A BIOLOGICAL APPROACH TO ENHANCE STRENGTH AND DURABILITY IN CONCRETE STRUCTURES

Srinivasa Reddy V[1], Achyutha Satya K[2], Seshagiri Rao M V[3], Azmatunnisa M[4]

[1&2]Department of Civil Engineering, JNTUH CEH, Hyderabad -500085, India
[3]Professor in Civil Engineering, JNTUH CEH, Hyderabad -500085, India
[4]Centre for Environment, JNTU, Hyderabad -500085, India

ABSTRACT

Concrete is the most critical element applied in public infrastructure/buildings and is often difficult to service, yet requires lengthy service periods. Recent research has shown that specific species of bacteria can actually be useful as a tool to repair cracks in already existing concrete structures. This new concrete, that is equipped to repair itself, presents a potentially enormous lengthening in service-life of public infrastructure/buildings and also considerably reduces the maintenance costs. In addition, concrete by its nature is very prone to deformations that expose its reinforcements, corroding them. Self-healing concrete offers a solution to prevent this. A novel eco friendly self healing technique called Biocalcification is one such approach on which studies were carried out to investigate the crack healing mechanism in enhancing the strength and durability of concrete. Microbiologically induced calcite precipitation (MICP), a highly impermeable calcite layer formed over the surface of an already existing concrete layer, due to microbial activities of the bacteria (Bacillus subtilis JC3) seals the cracks in the concrete structure and also has excellent resistance to corrosion.

KEYWORDS: *Biominerilization, Calcium Carbonate, Bacillus subtilus, Self-healing concrete, bacterial concrete*

I. INTRODUCTION

Concrete is a vital building material that is an absolutely essential component of public infrastructure and most buildings. It is most effective when reinforced by steel rebar, mainly because its tensile strength without reinforcement is considerably low relative to its compressive strength. It is also a very brittle material with low tolerance for strain, so it is commonly expected to crack with time. These cracks, while not compromising structural integrity immediately, do expose the steel reinforcement to the elements, leading to corrosion which heightens maintenance costs and compromises structural integrity over long periods of time. That being said, concrete is a high maintenance material. It cracks and suffers serious wear and tear over the decades of its expected term of service. It is not flexible and cannot handle significant amounts of strain. Standard concrete will bear up to approximately 0.1% strain before giving out [1]. Self-healing concrete in general seeks to rectify these flaws in order to extend the service life of any given concrete structure. There is a material in the realm of self-healing concrete in development, now, that can solve many of the problems commonly associated with standard concrete. This material is bacterial self-healing concrete. Self-healing concrete consists of a mix with bacteria (Bacillus subtilus) incorporated into the concrete and calcium lactate food to support those bacteria when they become active. The bacteria, feeding on the provided food source, heal the damage done and can also reduce the amount of damage sustained by the concrete structure in place [2]. This paper will also explain, in-depth, the processes that are behind bacterial self-healing in concrete and will describe the many components that are included in the process and how they work independently and collectively. This paper will also delve into practical applications of this self-healing method, including real-world integrations in currently standing structures. Sustainability and economics of these materials will also be discussed, as this new improvement on the staple building material, yet often taken for granted, of our modern civilization presents an opportunity to both reduce the environmental and financial impact of concrete production and its wide array of applications.

II. THE BIOLOGICAL SELF-HEALING PROCESS

It is important to cover what kinds of bacteria will live in the concrete, how they work to improve the longevity of public infrastructure, what the catalyst will be that causes the chemical reaction in the bacteria, what happens to the specific kinds of specialized bacteria when exposed to the catalyst, and how they work together to not only heal cracks before they form, but also strengthen the overall structure they are incorporated into. When the bacteria are exposed to the air and the "food," the bacteria go through a chemical process that causes them to harden and fuse, filling in the crack that has formed, strengthening the structure of the concrete, and adhering to the sides of the crack to seal the damage site. This process extends the lifespan of the structure while also fixing the damage caused. The process of healing a crack can take as little as a few days [3].

When we look at the crack sizes, we generally are looking in then micro- to nano meter range to maximize the healing potential. Concrete constructions are currently designed according to set norms that allow cracks to form up to 0.2 mm wide [4][5]. Such micro cracks are generally considered acceptable, as these do not directly impair the safety and strength of a construction. Moreover, micro cracks sometimes heal themselves as many types of concrete feature a certain crack-healing capacity. Research has shown that this so called 'autonomous' healing capacity is largely related to the number of non-reacted cement particles present in the concrete matrix[7]. On crack formation, ingress water reacts with these particles, resulting in closure of micro cracks. However, because of the variability of autonomous crack healing of concrete constructions, water leakage as a result of micro crack formation in tunnel and underground structures can occur. While self-healing of 0.2 mm wide cracks occurred in 30% of the control samples, complete closure of all cracks was obtained in all bacteria-based samples. Moreover, the crack sealing capacity of the latter group was found to be extended to 0.5 mm cracks.

The basic concept behind our specific version of self-healing concrete is utilizing certain types of bacteria (in the present case bacillus subtilus) and how they function to seal microscopic cracks in the concrete before they grow into larger and harder to manage cracks and breaks. This biocalcification process involves several elements, working in unison, to complete these tasks. During the process the enzymatic hydrolysis of urea takes place forming ammonia and corbondioxide. Urease which is provided by bacteria deposits $CaCo_{3,}$ a highly impermeable calcite layer, over the surface of an already existing concrete layer which is relatively dense and can block cracks and thus hamper ingress of water efficiently increasing corrosion resistance and consequently increasing the strength and durability of concrete structures[8]. MICP is a complex mechanism and is a function of cell concentration, ionic strength, nutrient and pH of the medium. Modern techniques such as X-ray diffraction tests, TEM & SEM analysis can be used to quantify the study of stages of calcite deposition on the surface and in cracks [9].

III. HOW DOES BACTERIA REMIDIATE CRACKS

When the concrete is mixed with bacteria (bacillus subtilus), the bacteria go into a dormant state, a lot like seeds. All the bacteria need is exposure to the air to activate their functions. Any cracks that should occur provide the necessary exposure. When the cracks form, bacteria very close proximity to the crack, starts precipitating calcite crystals. When a concrete structure is damaged and water starts to seep through the cracks that appear in the concrete, the spores of the bacteria germinate on contact with the water and nutrients. Having been activated, the bacteria start to feed on the calcium lactate nutrient. Such spores have extremely thick cell walls that enable them to remain intact for up to 200 years while waiting for a better environment to germinate. As the bacteria feeds oxygen is consumed and the soluble calcium lactate is converted to insoluble limestone. The limestone solidifies on the cracked surface, thereby sealing it up. 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. Tests all show that bacteria embedded concrete has lower water and chloride permeability and higher strength regain than the surface application of bacteria.

The last, but certainly not least, key component of the self-healing concrete formula is the bacteria themselves. The most promising bacteria to use for self-healing purposes are alkaliphilic (alkali-resistant) spore-forming bacteria. The bacteria, from the genus *Bacillus*, subtilus is adopted for present study. It is of great concern to the construction industry whether or not these bacteria are "smart" enough to know when their task is complete because of safety concerns. Bacillus Subtilus which is a soil bacterium (isolated from JNTUH soil) is harmless to humans as it is non-pathogenic microorganism.

3.1 Chemistry of the Process

Microorganisms (cell surface charge is negative) draw cations including Ca^{2+} from the environment to deposit on the cell surface. The following equations summarize the role of bacterial cell as a nucleation site

$$Ca^{2+} + Cell \text{--------}> Cell\text{-}\ Ca^{2+}$$
$$Cell\text{-}\ Ca^{2+} + CO_3^{2-} \text{----}> Cell\text{-}CaCO_3$$

The bacteria can thus act as a nucleation site which facilitates in the precipitation of calcite which can eventually plug the pores and cracks in the concrete. This microbiologically induced calcium carbonate precipitation (MICCP) comprises of a series of complex biochemical reactions. As part of metabolism, B.Subtilus produces urease, which catalyzes urea to produce CO_2 and ammonia, resulting in an increase of pH in the surroundings where ions Ca^{2+} and CO_3^{2-} precipitate as $CaCO_3$ **[10].**

These create calcium carbonate crystals that further expand and grow as the bacteria devour the calcium lactate food. The crystals expand until the entire gap is filled. In any place where standard concrete is currently being used, there is potential for the use of bacterial self-healing concrete instead. The advantage of having self-healing properties is that the perpetual and expected cracking that occurs in every concrete structure due to its brittle nature can be controlled, reduced, and repaired without a human work crew. Bacterial self-healing concrete also prevents the exposure of the internal reinforcements. This form of self-healing concrete was created to continuously heal any damage done on or in the concrete structure. It was made to extend the life span of a concrete structure of any size, shape, or project and to add extra protection to the steel reinforcements from the elements. With this process, money can be saved, structures will last far longer, and the concrete industry as a whole will be turning out a far more sustainable product, effectively reducing its CO_2 contribution.

IV. EXPERIMENTAL PROGRAM

The main aim of the present experimental program is to obtain specific experimental data, which helps to understand the crack healing ability of Bacterial concrete and its characteristics (Strength and Durability).This experimental program is categorized into four phases:

Phase 1: Culture and Growth of Bacillus subtilus
Phase 2: Evaluation of compressive strength enhancement in Bacterial concrete specimens
Phase 3: Evaluation of Durability enhancement in Bacterial concrete specimens
Phase 4: Microscopic analysis of $CaCo_3$ precipitation in Bacterial concrete specimens

4.1 Materials Used

The following are the details of the materials used in the investigation:

4.1.1 Cement

Ordinary Portland cement of 53 grade available in local market is used in the investigation. The cement used has been tested for various properties as per IS: 4031-1988 and found to be confirming to various specifications of IS: 12269-1987 having specific gravity of 3.0.

4.1.2 Fine Aggregate

Locally available clean, well-graded, natural river sand having fineness modulus of 2.89 conforming to IS 383-1970 was used as fine aggregate.

4.1.3 Coarse Aggregate

Crushed granite angular aggregate of size 20 mm nominal size from local source with specific gravity of 2.7 was used as coarse aggregate.

4.1.4 Water

Locally available potable water conforming to IS 456 is used.

4.1.5 Microorganisms

Bacillus subtilis JC3**,** a model laboratory Soil bacterium which is cultured and grown at JNTUH Biotech Laboratory was used.

4.1.6 Mix Design

The mix proportions for ordinary grade concrete and standard grade concrete are designed using IS: 10262-1982. Materials required for 1 cubic meter of concrete in ordinary grade concrete and standard grade concrete are:

Ordinary grade concrete (M20)	**Standard grade concrete (M40)**	**High grade Concrete**	
		(M60)	**(M80)**
Mix proportion 1: 2.43: 3.48: 0.55	Mix proportion 1: 1.76: 2.71: 0.45	Mix proportion 1:1.24:2.41:0.28	Mix proportion 1:1.06:1.96:0.26

V. RESULTS AND DISCUSSION

Table 1 summarizes the 3 days, 7 days and 28 days compressive strength of the mortar cubes containing different cell concentration of alkaliphilic microorganism (Bacillus subtilus). The greatest improvement in compressive strength occurs at cell concentrations of 10^5 cells/ml for all ages: this increase reaches to 16.15 % at 28 days. This improvement in compressive strength is due to deposition on the microorganism cell surfaces and within the pores of cement–sand matrix, which plug the pores within the mortar. The extra cellular growth produced by the microorganism is expected to contribute more to the strength of cement mortar with a longer incubation period and thus the strength improvement is found to be more at 28 days. Even the dead cells may simply remain in the matrix as organic fibers. Quantification and Characterization was done using Scanning Electron Micrograph analysis, only to be noted that cracks are sealed up by crystalline material grown over the surface due to microbial activity of the bacteria.

Table 1: Effect of Bacillus subtilis, JC3 bacteria Cell Concentration on Strength

Cell concentration/ml of mixing water	Compressive Strength of Cement Mortar in MPa					
	7 days	% Increase	14 days	% Increase	28 days	% Increase
Nil (control)	37.32	-	44.10		51.81	-
10^4	41.68	11.68	45.23	2.56	58.02	11.99
10^5(optimum)	45.02	20.63	49.21	11.59	61.79	16.15
10^6	43.09	15.46	47.69	8.14	57.21	10.42
10^7	40.11	7.48	45.97	4.24	54.66	5.51

To study strength characteristics standard cubes (100mm x 100mm x 100mm) with and without bacteria were casted and tested as per IS Code. The compressive strengths of ordinary, standard and high grades are tabulated as shown in Table 2. The increase in compressive strength in bacteria induced specimens is nearly 23% than controlled specimens. For higher grades of concrete, the improvement in compressive strength is observed to be more. Scanning Electron Microscopy (SEM) and X-ray diffraction analyses was done on broken samples of both controlled and bacterial specimens of age 28 days as shown in Figure 1 and 2.

Table 2: Effect of the Bacillus subtilis, JC3 bacteria addition on Compressive Strength

Age (No. of days)	Compressive Strength (MPa) at 28 days		
	Controlled Concrete (MPa)	Bacterial Concrete (MPa)	% Increase
Ordinary grade concrete (M20)	28.18	32.74	16.18
Standard grade concrete (M40)	51.19	60.17	17.54
High grade Concrete (M60)	72.61	94.21	29.75
High grade Concrete (M80)	93.8	119.2	27.08

To study durability characteristics, the specimens are subjected to 5% solution of HCL and H_2SO_4. For determining the resistance of concrete specimens to aggressive environment such as acid attack, the durability factors are proposed by the author, with the philosophy of ASTM C 666–1997, as the basis. In the present investigation, the author derived the “Acid Durability Factors” directly in terms of relative strengths. The relative strengths are always with respect to the 28 days value (i.e. at the start of the test). The “Acid Durability Factors” (ADF) can be designed as follows.

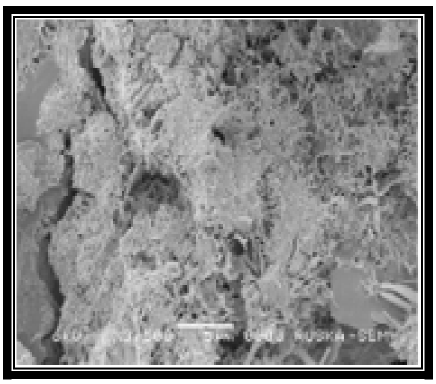
Acid Durability Factor (ADF) = Sr (N / M)

where, Sr = relative strength at N days, (%)N = number of days at which the durability factor is needed and M = number of days at which the exposure is to be terminated.

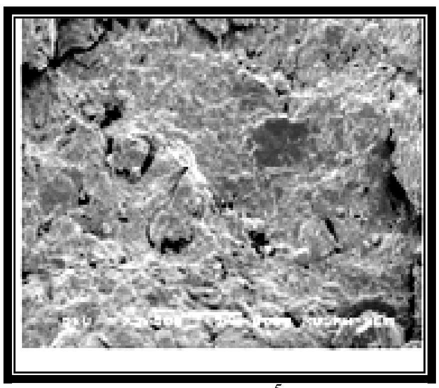
Acid attack test was terminated at 90 days. So, M is 90 in this case. The extent of deterioration at each corner of the struck face and the opposite face is measured in terms of the acid diagonals (in mm) for each of two cubes and the “Acid Attack Factor” (AAF) per face is calculated as follows.

AAF = (Loss in mm on eight corners of each of 2 cubes) / 4

Acid Durability Factors (ADF), Acid Attack Factors (AAF), percentage weight loss and strength loss at 30, 60 and 90 days of immersion are evaluated and tabulated in Table 3 and 4.



Controlled Specimen



Cell Concentration – 10^5/ml (Optimum)

Figure 1: Magnified SEM Micrographs: Hydrated Structure of Cement-sand Mortar without Bacteria and with Bacteria

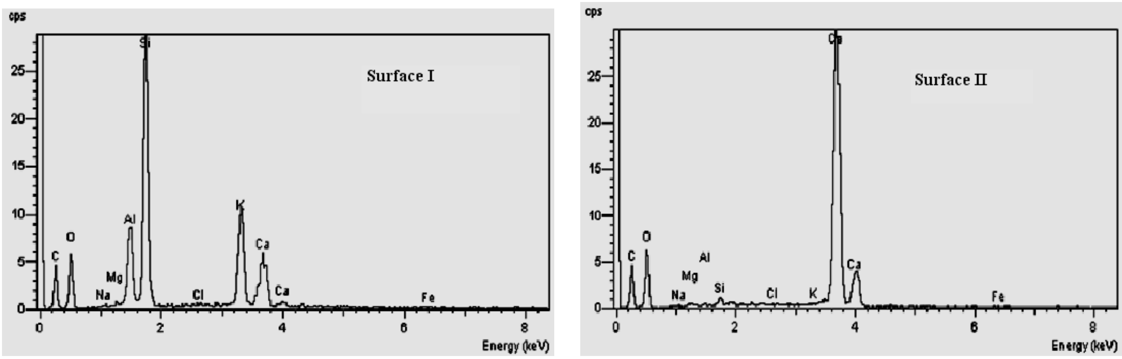


Figure 2: Energy-dispersive X-ray spectrum of the microbial precipitation shows the abundant presence of Ca and precipitation was inferred to as calcite ($CaCO_3$) crystals

Table 3: Weight loss and Strength loss in acid immersion test on different grades of Concrete

Grades of Concrete		Days of Immersion	Immersion in 5% H_2SO_4		Immersion in 5% HCL	
			% Weight loss	% loss in Compressive Strength	% Weight loss	% loss in Compressive Strength
M 20	Controlled Concrete	30	0.99	2.80	0.97	0.53
		60	3.17	7.77	2.93	2.62
		90	6.65	12.46	4.59	4.89
	Bacterial Concrete	30	0.79	0.67	0.51	0.40
		60	2.70	4.12	2.30	2.17
		90	5.60	7.61	3.80	4.01
M 40	Controlled Concrete	30	1.14	0.94	0.55	0.43
		60	5.59	7.93	2.46	1.92
		90	8.87	16.48	4.75	3.56
	Bacterial Concrete	30	0.91	0.68	0.48	0.32
		60	4.66	4.92	2.10	1.71
		90	7.73	10.2	3.88	3.01
M 60	Controlled Concrete	30	1.02	1.11	0.35	0.36
		60	4.53	5.63	2.12	1.09
		90	7.56	12.31	3.62	2.30
	Bacterial Concrete	30	0.85	0.75	0.23	0.17
		60	2.33	3.21	2.11	0.93
		90	6.03	8.23	2.36	1.86
M 80	Controlled Concrete	30	0.82	0.96	0.16	0.22
		60	2.59	5.21	1.02	0.85
		90	4.26	11.05	2.11	1.64
	Bacterial Concrete	30	0.53	0.46	0.15	0.13
		60	1.60	2.13	0.86	0.56
		90	2.95	5.62	1.23	0.95

Table 4: Acid Durability Factors and Acid Attack Factors of different grades of Concrete

Grades of Concrete		Days of Immersion	Immersion in 5% H_2SO_4		Immersion in 5% HCL	
			ADF	AAF	ADF	AAF
M 20	Controlled Concrete	30	27.77	0.22	28.42	0.23
		60	52.70	0.72	55.65	0.64
		90	75.03	1.16	81.52	0.99
	Bacterial Concrete	30	28.38	0.16	28.48	0.19
		60	54.79	0.59	55.90	0.51
		90	79.19	0.94	82.28	0.90
M 40	Controlled Concrete	30	28.30	0.19	28.45	0.19
		60	52.61	0.78	56.05	0.59

		90	71.61	1.28	82.66	0.97
	Bacterial Concrete	30	28.28	0.16	28.48	0.16
		60	54.33	0.47	56.17	0.50
		90	76.97	0.91	83.13	0.84
M 60	Controlled Concrete	30	32.96	0.15	33.22	0.11
		60	62.91	0.68	65.25	0.40
		90	87.69	1.01	96.38	0.81
	Bacterial Concrete	30	33.08	0.13	33.26	0.14
		60	64.53	0.47	65.26	0.45
		90	91.77	0.79	97.64	0.74
M 80	Controlled Concrete	30	33.01	0.11	33.28	0.08
		60	63.19	0.57	65.99	0.22
		90	88.95	0.92	97.89	0.60
	Bacterial Concrete	30	33.18	0.06	33.28	0.06
		60	65.25	0.45	66.09	0.30
		90	94.38	0.62	98.77	0.64

VI. CONCLUSIONS

Based on the present experimental investigations, the following conclusions are drawn:
Deposition of a layer of calcite crystals on the surface of the specimens resulted in a decrease of permeability of water and other liquids in concrete.
The addition of Bacillus subtilis bacteria improves the hydrated structure of cement in concrete for a cell concentration of 10^5 cells per ml of mixing water. So, bacteria of optimum cell concentration of 10^5 cells per ml of mixing water was used in the investigation.
The addition of Bacillus subtilis bacteria increases the compressive strength of concrete. The compressive strength is increased nearly 23% at 28 days for ordinary, standard and high grades of concrete when compared to controlled concrete.
From the durability studies, the percentage weight loss and percentage strength loss with 5% HCl and 5% H_2SO_4 revealed that Bacterial concrete has less weight and strength losses than the controlled concrete. Durability studies carried out in the investigation through acid attack test with 5% HCl and 5% H_2SO_4 revealed that bacterial concrete is more durable in terms of “Acid Durability Factor” than conventional concrete and bacterial concrete is less attacked in terms of “Acid Attack Factor” than conventional concrete.
From the above proof of principle, it can be concluded that *Bacillus subtilis* can be safely used in crack remediation of concrete structure. Bacillus subtilis (JC3) which is available in soil can be produced from laboratory which is proved to be a safe, non pathogenic and cost effective.

VII. SCOPE OF FUTURE RESEARCH

This study can be extended to evaluate the durability performance of the bacterial concrete in terms of Chloride penetration, porosity, elevated temperature studies and corrosion resistance studies.

ACKNOWLEDGEMENTS

We would like to take this opportunity to thank Dr Ch Sasikala Professor at Centre for Environment in JNTU Hyderabad for her constant support and guidance in this project.

REFERENCES

[1]. Wang, J., Van Tittelboom, K., De Belie N., and Verstraete, W.. "Use of Silica Gel or Polyurethane Immobilized Bacteria for Self-healing Concrete." Construction and Building Materials 26.1 (2012): 532-40. Print.
[2]. Li, V., University of Michigan, “Self-healing concrete for safer, more durable infrastructure.” Science Daily, 22 Apr. 2009. Web. 28 Feb. 2012.

[3]. Jonkers, H. M., A. Thijssen, G. Muyzer, O. Copuroglu, and Schlangen, E. "Application of Bacteria as Self-healing Agent for the Development of Sustainable Concrete." Elsevier. Elsevier B.V., 30 Dec. 2008. Web. 25 Feb. 2012.
[4]. Brownell, Blaine. "Self-Healing Concrete." Architect, The AIA Magazine (2011): 90-91. Print.
O'Driscoll, Cath. "Bacteria Fill in the Gaps in Concrete." Chemistry & Industry (2010). Web. 11 Feb. 2012.
[5]. Zwaag, S. Van Der, and Schmets A. J. Self Healing Materials: An Alternative Approach to 20 Centuries of Materials Science. Dordrecht, The Netherlands: Springer, 2007. Print.
[6]. Yonkers, H. M., and E. Schlangen. "Crack Repair by Concrete-immobilized Bacteria." Proc. of First International Conference on Self Healing Materials, Delft University of Technology, Noordwijk Aan Zee. Springer, 2007. Print.
[7]. Joseph, C., A. D. Jefferson, and M. B. Cantoni. "Issues Relating to the Autonomic Healing of Cementitious Materials." Proc. of First International Conference on Self Healing Materials, Delft University of Technology, Noordwijk Aan Zee. Springer, 2007. Print.
[8]. Kessler, M.R., N.R. Sottos, and S.R. White. "Self-healing Structural Composite Materials." Composites Part A: Applied Science and Manufacturing 34.8 (2003): 743-53. Print
[9]. Santhosh KR, Ramakrishnan V, Duke EF, and Bang SS, "SEM Investigation of Microbial Calcite Precipitation in Cement", Proceedings of the 22nd International Conference on Cement Microscopy, pp. 293-305, Montreal, Canada, 2000.
[10]. Ramakrishnan V, Ramesh KP, and Bang SS. South Dokata School of Mines and Technology, USA, "Bacterial Concrete", Proceedings of SPIE 2000, Vol. 4234 pp. 168-176, Smart Materials.

AUTHORS

Srinivasa Reddy V is currently pursuing PhD in Civil Engineering at JNTUH College of Engineering. He has obtained BTech degree from Nagarjuna University in 1996 and MTech from JNTU Hyderabad in 2002.He has published one international journal paper and seven National/International conference papers.

M V Seshagiri Rao is Professor in Civil Engineering at JNTUH College of Engineering. He has enormous experience in teaching and research for nearly 30 years. He has guided 18 PhDs and published nearly 135 papers in various international/national journals and conferences. He won best teacher award in 2009 from State Government of Andhra Pradesh. He has published one book on Engineering Mechanics. He is recipient of many more awards and also associated with various professional bodies.

Achyutha Satya K is a post graduate student in Civil Engineering at JNTUH College of Engineering. Her specialization is Infrastructural Engineering.

M. Azmatunnisa is presently working on characterization of a novel species of Bacillus isolated from organic solvent. She has done Masters in Biotechnology from Sri Krishnadevaraya University. Her Masters Project on "Isolation of solvent tolerant bacteria from aromatic organic solvents" under the guidance of Dr. Ch. Sasikala, Professor, Centre for Environment, Institute of Science and Technology, Jawaharlal Nehru Technological University, Kukatpally, Hyderabad – 500085.

.