Effect of Selected Important bacteria on Physicochemical Properties of Cement

By

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Introduction

- Durability, physico-chemical and mechanical properties of concrete/mortar are pore structure characteristics[1 & 2]
- Microorganisms in soil and water can exhibit microbially induced calcite precipitation (MICP) process or microbially induced deterioration (MID)
- MID causes disintegration and degradation of concrete/mortar by introduction of degrading reagents[3]
- MICP results to green and smart concrete/mortar

1. Mulwa, O. M., Wachira, J. M., Thiong'o, J. K., Mutitu, D. K., Mwirichia, R., Muriithi, G. L. (2020). Study on the effect of *Thiobacillus intermedius* bacteria on the physico-mechanical properties of mortars of ordinary portland cement – a research; https://doi.org/10.1016/j.heliyon.2020.e03232, Elsevier.

2. Mutitu, D. K., Wachira, J. M., Mwirichia, R., Thiong'o, J. K., Mulwa, O. M., Muriithi, G. L. (2020). Biocementation Influence on Flexural Strength and Chloride Ingress by Lysinibacillus sphaericus and Bacillus megaterium in Mortar Structures– a research; https://doi.org/10.1155/2020/1472923, Hindawi.

3. Reginah WanguiNgari, Joseph KaranjaThiong'o, Jackson MuthengiaWachira, GensonMuriithi, Daniel KaranjaMutitu (2021). Bioremediation of mortar made from Ordinary Portland Cement degraded by *Thiobacillus thioparus* using *Bacillus flexus* – a research; https://doi.org/10.1016/j.heliyon.2021.e07215, Heliyon.

- MICP process summary

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3 \quad \cdots\cdots\cdots(1)$$

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3 \quad \cdots\cdots\cdots\cdots\cdots(2)$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^- \quad \cdots\cdots\cdots\cdots\cdots(3)$$

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(4)$$

$$HCO_3^- + H^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2H_2O \quad \cdots\cdot(5)$$

$$Ca^{2+} + \text{Bacterial cell} \rightarrow \text{Bacterial cell} - Ca^{2+} \cdot(6)$$

$$\text{Bacterial Cell} - Ca^{2+}CO_3^{2-} \rightarrow \text{Cell} - CaCO_3 \cdot(7)$$

- A sediment, a coating and a bridge is formed sequentially around and between the particles strengthening/increasing particles linkage

Microbiologically Induced Deterioration (MID) process summary

$$SO_4^{2-} \xrightarrow{\text{MID Bacteria}} H_2S$$

$$H_2S + 2O_2 \rightarrow H_2SO_4$$

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4.H_2O$$

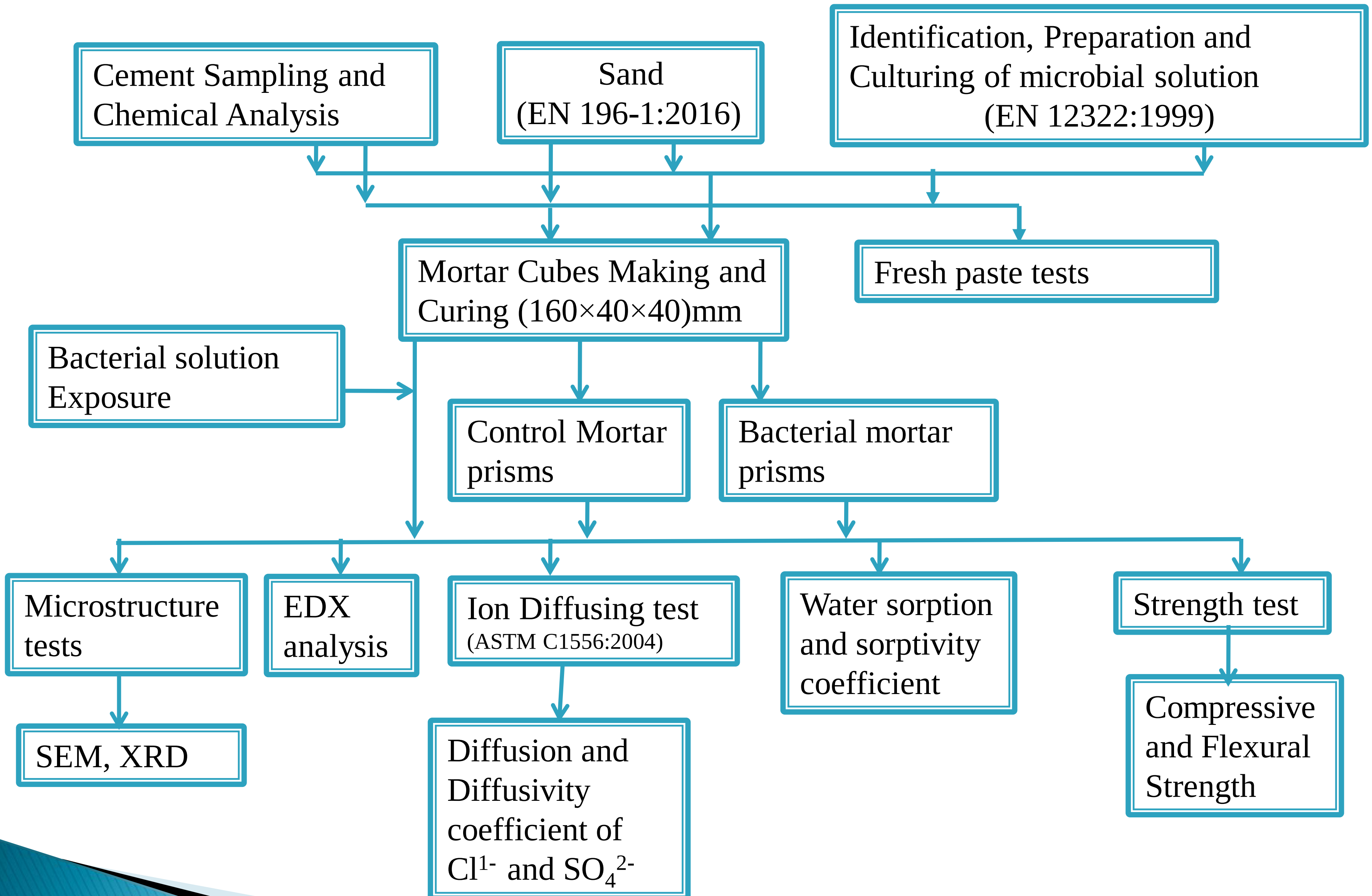
$$3CaO.Al_2O_3.12H_2O + 3CaSO_4.2H_2O + 13H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.32H_2O$$

Sulphur-oxidizing bacteria oxidize the unstable hydrogen sulphide to form biogenic sulphuric acid

Research Directions

- Improving the performance of mortar using MICP
- Investigating the effect of degrading bacterial (MID) on performance of mortar
- Using MICP to repair MID mortar

Materials and Methodology



Incorporation of bacteria into the mortar

1. Bacterial cultures were grown and prepared for each bacterial strain in accordance with each bacterial species nutrient and media preparation procedure to obtain a microbial solution with a cell population of 1.0×10^7 cell/ml.
2. Mix Waters: Distilled water or bacterial solution
3. Control experiments for OPC and PPC: Prepared using distilled water as the mix media
4. Experimental Samples: Prepared using the microbial solution as the mix media across all the bacteria under study.
5. Curing Regimes: Distilled and bacterial solution across all the bacteria under study
6. MID done for 28 days then analysed or remediated in bacterial solution for further 28 days

Key

- OPC – Ordinary Portland Cement
- PPC – Portland Pozzolana Cement
- OPC (x) – OPC paste prepared using preparation media (x); where x could be H for tap water, LB for *Lysinibacillus sphaericus* or BM for *Bacillus megaterium* respectively.
- PPC (x) – PPC paste prepared using preparation media (x).
- OPC-x (y) – OPC mortar prepared using media x and cure in media y where either x or y could be:

  H for distilled water, LB for *Lysinibacillus sphaericus*, BM for *Bacillus megaterium*, TT for *Thiobacillus thioparus*, BF for *Bacillus flexus*, BC for *Bacillus cohnii*, SK for *Starkeya novella*, TI for *Thiobacillus intermedius*, and AT for *Acidothiobacillus thiooxidans*.
- C-S-H – Calcium silicate Hydrate bond.

Table 1: Setting time, Normal consistency and Soundness for control and microbial OPC and PPC paste

Test Cement Mortar paste	Setting Time (min)		Normal consistency (%)	Soundness (mm)
	Initial	Final		
OPC (H)	98.0 ± 5.0	178.0 ± 5.0	28.0 ± 0.05	1.0 ± 0.05
PPC (H)	150.0 ± 5.0	220.0 ± 5.0	31.2 ± 0.05	0.8 ± 0.05
OPC (LB)	78.0 ± 5.0	167.0 ± 5.0	26.4 ± 0.05	1.0 ± 0.05
PPC (LB)	130.0 ± 5.0	190.0 ± 5.0	29.1 ± 0.05	1.0 ± 0.05
OPC (BM)	80.0 ± 5.0	170.0 ± 5.0	27.5 ± 0.05	1.0 ± 0.05
PPC (BM)	135.0 ± 5.0	200.0 ± 5.0	30.2 ± 0.05	1.0 ± 0.05
OPC (SK)	110 ± 5.0	195± 5.0	27.60 ± 0.05	1.4 ± 0.05
PPC (SK)	195 ± 5.0	255 ± 5.0	34.40 ± 0.05	0.9 ± 0.05

SEM micrographs for MICP Mortars

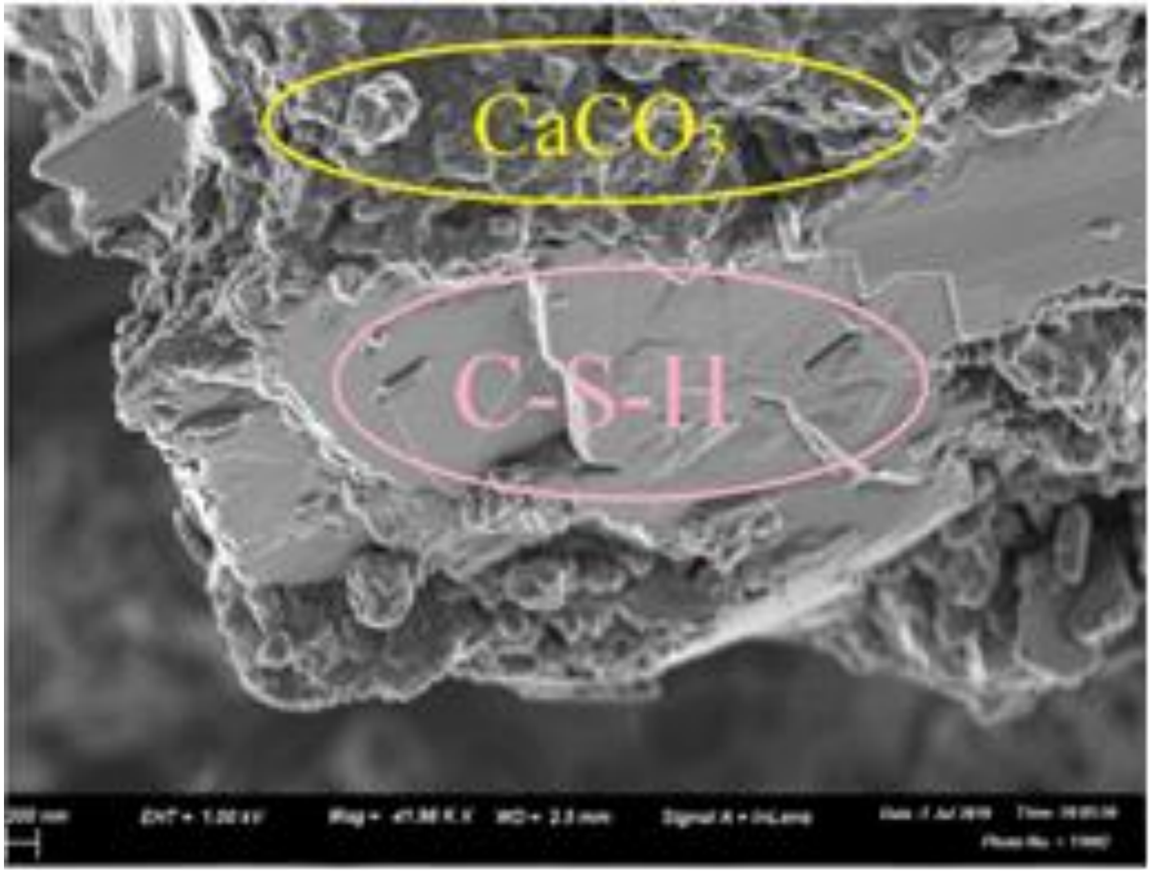


Figure 1: SEM micrographs for OPC-LB (LB).

SEM micrographs for MICP Mortars

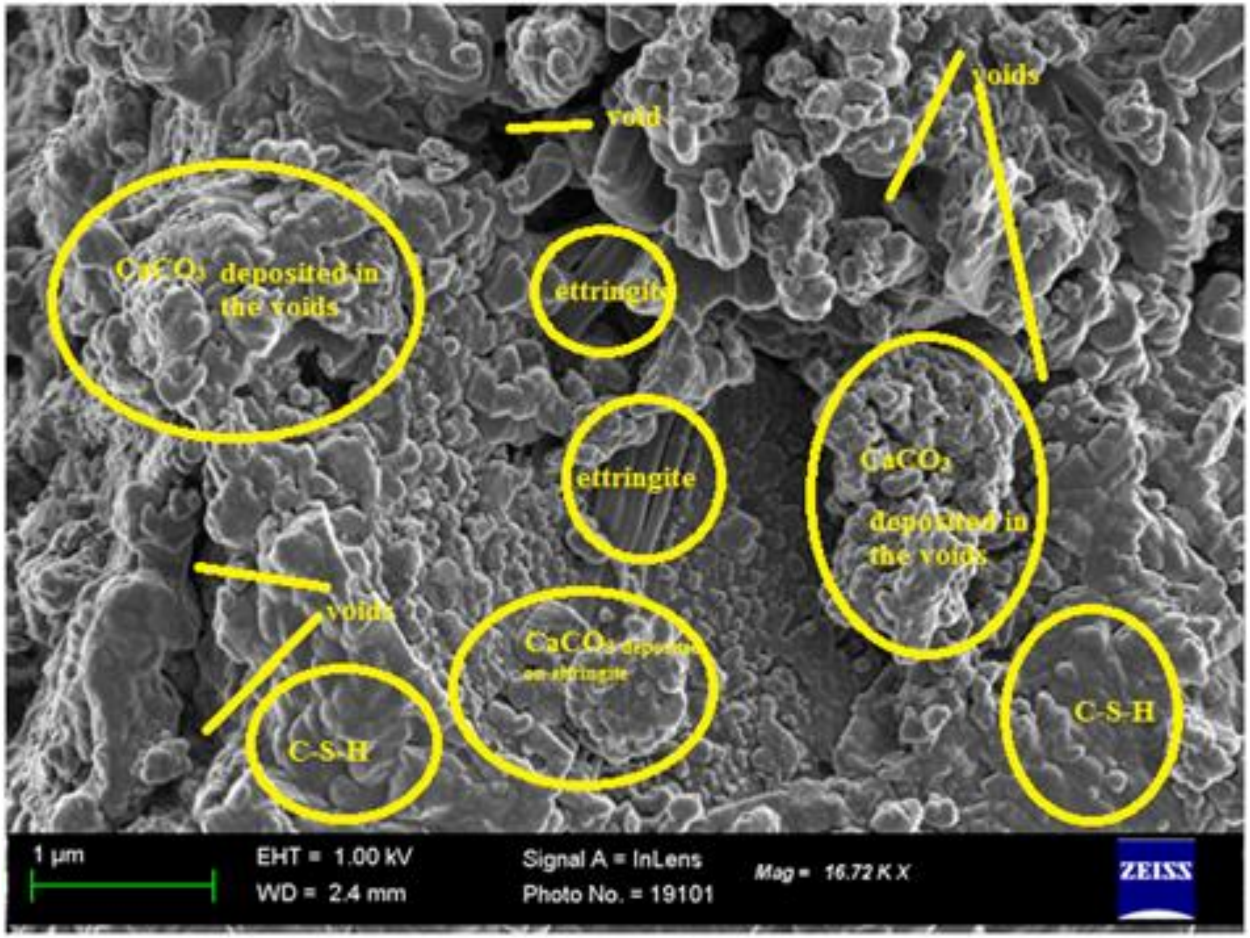


Figure 2: SEM micrographs for OPC-H (BF)

Beneficiation Bacteria

- Mcrographs were denser, more refined and less permeable mortar matrix.
- *Lysinibacillus sphaericus*, *Bacillus megaterium*, *Bacillus cohnii* and *Bacillus flexus* results to MICP beneficiation.

SEM micrograph for biodegraded mortar

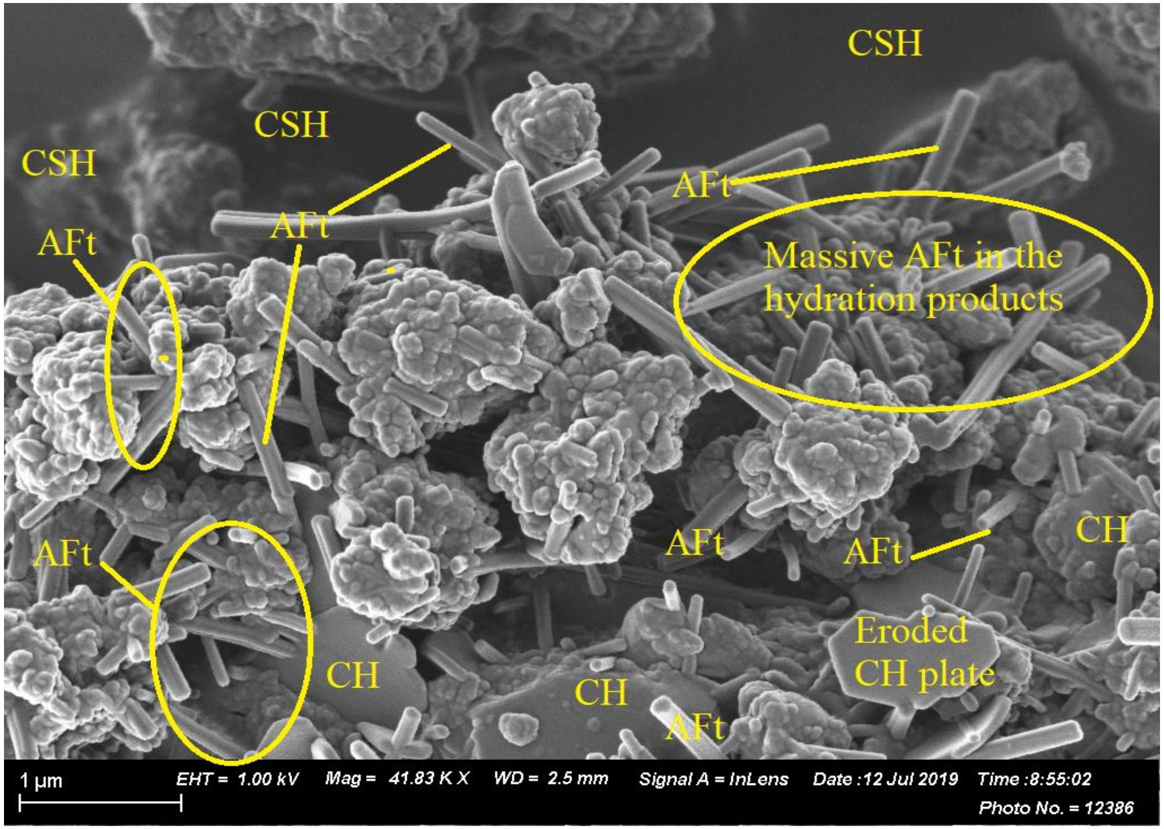


Figure 3: SEM micrographs for PPC-SK (SK)

Biodegrading Bacteria

- Cement hydration forms portlandite (calcium hydroxide) as part of hydration products, which is highly alkaline.
- The pH of the placed concrete is eventually lowered by H_2SO_4 resulting from MID
- More H_2SO_4 attack CH giving $CaSO_4.2H_2O$ that react with C_3A to form ettringite

Table 2: XRD (% w/w ± S. D. values) summary for hydrated OPC microbial mortars prepared and cured in respective microbial solution after the 28^{th} day of curing

Hydration Compound	Mortar Category (% w/w ± S. D.)		
	OPC-H (H)	OPC-LB (LB)	OPC-BM (BM)
Bavenite, $Al_2Be_2Ca_4H_2O_{28}Si_9$	-	2.53 ± 0.02	1.33 ± 0.03
Dellaite, $Ca_6H_2O_{13}Si_3$	83.93 ± 0.03	83.47± 0.02	84.18 ± 0.02
Calcite, $CaCO_3$	0.64 ± 0.02	10.23 ±0.02	10.27 ± 0.02
Portlandite, $Ca(OH)_2$	15.47 ± 0.03	3.77 ± 0.02	4.19 ± 0.02

Table 3: Percent gains Compressive strength for varied microbial mortars at 14th, 28th, and 56th day of curing.

Test Mortar Category	% gain Compressive strength at		
	14th day	28th day	56th day
OPC-H (BM)	2.5	10.4	12.1
OPC-BM (H)	3.9	12.8	15.3
OPC-BM (BM)	5.1	16.1	17.2
OPC-H (LB)	1.8	9.1	11.0
OPC-LB (H)	5.8	14.7	18.0
OPC-LB (LB)	6.9	17.0	19.8
PPC-H (BM)	1.2	9.9	10.8
PPC-BM (H)	1.2	10.2	13.7
PPC-BM (BM)	2.5	12.9	15.1
PPC-H (LB)	1.8	9.1	9.7
PPC-LB (H)	4.3	12.1	16.2
PPC-LB (LB)	5.5	14.3	18.1

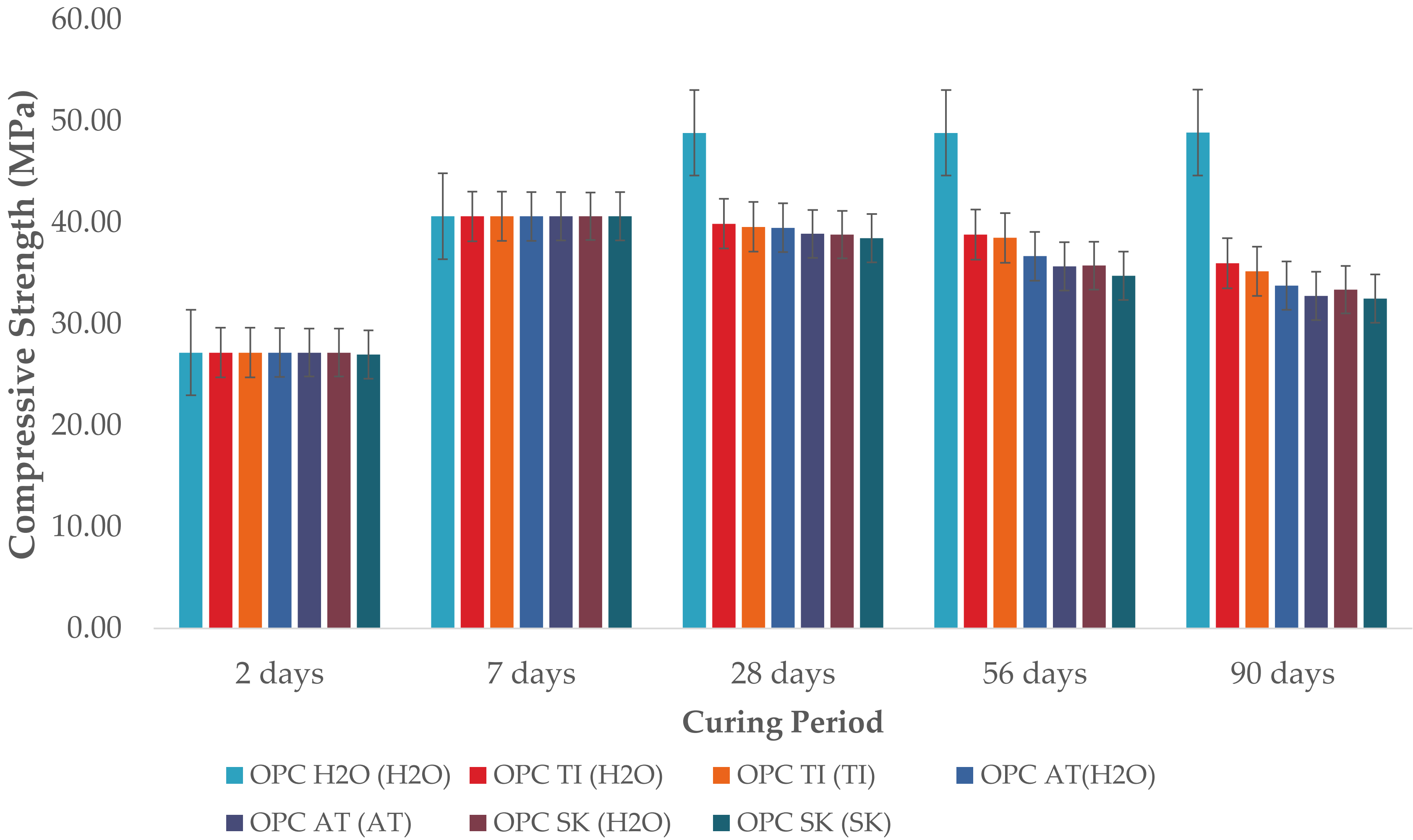


Figure 4: OPC Compressive Strength Performance in Biodegrading bacterial Solutions

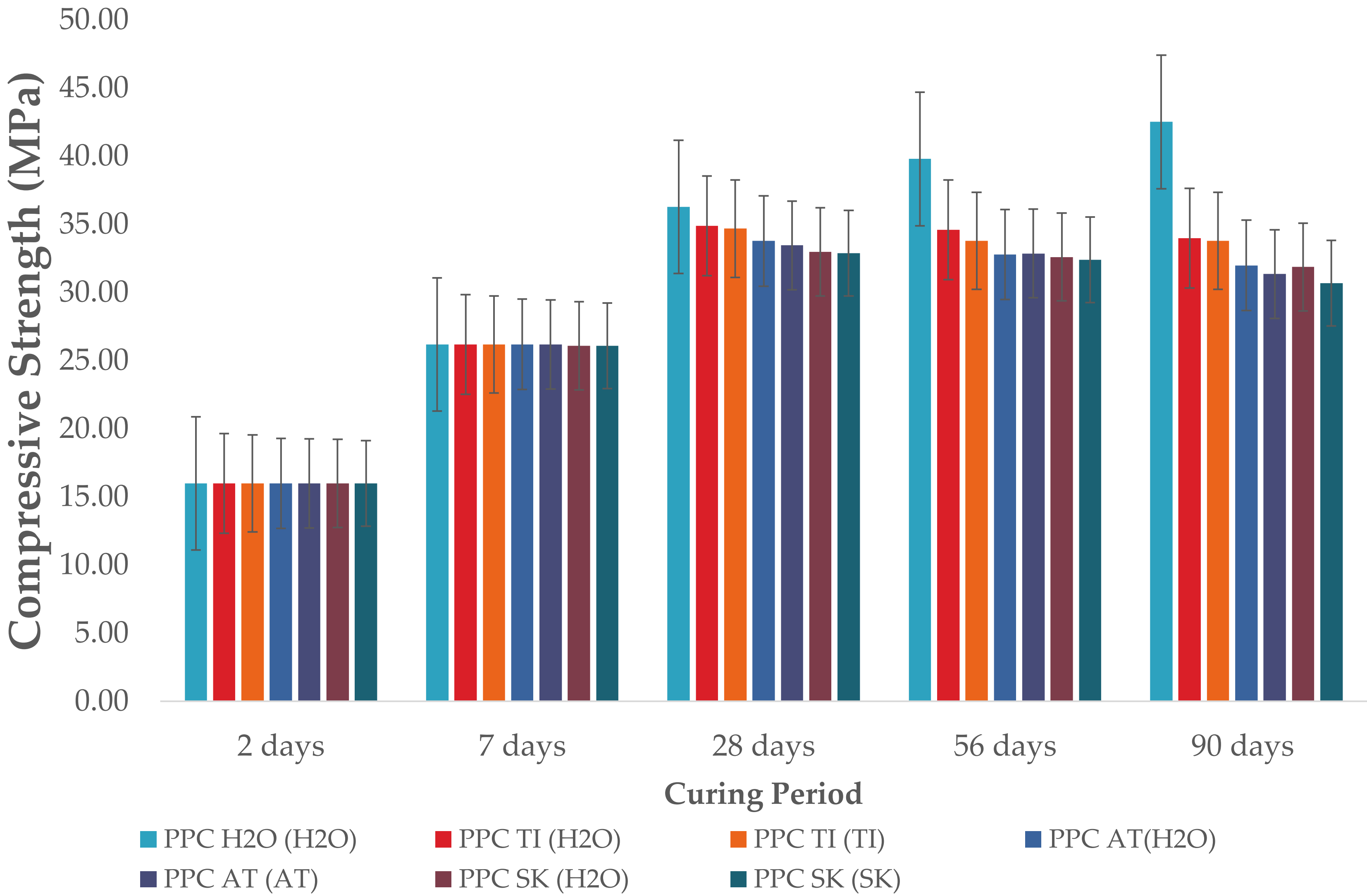
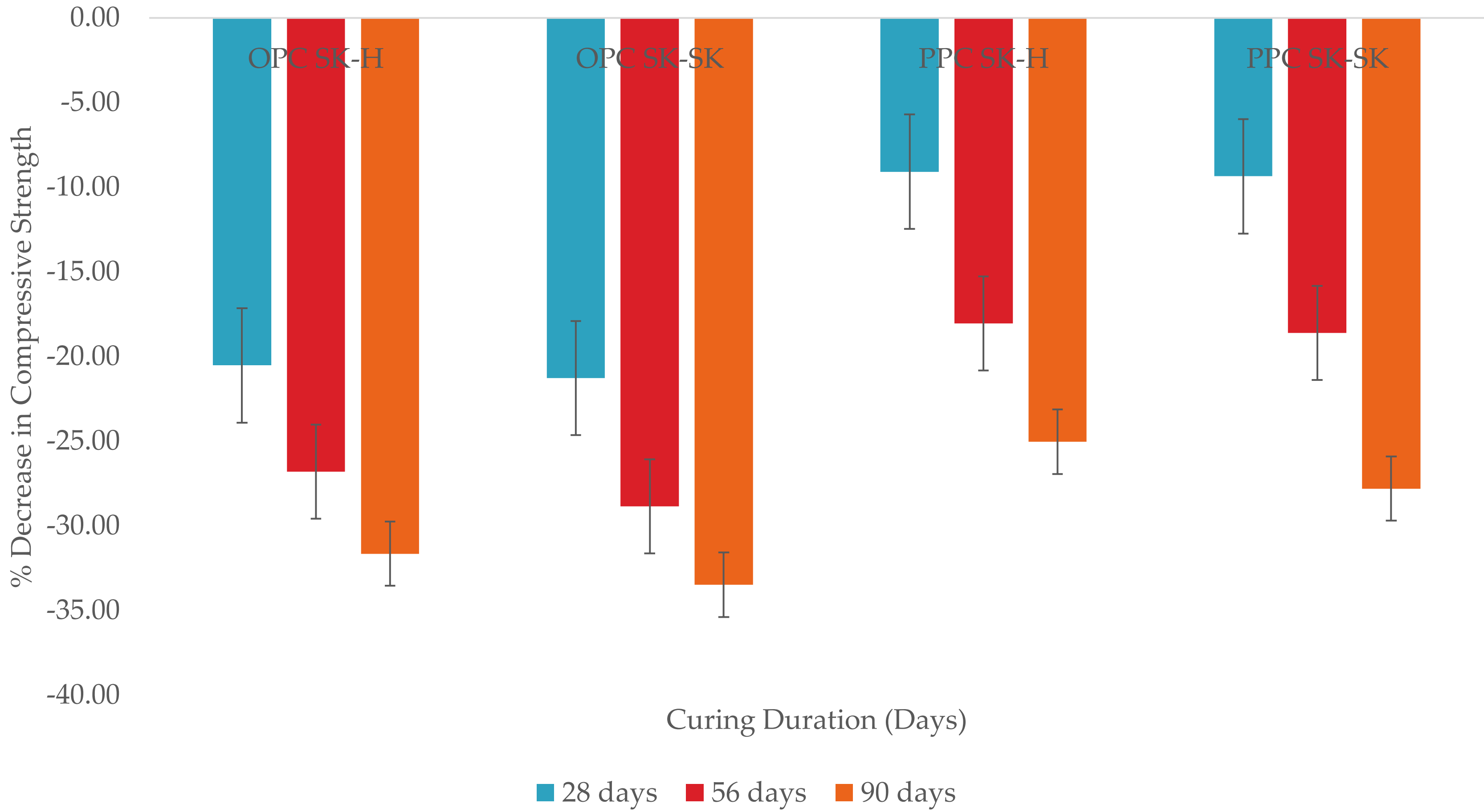
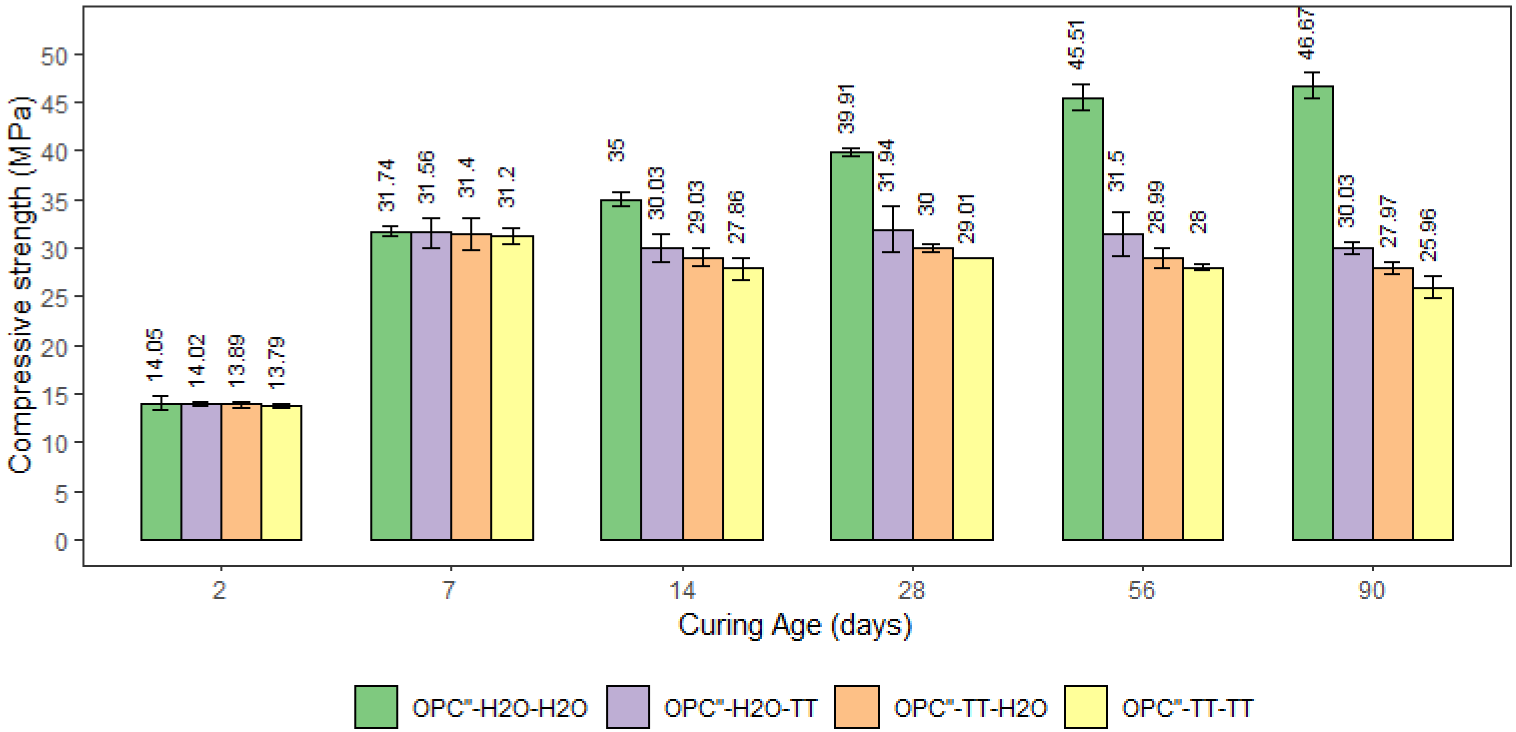


Figure 5: PPC Compressive Strength Performance in Biodegrading bacterial Solutions

Compressive strength decrease by *Starkeya novella*





Compressive strength results for *Thiobacillus thioparus* at varied curing

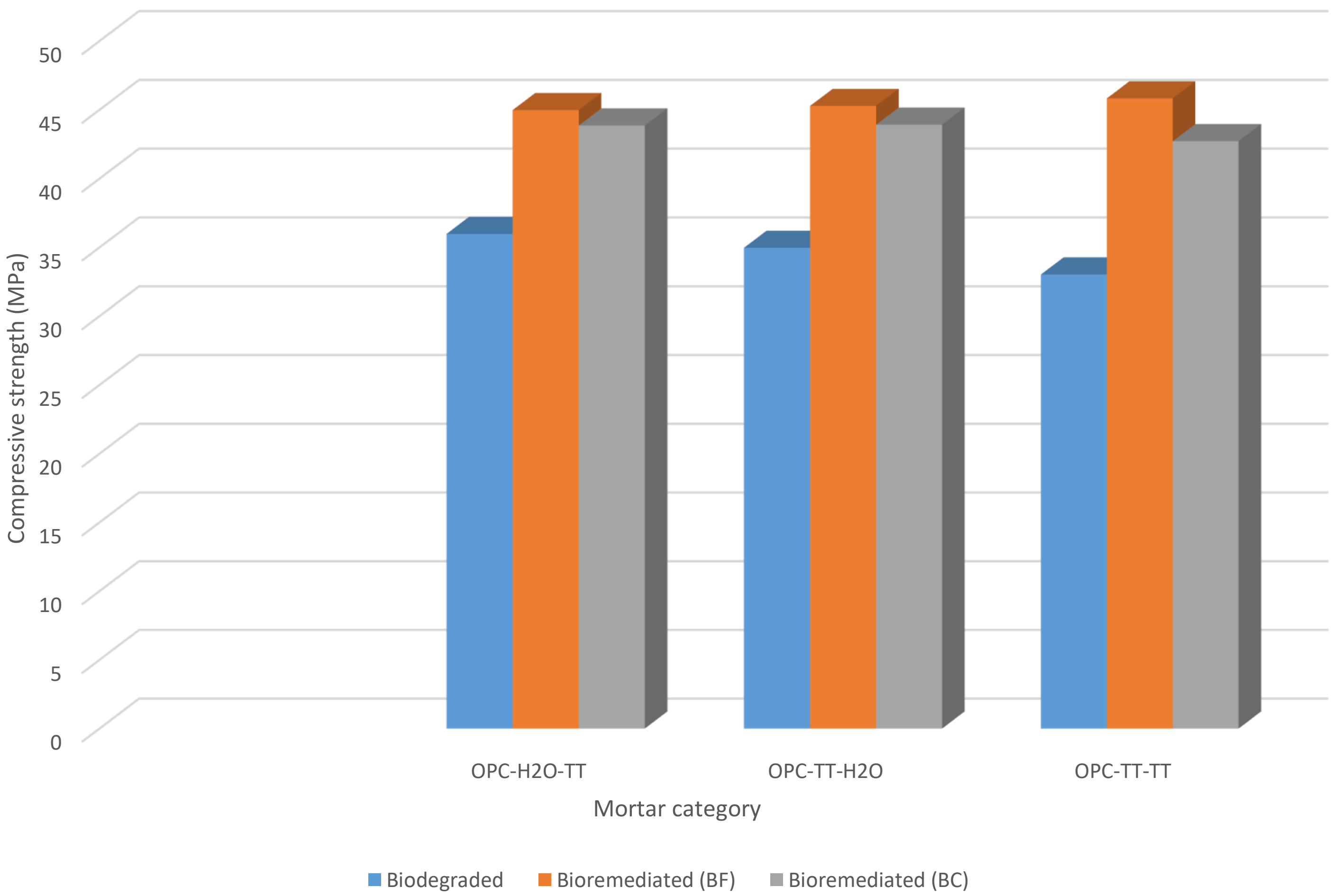
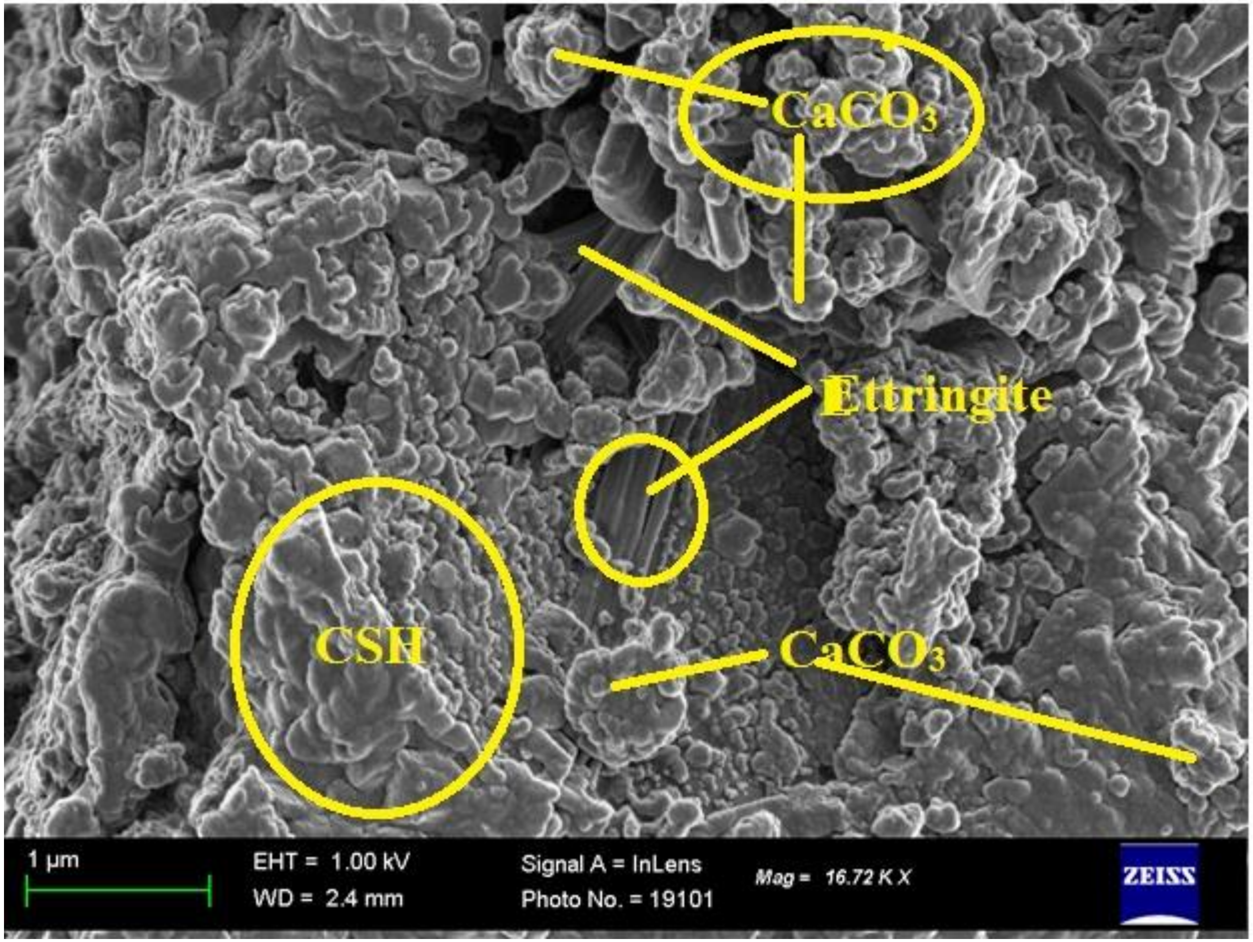
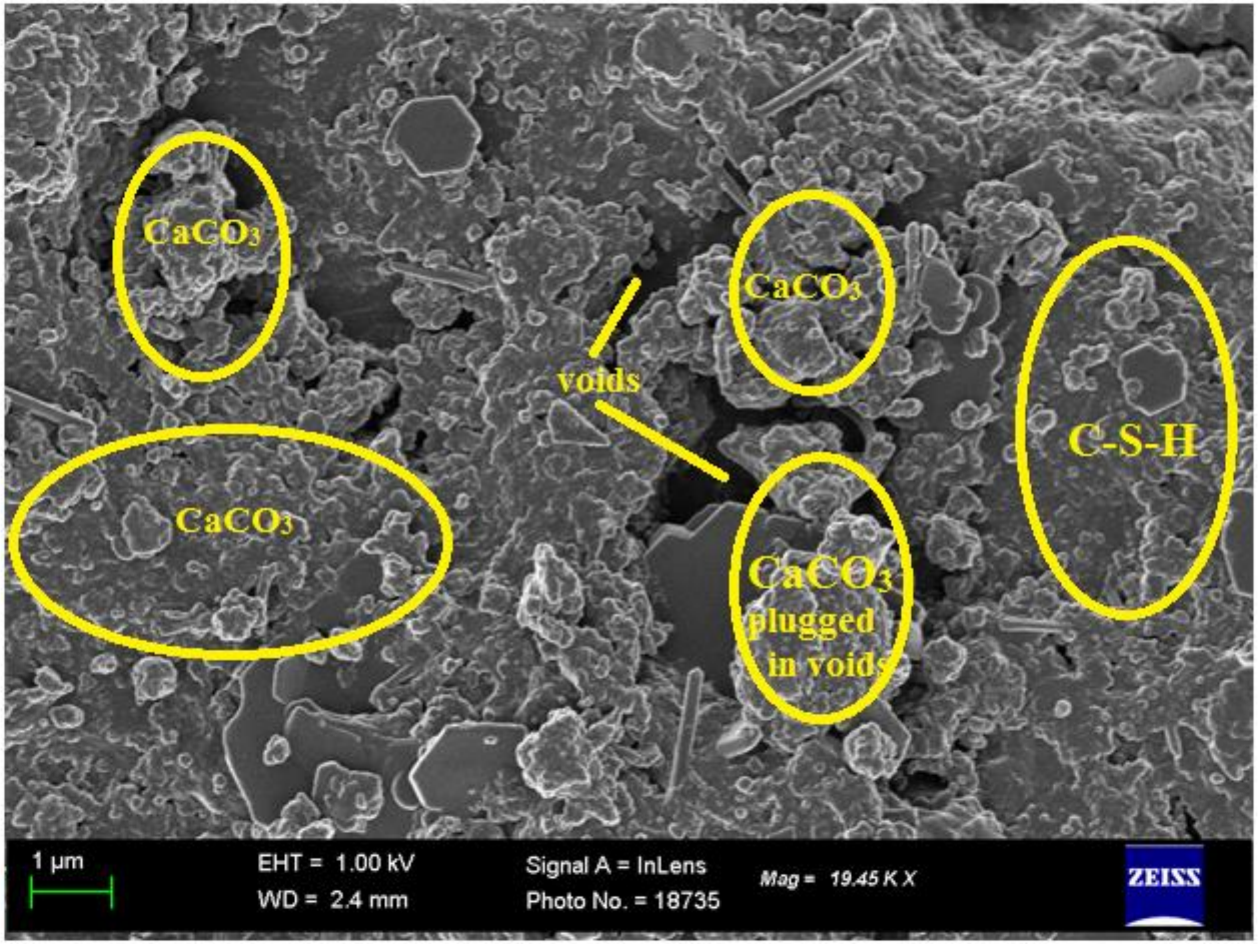


Figure 6: Per cent compressive recovery for biodegrade mortars by *Thiobacillus thioparus*



Bioremediated OPC-TT with BF



Bioremediated OPC-TT with BC

Conclusions

1. Incorporation of the test MICP *Bacillus* bacteria to the fresh cement paste, lowered the Normal Consistency, accelerated the Setting Time but had no influence on soundness. CH_3COO^{1-} was a better Setting Time accelerator than the Cl^{1-}. Calcite and Bavenite hydration is implicated with porosity improvement which was more pronounced in PPC than OPC across all MICP bacteria.

2. There was significant MICP biomineralization by *Lysinibacillus sphaericus*, *Bacillus megaterium*, *Bacillus cohnii* and *Bacillus flexus*. On the contrary, *Thiobacillus thioparus*, *Thiobacillus intermedius*, *Starkeya novella and Acidothiobacillus thiooxidans* decreased compressive strength due to adverse attack on the C-S-H.

3. Microstructural analysis (SEM) showed denser, more refined and less permeable mortar matrix with microbial incorporation using *Lysinibacillus sphaericus*, *Bacillus megaterium*, *Bacillus cohnii* and *Bacillus flexus* as opposed to incorporating *Thiobacillus thioparus*.

Conclusion

4. *Bacillus cohnii* and *Bacillus flexus* aided in bioremediation/repair of biodegraded mortars by *Thiobacillus thioparus*. This shows that *Bacillus cohnii* and *Bacillus flexus* could perhaps heal deteriorated cement based materials in sewer lines and waste water treatment systems.

5. *Bacillus megaterium*, *Lysinibacillus sphaericus*, *Bacillus cohnii* and *Bacillus flexus* MICP provides an improved ingress and sorption inhibitor.