	18.64	21.64
0.0008	32.59	39.4	0.0005	25.54	25.13
0.0009	36.33	46.45	0.0006	36.11	38.78
0.0009	41.25	46.45	0.0007	40.99	32.54
0.001	48.99	53.73	0.0009	53.28	56.34
0.0011	55.09	61.04	0.001	61.01	63.75
0.0012	67.32	68.19	0.00112	68	68.2
0.0016	85.4	90.92	0.00139	82.1	84
0.0022	98.5	98.5	0.00176	100.5	94.2
0.00283	70.3	69.04	0.00202	109.7	103.8
0.00337	36.8	42.3	0.00243	113	109.3
0.00351	30.3	29.54	0.003	92.11	93.48
			0.0036	41.6	39.73

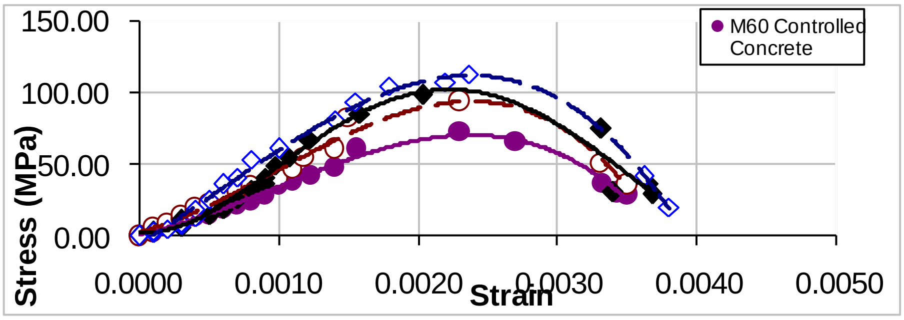

Fig 1: Stress- Strain Curves

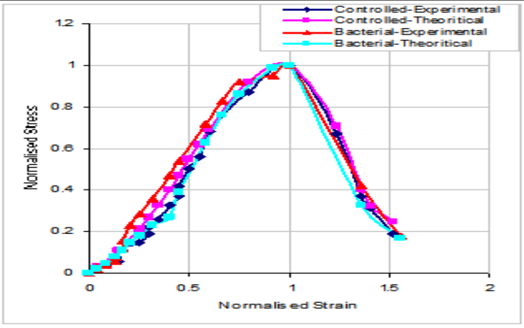

Fig 2: Graph showing Theoretical and Experimental Experimental non-dimensional stress strain values of controlled and and bacterial concrete in High strength grade concrete (M60) (M80)

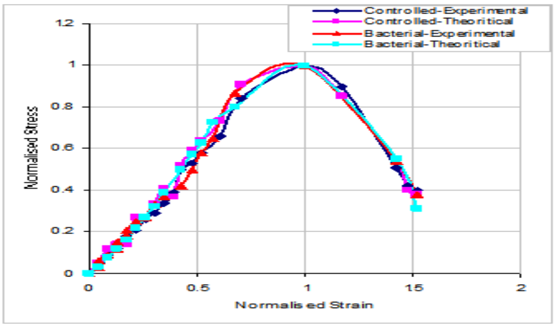

Fig 3: Graph showing Theoretical and non-dimensional stress strain values of controlled bacterial concrete High strength grade concrete

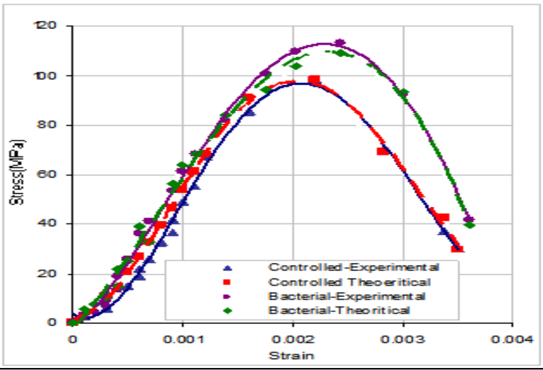

Fig 4: Graph showing Experimental and Theoretical Theoretical stress strain values of controlled and bacterial concrete High strength grade concrete (M60) concrete in

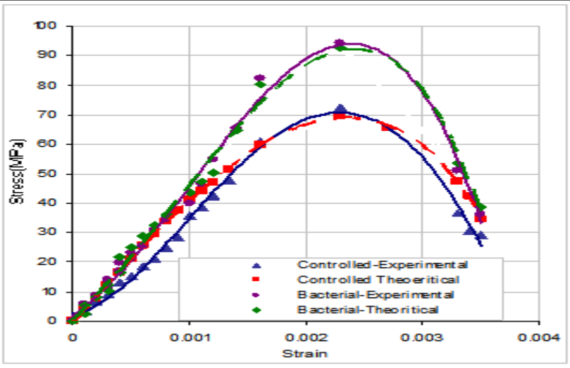

Figure 5: Graph showing Experimental and stress strain values of controlled and bacterial in High strength grade concrete (M80)

VI. DISCUSSIONS

From experimental non- dimensional stress-strain data, the theoretical non dimensional stress – strain data is generated. There is a good agreement in experimental and theoretical values which confirms the validation of proposed model adopted to study the stress-strain behaviour of controlled and bacterial concrete of high strength grades (M60 and M80).

From the values of stresses and strains, stress-strain curve for each mix is plotted, taking the average values of the results of the three cylinders. From the stress-strain values of controlled and bacterial concrete mixes the corresponding normalized stress-strain values are calculated by dividing each stress value by the peak stress and dividing each strain value by strain at peak strain. From the normalized stress-strain values of controlled and bacterial concrete mixes, the average normalized stress-strain curves are plotted for controlled and bacterial concrete separately and empirical equations are proposed in the form of $y= Ax/(1+Bx+Cx^2)$ for ascending and descending portions of controlled and bacterial concrete mixes for high strength grades of concrete. Theoretical stresses are evaluated and compared with experimental stress values to found that there is very little variation which validates the proposed mathematical model.

From the stress-strain curves of controlled and bacterial concrete mixes different parameters like modulus of elasticity, energy absorption capacity are computed. Energy absorption capacity expressed in terms of area under stress-strain diagram of controlled and bacterial concrete mixes are evaluated. The average value of area under stress-strain diagram for all grades of concrete for controlled and bacterial concrete mixes are computed. Toughness or energy absorption capacity of different grades of bacterial concrete mixes has shown an increase of 20 % when compared to same grades of controlled concrete mixes. rom the observations made from stress-strain curves of all the controlled and bacterial concrete mixes, the stress-strain behaviour is observed to be almost similar. The only difference is that bacterial concrete mixes have shown improved stress values for the same strain levels compared to that of controlled concrete mixes. It can be observed from stress-strain curves that for high strength concrete, the shape of the ascending part of the stress-strain curve is more linear and steeper, that results in the increase of elastic modulus. The strain at peak stress is slightly higher, and the slope of the descending part is steeper as compared to normal strength concrete. That was due to the decrease in the extent of internal micro cracking in higher strength concrete.

In the uniaxial compression of concrete cylinders, the results show that the strain at peak stress of normal strength concrete is usually less than that of high performance concrete, modulus of elasticity of high performance concrete is higher than that of normal strength concrete.

The proposed empirical equations can be used as stress block in analyzing the flexural behavior of controlled and bacterial concrete sections. For all different grades of controlled and bacterial concrete, the proposed equations have shown good correlation with experimental values. From the literature it appears that modified second degree polynomial as suggested by L.P. Saenz seems to be better fit with appropriate constants suitable for present curves

VII. CONCLUSIONS

From the experimental results obtained throughout the course of this study, the following conclusions can be drawn as follows:

1. The Bacterial concrete mixes have shown improved stress values for the same strain levels compared to that of controlled concrete mixes in all high strength grades
2. Average values of strain at peak stress for controlled and bacterial concrete are very close to the value of strain at peak stress for controlled concrete in axial compression which is 0.002 as per IS 456-2000.
3. The analytical equations for the stress-strain response of controlled and bacterial concrete mixes have been proposed in the form of $y = Ax / (1+Bx+Cx^2)$, both for ascending and descending portions of the curves with different set of values for constants. The proposed equations have shown good correlation with experimental values.
4. The proposed empirical equations can be used as stress block in analyzing the flexural behaviour of sections of controlled and bacterial concrete.
5. Toughness or energy absorption capacity of different grades of bacterial concrete mixes has shown an increase when compared to same grades of controlled concrete mixes.
6. The stress-strain curves obtained in the experiment for different grades of controlled and bacterial concrete exhibit a similar trend when compared to the empirical equations of modified Saenz model. So Saenz mathematical model is successfully evaluated and validated for bacterial concrete.

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