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FLEXURAL BEHAVIOR OF BACTERIA INCORPORATEI REINFORCED CONCRETE BEAMS

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Abstract— **This paper presents the studies on the flexural behavior of reinforced concrete beams induced with bacteria Bacillus subtitles JC3. Application of self crack healing capacity of concrete induced with bacteria is the promising technology of the future to repair and maintain the cracks in concrete structures. This mechanism of self crack healing using precipitated calcite by microorganisms enhances both strength and durability characteristics of concrete significantly. This paper focuses the investigations on improved flexural behavior of bacteria induced concrete compared to conventional concrete. Data presented includes the deflection characteristics, cracking behaviour and toughness properties of bacterial concrete. The beams are cast using with bacteria and without bacteria in ordinary grade concrete (M20), standard grade concrete (M40) and High strength grade concretes (M60 and M80). The beams are tested under symmetrical two-point flexural loading as per IS: 516-1999. From the analysis, it was observed that the first crack load, pre-cracking and post-cracking behaviour, deflection pattern, crack development pattern and ultimate load carrying capacity of bacteria incorporated beams improved and this improvement is more pronounced in higher grades of bacteria incorporated concrete beams. Also it is observed that the bacteria incorporated concrete beams exhibited better ductile behaviour than beams without bacteria.**

Index Terms— **bacterial concrete, Bacillus subtilis JC3, flexural behaviour, first crack load, ultimate load carrying capacity.**

INTRODUCTION

A concrete beam is a structural element that carries load primarily in bending. Bending subject beam to compression and tension. Beams generally carry vertical gravitational forces but can also be used to carry horizontal loads. The loads carried by a beam are transferred to columns, walls, which is then transferred to foundations. The compression section must be designed to resist buckling and crushing, while the tension section must be able to adequately resist to the tension. For a concrete structure to be serviceable, cracking must be controlled and deflection must not be excessive.

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Modes of Failure

If the ratio of steel to concrete in a beam is such that the maximum strain in the two materials reaches simultaneously, a sudden failure would occur with less alarming deflection. Such a beam is referred as a *balanced reinforced beam*. All 16 beams used for this investigation are balanced sections. When the amount of steel is kept less than that in the balanced condition, under increasing bending moment, steel is strained beyond the yield point and the maximum strain in concrete remains less than 0.35%. Such a beam is referred to as an *under reinforced beam*. When the under reinforced concrete element is subject to increasing bending moment, the tension steel yields while the concrete does not reach its ultimate failure condition exhibiting a large deformation and warning before its ultimate failure. When the amount of steel is kept more than that in the balanced condition, the maximum strain in the concrete reaches its ultimate value (0.0035) and crushing of concrete occurs, the steel is still well within the elastic limit. Such a beam is referred as an *over reinforced beam* and such failure as a compression failure which does not provide any warning before failure as the failure is instantaneous. The applied bending moment at collapse, i.e., factored bending moment is equal to the resisting moment on the section provided by internal stress, this is called the *ultimate moment of resistance*. For balanced section, Moment of resistance with respect to concrete is equal to the Moment of resistance with respect to steel

MIX PROPORTIONS

1. Microorganisms - *Bacillus subtilis JC3*, an alkaliphilic soil bacterium which is cultured

and grown at JNTUH Biotech Laboratory was used.

2. Mix proportion of concrete in ordinary grade (M20), standard grade (M40) and high strength grade concretes (M60 and M80) are:

Ordinary grade concrete (M20)	1: 2.27: 3.45: 0.54
Standard grade concrete (M40)	1: 1.73: 2.60: 0.42
High Strength Grade(M60)	1:1.25:2.41:0.26 (Micro Silica - 6% bwc*)
High Strength Grade(M80)	1:1.06:1.96:0.23 (Micro Silica - 10% bwc*)

*bwc-by weight of cement

EXPERIMENTAL INVESTIGATION

The investigation is carried to study the flexural behavior of concrete. A total 16 beams of M20, M40, M60 and M80 grades are fabricated and cast with bacteria Bacillus subtilis JC3 and other sixteen reference beams (normal concrete) of the above grades are also fabricated and cast to test at 28 days, 60 days, 90 days and 180 days of age. The beam sizes and length were chosen to ensure that the beams would fail in flexure (shear span to effective depth ratio = 5.75). The beam dimensions were also sufficiently large to simulate a real structural element. The beam details are shown in figure 1 and table 1. In the pure bending zone (middle third), no stirrups were provided so as not to influence crack development in the constant moment zone. Two 6 mm steel bars were used as top reinforcement to hold stirrups in place in the shear span zone.

Test Methodology

Testing is performed as per IS: 516-1999 under two-point loading under strain rate control. Dial gauges of 0.001 mm least count were used for measuring the deflections at mid span for measuring the deflection. The dial gauge readings were recorded at different loads until failure. The load was applied at intervals of 2.5 kN/sec until the first crack was observed. Subsequently, the load was applied in increments of 5 kN/sec. The behaviour of the beam was observed carefully and the first crack was identified using a hand held microscope. The failure mode of the beams was also recorded. Deflections at the central point, the ultimate load (Peak load), crack width are measured and development of crack pattern are observed for all the grades of bacterial and reference beams considered. The test is continued until the load drops to 15-20% of peak load recorded, in the descending portion of load deflection curves. At that stage the testing is stopped by gradually unloading. The experimental test set-up is shown in figure 2 and 3.

Fabrication of Specimens

The beams of M20, M40, M60 and M80 grades are designed using limit state method for the balanced section to calculate area of steel. The required length of the longitudinal TOR steel bars are cut and straightened. Similarly for stirrups, MS bars are cut and bent in position and spaced according to the designed centre-to-centre spacing. One day before the testing, the cured beams are white washed and the locations of supports; load points and the central deflection gauge are marked with a pencil.

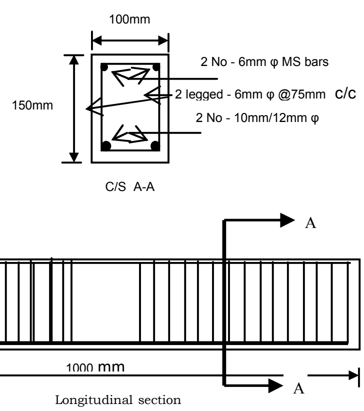
Load Deflection Characteristics

From the load-deflection curve, four distinct stages can be defined for the all beams. The first stage corresponds to the part where beam behaves elastically, and the load-deflection relation is linear, the extent of this stage depends mainly on the physical properties of the beams. In the second stage, flexural cracks formed, the change in slope of the load-deflection curve was observed and this slope remained fairly linear until the third stage started which represent redistribution of stresses in concrete, then the fourth stage continues until yielding of the steel reinforcement take place, in this stage, it can be seen that the load-deflection is a straight line toward horizontal when failure approaches. The gradient of the load-deflection is an indication of beam stiffness. In all beams attainment of ultimate strength was accompanied by crushing of the concrete and a sudden drop in the applied load. The load-deflection curves of the tested beams are shown in Figure 4. An initial linear branch with a steep slope, corresponding to the un-cracked behaviour of the beam. When the first cracking load is achieved, a drop in the slope is observed, due to the progressive cracking of the beam. Finally, the cracking process stabilizes and an almost linear segment is observed until failure. All beams were initially un-cracked. When the cracking moment was reached in the pure bending zone, some cracks began to appear. These first cracks were predominantly vertical and perpendicular to the direction of the maximum stress induced by the bending moment. Then, for higher loads, more cracks appeared along the length of the beam. Whilst cracks grew predominantly in a vertical direction in the pure bending zone, in the shear span they acquired some inclination towards the central zone, due to shear stresses in these regions. Soon after the service load was attained, no more new cracks appeared and only the opening of the existing cracks could be observed.

Crack widths were measured by means of microscope at the steel levels and at the bottom face of the beam.

Table 1: Flexure Test beam details

Beam Section	Grade of Concrete	Grade of Steel	Tensile Reinforcement	Nominal Compression Reinforcement	Shear Reinforcement	Beam dimensions
Balanced	M20	Fe 415	2 No - 10mmφ Tor steel bars	2 No - 6mm φ MS bars	2 legged - 6mm φ @75mm c/c	100 mm x 150 mm x 1200 mm
Balanced	M40	Fe 415	2 No - 12mmφ Tor steel bars	2 No - 6mm φ MS bars	2 legged - 6mm φ @75mm c/c	100 mm x 150 mm x 1200 mm
Balanced	M60	Fe 415	2 No - 16mmφ Tor steel bars	2 No - 6mm φ MS bars	2 legged - 6mm φ @75mm c/c	100 mm x 150 mm x 1200 mm
Balanced	M80	Fe 415	3 No - 16mmφ Tor steel bars	2 No - 6mm φ MS bars	2 legged - 6mm φ @75mm c/c	100 mm x 150 mm x 1200 mm



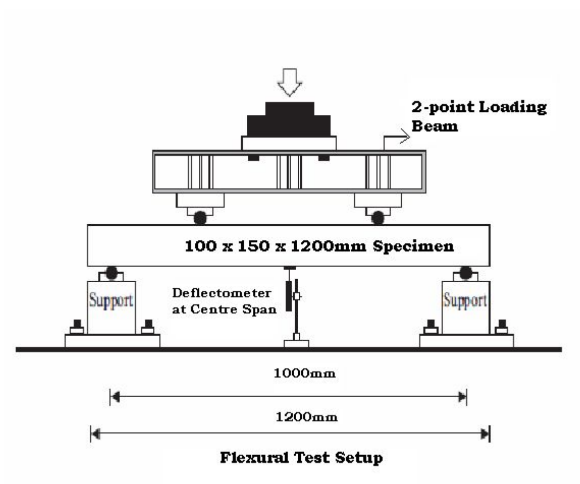


Figure 1: The reinforcement details

Figure 2: Flexural Test Set up – Schematic Diagram

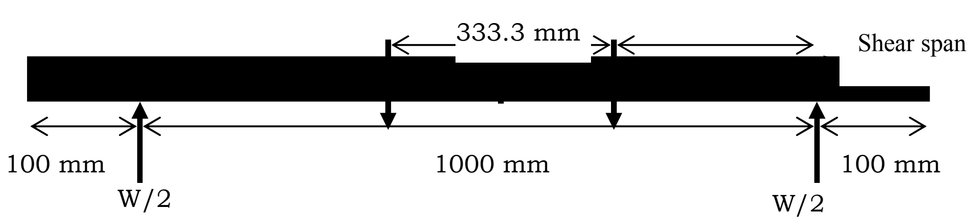


Figure 3: Flexural Test Setup

Toughness

Load deflection curves are a standardized method of quantifying the energy a beam absorbs during its load induced flexural deflection. The area under the curve represents the energy absorbed by the beam and is often referred to as the toughness. Toughness, according to ASTM C1018, is defined as the ability of a material to counteract crack propagation by dissipating deformation energy. 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.

TEST RESULTS

Table2: Flexural Test results of ordinary grade (M20) concrete beams

Age of Concrete	Load at first crack (kN)	Ultimate Flexural Strength (kN)	Central Deflection at Max. Load (mm)	Maximum Crack Width (mm)
		Normal concrete		
28	18	83	36.9	3.1
60	19	85	35.3	3.0
90	19	85	34.6	2.8
180	20	87	34.2	2.8
		Bacterial concrete		
28	32	109	27.9	2.9
60	32	111	27.2	2.8
90	33	114	26.8	2.7
180	34	116	26.3	2.7

Table 3: Flexural Test results of standard grade (M40) concrete beams

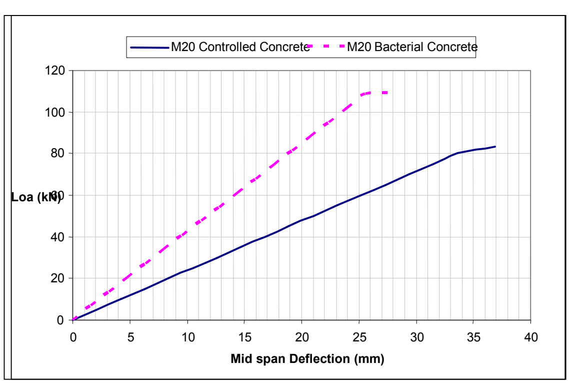
Age of Concrete	Load at first crack (kN)	Ultimate Flexural Strength (kN)	Central Deflection at Max. Load (mm)	Maximum Crack Width (mm)
		Normal concrete		
28	25	96	30.1	3.0
60	27	98	29.8	2.9
90	27	99	28.9	2.8
180	29	103	28.6	2.8
		Bacterial concrete		
28	42	117	22.0	2.6
60	42	119	21.9	2.5
90	45	122	20.3	2.4
180	48	125	19.6	2.4

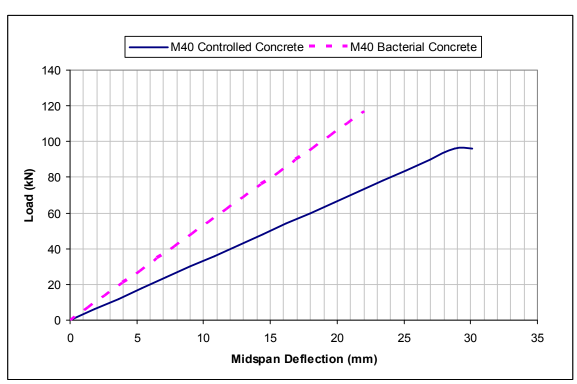
Table 4: Flexural Test results of high strength grade (M60) concrete beams

Age of Concrete	Load at first crack (kN)	Ultimate Flexural Strength (kN)	Central Deflection at Max. Load (mm)	Maximum Crack Width (mm)
		Normal concrete		
28	44	109	29.5	1.6
60	47	112	28.9	1.6
90	47	115	25.7	1.5
180	53	119	23.2	1.5
		Bacterial concrete		
28	51	129	19.3	1.3
60	52	132	17.9	1.3
90	55	133	14.7	1.3
180	61	139	15.8	1.2

Table 5: Flexural Test results of high grade (M80) concrete beams

Age of Concrete	Load at first crack (kN)	Ultimate Flexural Strength (kN)	Central Deflection at Max. Load (mm)	Maximum Crack Width (mm)
		Normal concrete		
28	46	125	29.2	1.4
60	48	128	25.1	1.4
90	50	128	23.5	1.3
180	54	131	22.4	1.3
		Bacterial concrete		
28	64	137	19.4	1.2
60	65	139	18.1	1.2
90	65	141	16.3	1.2
180	67	145	11.0	1.2





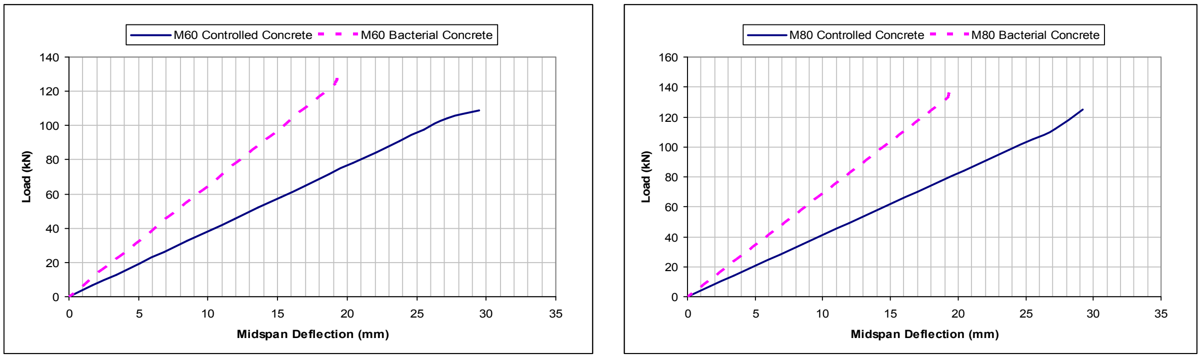


Figure 4: Load- deflection plots

DISCUSSIONS OF TEST RESULTS

General observations

No horizontal cracks were observed at the level of the reinforcement, which indicated that there was no occurrence of bond failure. Vertical flexural cracks were observed in the constant moment region (middle third) and final failure occurred due to crushing of the compression concrete with significant amount of ultimate deflection. Since all beams were balanced, yielding of the tensile reinforcement and crushing of the concrete cover occurred almost at the same time in the pure bending zone. When peak load was reached, the concrete cover on the compression zone starts to spall. Eventually, crushing of the concrete cover occurred during failure.

Cracking behavior

Crack widths were measured at regular interval at the tension side and the crack formations were marked on the beam. For beams, initial cracking occurred at about 11 to 15% of the ultimate load. It was noticed that the first crack always appears close to the mid-span of the beam. The cracks forming on the surface of the beams were mostly vertical, suggesting failure in flexure. First crack formation was delayed in bacteria incorporated beams. Due to mineral precipitation in bacteria incorporated beams internal micro cracking in the cementitious matrix is delayed and as micro cracks develop in the matrix, plugging up of cracks takes place due to continuous calcite mineral precipitates of Bacillus subtilis JC3, due to which cracks are arrested and prevented further propagation. Hence the cracks appearing inside the matrix have to change the path, resulting in demand for more energy for future propagation, which in turn increases the first crack load and thereby increasing the load carrying capacity and enhances the tensile response of bacteria mediated matrix.

Loads at first crack in bacteria incorporated beams are higher than the controlled concrete beams in all grades confirming that self healing ability of bacteria incorporated beams offer greater resistance to cracking. The first crack load of bacteria incorporated beams for all the grades and ages considered was 1.2 to 1.7 times than that of corresponding controlled normal reinforced beams.

Crack width and crack spacing

The flexure cracks were the first to initiate in the Constant Bending moment Zone (middle third) as expected. As the load increased, the existing cracks propagated and new cracks developed in the farther regions of Constant Bending moment Zone. In the shear span regions, the flexural cracks gave way to inclined cracks with increasing load. Beyond the peak load, the number of flexural cracks stabilized and the cracks at the mid-span opened widely thereafter with the yielding of steel. At failure load, all the beams deflected significantly. The failure in all the cases was initiated by yielding of the tensile steel (followed by the crushing of concrete in the compression face. Crack width was reduced in bacteria incorporated beams because calcite mineral precipitated bridges the cracks and limits its width.

Deflection behavior

The deflection at the mid span decreased in bacteria incorporated reinforcement beams which show that crack healing mechanism using calcite mineral precipitation improved the flexural stiffness of the elements thereby reducing the structural member's deformability, increasing strength and hence controlling deflection. The increase in improved modulus of elasticity in bacteria incorporated reinforcement beam also resulted in reduced deflection.

The ultimate deflection in case of bacteria incorporated beams was 25 to 35 % less than the ultimate deflections in case of normal reinforced beams. Mid span deflections at peak load reduced as the grade of the concrete increases.

Load carrying capacity

In M20, M40, M60 and M80 grades of concrete, load deflection behaviour of bacterial and reference concrete beams is observed to be similar except the increased values of loads at ultimate and at first crack in bacterial concrete beams. The stress-strain behavior of concrete is very important parameter in design to predict the flexural behavior and toughness of concrete. The ultimate flexural strengths of bacterial concrete beams are observed to be higher than normal concrete beams for all grades and at all ages considered for the investigation. The ratio of ultimate load to first crack load is reduced for bacterial concrete beams due to high first crack loads. The Ultimate Flexural Strength of Bacterial Concrete beams have improved by 10 to 30 % when compared to normal reinforced beams.

CONCLUSIONS

The following observations and conclusions can be made on the basis of the current experimental results:

1. The Ultimate Flexural Strength of Bacterial Concrete beams have improved significantly when compared with controlled reinforced beams confirming the increase of load carrying capacity in bacteria incorporated beams. This increase is observed to be high for higher grades of concrete.
2. The first crack load of bacteria incorporated beams was 1.2 to 1.7 times higher than that of corresponding controlled normal reinforced beams for all the grades and ages considered.
3. Mid-span deflections at ultimate load in bacteria incorporated beams are reduced with the increase in age and grade of concrete.
4. Crack widths are wider in case of normal reinforced beams than bacteria incorporated beams by nearly 10%.
5. From the analysis it was obvious that the first crack load, pre-cracking and post-cracking behaviour, deflection pattern, crack development pattern and ultimate load carrying capacity of bacteria incorporated reinforced concrete beams improved with mineral precipitating bacteria addition.

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