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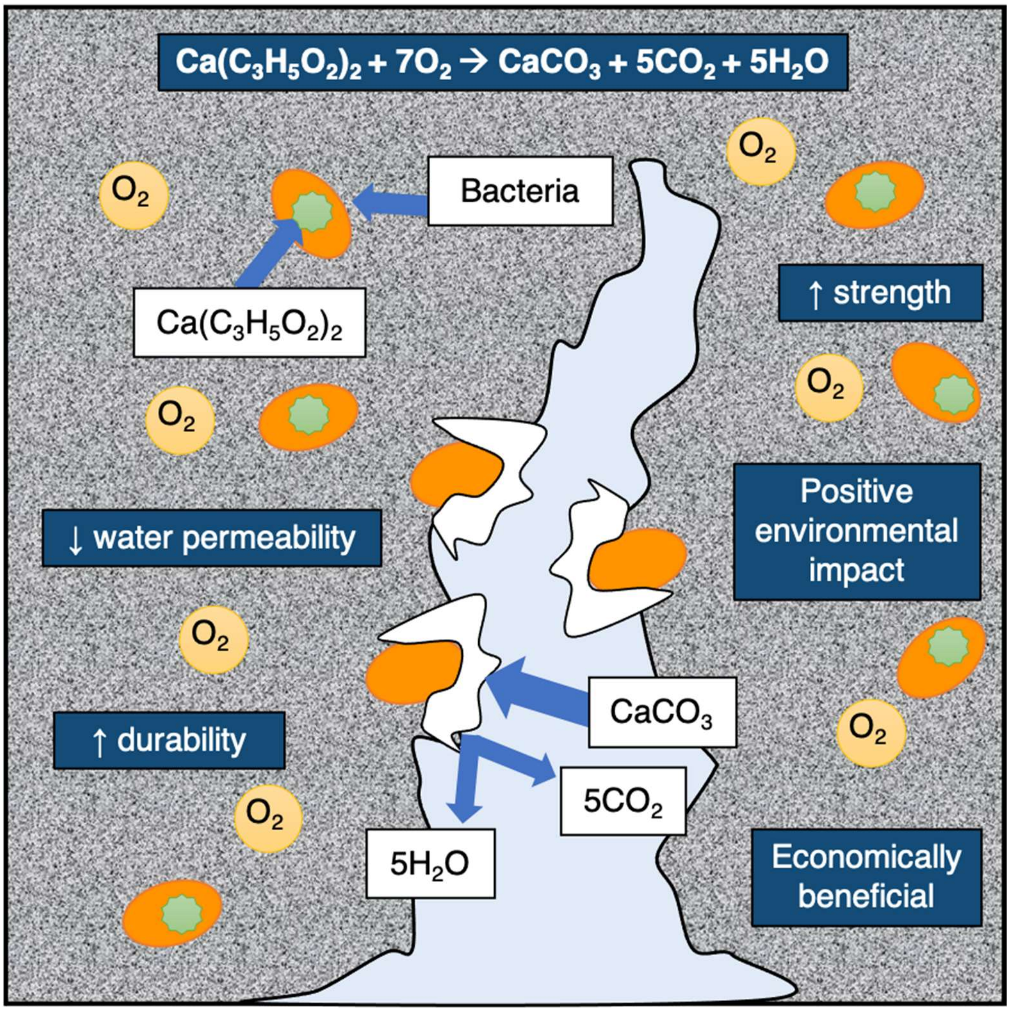
Bacterial Concrete: A Sustainable Building Material with Advantageous Properties



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REVIEW ARTICLE

Bacterial Concrete: A Sustainable Building Material with Advantageous Properties

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ABSTRACT

Bacterial concrete is concrete in which bacteria are embedded and is a material which exploits the metabolic functions of these specially selected bacteria, genus *Bacillus*. The bacteria are amalgamated within clay pellets along with the nutrient calcium lactate. When the concrete around the pellet cracks, the pellets break, and the bacteria metabolise the calcium lactate to produce insoluble calcium carbonate, filling cracks up to ~2 mm wide. The addition of the clay pellets and the bacteria to the concrete improves its compressive and tensile strengths, making it better suited for applications where the concrete must endure severe stress. Consequently, the modulus of toughness is improved, though the extent of the improvement depends on the grade of concrete used. Bacterial concrete is industrially advantageous as its low coefficient of permeability and high acid durability factor makes it less prone to corrosion and less likely to require extensive repairs. This is ideal for structures that are difficult or expensive to maintain as well as for use in motorways that endure corrosion from salt used in de-icing. This review will focus on the properties of bacterial concrete and its industrial use. It reveals that despite higher initial costs, the enhanced properties of bacterial concrete compared to conventional concrete, makes it a more sustainable material in the long run with an overall benefit to global carbon emissions.

Keywords: strength, *Bacillus*, durability, self-healing concrete, bacteria

INTRODUCTION

Concrete is currently the most used man-made material, with around 12 billion metric tons being used for construction annually [1]. Amounting to approximately two metric tons per person per year, this is therefore the second-largest volume of a substance utilised by humans, following water [1]. Concrete consists of multiple substances, making it a composite. The different materials that make up a composite are often referred to as the matrix and the binder. A matrix is a homogenous material in which the fibre system of the composite is embedded: concrete has a matrix of aggregate, which is a rocky material [2]. A binder is a substance that holds the matrix together and, in the case of concrete, is either Portland cement or asphalt [3].

Problematically, concrete is not indestructible, and cracks will inevitably form. Whilst some concrete structures can be fixed due to autogenous healing, many require repair and sometimes even the replacement of a concrete structure. Many of these structures can be difficult and expensive to repair due to their location and accessibility. Worldwide, a sizeable budget is allocated for the repair of existing concrete structures, with each m^3 of concrete estimated to require £117 in repairs [4]. For example, in the UK, 45% of the construction and building industry is related to repair and maintenance [1]. There are also indirect costs of closing bridges, motorways, and roads for repairs due to the economic activities they interrupt. This cost is estimated to be 10 times higher than the direct maintenance costs, which may reach $63 billion per year in the USA [5]. The costs of repairing these structures, both direct and indirect, can be substantially reduced by the implantation of certain bacteria into the concrete matrix.

Bacterial concrete has the ability to fill cracks which develop in its structure without human intervention. To do this, specially selected types of bacteria genus *Bacillus,* a calcium-based nutrient (calcium lactate), nitrogen, and phosphorus are added to the concrete and are encased in clay pellets in the ratio 1:19 of bacteria to calcium source [6]. These range in size from 0.1 mm to 0.5 mm for protection purposes, as this prevents the exposure of the bacteria to the external environment [6]. *Bacillus* is spore-forming, meaning it forms specialised, thick cell walls that protect it. This allows the bacteria to lie dormant within the concrete for up to 200 years [6, 7]. Although most organisms cannot survive in conditions where pH ≤ 10, the bacteria are alkaliphilic, allowing them to survive in the very alkaline (~pH 13) conditions of the concrete [8]. Once a crack forms in the concrete, the clay pellets around the crack are broken, allowing the bacteria to metabolise the nutrient and perform their regular metabolic functions. This results in the production of insoluble calcium carbonate ($CaCO_3$), which consequently fills the cracks.

Conventional concrete costs roughly £65-£75 per m^3, whilst bacterial concrete costs around £90 per m^3, but it could prove to be a worthwhile investment [4, 9, 10]. Although the cost of bacterial concrete is initially higher, in the long term, its use is thought to reduce the amount spent on repairs and the associated disruptions. The ability to seal cracks is not the only advantageous property of bacterial concrete: the compressive and tensile strengths are increased, and the decreased porosity of bacterial concrete results in greater durability. The permeability is reduced, reducing the penetration of harmful substances which may adversely affect the concrete's structure. If bacterial concrete was in more widespread use, it would decrease global cement production and thus CO_2 emissions. Therefore, despite higher initial costs, bacterial concrete is a promising development in the field of civil engineering (Table 1).

Healing Capacity

Whilst both conventional concrete and bacterial concrete have the ability to seal their cracks without human intervention, the healing capacity of conventional (normal) concrete is very limited and comparatively insignificant [12]. The extent of autogenous healing that can happen in conventional concrete is completely reliant on the quantity of non-hydrated cement particles in the concrete matrix and the volume of ingress water [8]. This is because when concrete cracks, the non-hydrated cement particles exposed will go through secondary hydration forming portlandite (calcium hydroxide) [7]. CO_2 then reacts with the portlandite to produce calcium carbonate-based mineral precipitates (Eqn. 1) [7].

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \quad (1)$$

The width of the cracks that can be fixed through autogenous healing is dependent on the environment the concrete resides in and the quantity of non-hydrated cement particles, but generally ranges between 0.1-0.3 mm [13]. Therefore, normal concrete structures are designed to allow cracks up to 0.2 mm wide to form, since these cracks will not compromise the strength of the construction [6]. However, the variability of autogenous crack healing means that it is very difficult to predict the healing capacity of concrete with accuracy: this can cause water leakage in underground structures due to the formation of microcracks [8].

Bacterial concrete, however, undergoes a much more efficient healing process than conventional concrete. The bacteria encased in the clay pellets only require exposure to air to activate them, which happens when the concrete around the pellet cracks, causing the pellet to break [7]. This allows the calcium lactate (the precursor material) to react with the bacteria, which then reacts to produce a highly impermeable calcite layer (Eqn. 2).

$$Ca(C_3H_5O_2)_2 + 7O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O \quad (2)$$

$CaCO_3$ is produced from the metabolic reactions of the bacteria and the reaction between the non-hydrated cement particles and CO_2 from the bacteria's metabolic reaction. In terms of molar quantity, reactions of the bacteria themselves produce one mole of $CaCO_3$. Once the five moles of CO_2 from these metabolic reactions react with the portlandite, five additional moles of $CaCO_3$ are produced, resulting in a net total of six moles of $CaCO_3$ [7]. This makes the crack filling process extremely efficient.

Wiktor & Jonkers illustrated that from a crack surface point of view, cracks of up to 0.46 mm wide healed in the bacteria-based concrete, whilst cracks of 0.18 mm healed in the normal concrete [13]. This is further supported in an additional study where an even larger artificial crack of width 1.88 mm was healed by the bacteria *Bacillus subtilis HU58* [14]. However, this large number is rather anomalous when compared to data proposed in other studies. Wang *et al.* observed that cracks up to 0.97 mm wide could be 'healed' through the addition of *Bacillus sphaericus* [15]. The ~250% improvement in healing properties highlights

Table 1 – Summary of the properties of bacterial concrete.

Property	Effect	Ref(s)	Industrial Applications	Future Research Directions
Healing Capacity	The healing capacity increases by approximately 250%.	7, 14, 12, 15	Any application because cracks inevitably form in concrete.	More studies must be conducted because the reported width of cracks that can be healed by the bacteria varies between papers.
Water Permeability	Permeability significantly decreases by an average of 78%.	19, 20, 21, 22, 23, 25, 29, 30, 31, 32	Any application where the concrete is surrounded by liquid or harmful chemicals, e.g., dams and underground structures.	Additional research to find other ways to make concrete less porous. The optimum conditions for bacteria to produce $CaCO_3$ need to be better studied.
Durability	Acid durability factor increases, alongside resistance to thawing and freezing.	21, 22, 34, 35	Underground structures, as they must endure harsh conditions. Motorways, and structures in cold areas.	More precise figures and data into how long bacterial concrete can last under different conditions, and the impact that these conditions have on the concrete and its properties.
Compressive Strength	Increases by around 30%.	16, 22, 36, 37, 38	Dams, underground structures, canals, sewage systems.	More investigation into the effects of different bacteria, genus *Bacillus*, such as *Bacillus pasteurii*, or other substances on compressive strength.
Stress Strain Behaviour	Stress strain behaviour is improved, it can withstand higher levels of stress without plastically deforming.	11, 38, 40, 43, 44	For use as a protective material, such as sea walls.	How stress strain behaviour changes with larger concrete specimens.
Cost	The cost is initially higher; however, the cost of repair is decreased.	4, 9, 10, 17	It is an investment, so its applications include every concrete structure.	Modelling to predict how the price changes when the production and use is scaled up.
Environmental Impact	Decreased CO_2 emissions as less cement will need to be produced globally.	7	It will help combat global warming and conserve resources for use in future buildings.	Specific data and figures as to how much cement production would decrease by.
Tensile Strength	Splitting tensile strength increases	11, 36, 37, 40, 41	For use as a protective material, such as sea walls.	How tensile strength changes with larger concrete specimens.
Grades of Concrete	Lower grades of bacterial concrete can replace higher grades of regular concrete.	20, 22	This could result in lower costs, so includes all applications of concrete, but effects are currently not well understood.	A study that directly compares lower grades of bacterial concrete with higher grades of regular concrete.

the vast advantage of using bacterial concrete as opposed to conventional concrete. This improvement, combined with the fact that this healing is independent of human intervention, indicates that it is a worthwhile investment, especially for applications like underground tunnels.

In theory, one could make high binder mixtures to increase the self-healing capacity of conventional concrete, because this would increase the quantity of non-hydrated cement particles in the matrix [7]. However, to ensure compliance with global climate targets the production of cement needs to be limited as it currently contributes to between 7-8% of global anthropogenic CO_2 emissions [7]. These high levels of CO_2 emissions originate from the sintering of $CaCO_3$ and clay at 1500°C, during which the $CaCO_3$ is converted into calcium oxide, further releasing CO_2 [16]. The superior healing capacity of bacterial concrete means there would be lower concrete consumption/production if there is an increased the use of bacterial concrete. This is because less cement would need to be produced for the repair or replacement of structures as bacterial concrete structures last longer than regular concrete. Therefore, opting for a longer-lasting form of concrete would be environmentally beneficial.

The healing process of bacterial concrete is much more effective than the autogenous healing that regular concrete undergoes [7]. This ability to self-heal means running costs are lower, which compensates for the higher initial price. This implies that for many applications with a high repair frequency and cost, bacterial concrete presents itself as a viable investment. Over time, as the technology evolves, the initial cost penalty would be expected to decline and the repair efficacy increase, improving the economic equation further.

Properties

Whilst the clay pellets protect the bacteria, they fill roughly 20% of the concrete's volume which would usually be taken up by a harder aggregate material such as gravel [8]. The bacteria and the clay pellets not only enhance the concrete's capacity to heal its cracks but also influence the properties of the concrete, such as its strength and permeability. However, these properties are also dependent on the grade of concrete in use. A grade of concrete is defined as the minimum strength that the concrete must possess after 28 days, which is determined by the ratio of its 'ingredients' (ratio of cement to sand to aggregate) and is denoted by prefixing M, which stands for mix, to the desired strength in MPa [17]. Each grade is therefore used for different applications correlating to the strength required for that purpose, ensuring cost efficiency. Grade M40 concrete is generally considered the standard, whilst grade M80 is considered very high strength concrete.

Corrosion

Having a low coefficient of permeability is a desirable quality in concrete because it ensures that fewer oxidising agents can corrode the concrete. Concrete corrodes due to the steel reinforcement inside it, which is implemented to increase its tensile strength but is vulnerable when it comes into contact with certain substances, such as water or oxygen [18]. It becomes more susceptible to corrosion due to cracks, which can form due to thermal expansion or tensile stress, because oxidising agents can reach the steel through these cracks. Longer term, concrete matrix degradation can result from the ingress of chemicals such as sulphates, chlorides, and acids.

Water Permeability

Water permeability, or how easily water can invade the material, of concrete is dependent on the porosity and on the connectivity of the pores. The more open the pore structures are, the more vulnerable the concrete is to matrix degradation [19]. Low permeability is desirable in order to limit the entrance of harmful chemicals into the concrete, allowing it to last longer.

Srinivasa Reddy *et al.* conducted a depth of penetration test to determine the water permeability of regular concrete and bacterial concrete using *Bacillus subtilus* [20]. The grade M20 concrete treated with bacteria faced only a 5 mm penetration depth after 96 hours, whilst the control specimen had a penetration depth of 23 mm [20]. The grade M80 conventional concrete also had a penetration depth of 5 mm, meaning that grade M20 conventional concrete has a very similar level of water permeability, emphasising the extent to which this property is improved through the addition of bacteria [20]. The coefficients of permeability of the concrete samples were then calculated by subjecting the samples to hydrostatic pressure, so that water percolated from above the specimen's top surface and collected in a bottle at periodic intervals [20]. The M20 concrete underwent an 88% reduction in its coefficient of permeability once the bacteria were introduced into the concrete matrix [20].

The depth of water penetration measured in the bacteria-treated specimens show that they are highly impermeable. The depth of penetration is reduced in bacteria-treated specimens by ~75% across all grades of concrete due to the formation of highly impermeable calcite ($CaCO_3$) layer on the surface and inside the pores [20]. The coefficient of permeability also decreased across all grades by an average of 78% upon the addition of bacteria to the concrete [20]. Their results are supported by tests conducted by Achal *et al*. and Azmatunnisa *et al.*, who showed that bacteria-embedded concrete has lower water and chloride permeability levels than regular concrete [21, 22]. In addition to this, Mukherjee *et al.* found that the permeability of concrete with *Bacillus sp. CT-5* added to its matrix was significantly decreased; over a period of 168 hours, bacterial treated specimen surfaces absorbed almost six times less water than their untreated counterparts [19]. However, these tests were performed under ideal lab conditions, which may not be the case when this form of concrete is used for real-life applications. Together, these studies demonstrate that the bacteria-treated concrete is less permeable, enhancing both its strength and durability. These qualities would be valuable in motorways as they are very vulnerable to corrosion due to the salts used to de-ice the roads. These salts can penetrate the cracks, which accelerates the corrosion of the steel because the salt destroys the steel's protective iron hydroxide layer, rusting the steel aggressively [18]. However, in the cold temperatures where ice occurs, the enzymatic performance of the bacteria may be negatively impacted, meaning $CaCO_3$ will be produced at a lower rate if a crack occurs [23].

An alternative way to increase the durability of concrete is by directly inhibiting the corrosion of the steel reinforcement through the addition of a corrosion-inhibiting admixture, such as calcium nitrite ($Ca(NO_2)_2$), which has a benign effect on the properties of concrete [24]. This is a relatively easy and economical way to prevent corrosion. Królikowski and Kuziak found that calcium nitrite can obstruct initiated corrosion of steel after exposing concrete samples to different concentrations of calcium nitrite and then to a 1% solution of sodium chloride (meaning that the chloride to nitrite ratio changed), before examining the corrosion caused through electrochemical impedance spectroscopy [25]. Many inhibitors act by forming a protective film around the steel to stabilise it while other inhibitors react with the concrete to reduce its permeability [26]. Calcium nitrite, an anodic inhibitor, modifies the electrochemistry of the steel's surface to reinforce the passive film against corrosion, thus decreasing the concrete's rate of corrosion [27]. The results of this study confirmed the development of passive film on the steel surface and showed that the repassivation of steel occurs for the chloride to nitrite ratio below 1 [25]. It has little effect on the concrete's chloride permeability, unlike bacteria-treated concrete [28].

Together, using *Bacillus* infused bacteria with corrosion inhibiting admixtures could improve the overall properties of concrete. Karimi *et al*. found that the presence of *Bacillus subtilis* in the concrete mixture combined with the curing of the concrete specimens in a solution containing calcium for 28 days led to a carbonation depth that was reduced by ~10% [29]. This reduction could be improved further by the addition of bar chip fibres, which prompts a ~19% decrease in the carbonation depth [29]. The reduction in the carbonation depth is caused by calcite sediments being deposited in the concretes pores as a result of bacterial activity [29]. Furthermore, Verstraete *et al.* also found that the combination of the addition of *Bacillus sphaericus* and a calcium source (acetate or chloride) caused a 58% drop in the carbonation rate of the concrete after being cured for 28 days when compared to that of untreated specimens [30]. However, Franke *et al.* found that when calcium nitrite was added, the carbonation depth of concrete was reduced by up to 40% depending on the cement type and test method [31]. Overall, the addition of calcium nitrite, or the addition of bacteria into the concrete matrix reduces the carbonation depth. The extent of the reduction varies between studies, likely as a result of the different conditions the concrete experienced, including the different types of bacteria used and the addition of other materials. Therefore, depending on the type of bacteria added, concrete with calcium nitrite displays a similar carbonation depth to that of bacterial concrete meaning that they will have similar levels of durability.

There are many other proposed corrosion protection systems that could be used instead of calcium nitrite, such as epoxy-coated reinforcing steel, stainless steel, surface impregnation of concrete, and cathodic protection [28]. Muynck *et al.* conducted a series of experiments to compare concrete treated with *Bacillus sphaericus* with concrete treated with different substances, such as water repellent and surface treatments. It was found that bacterial depositions of a layer of calcite on the surface of the specimens resulted in a decrease in capillary water uptake and gas permeability [32]. However, their results indicated that surface coatings, such as epoxy, improved the gas permeability to a larger extent than bacteria did; the reduction of permeability due to bacterial treatment was to the same extent as that for treatment with penetrating sealants [32]. Despite this, surface treatments have many disadvantages, such as degradation over time, the different coefficients of thermal expansion for their layers, and the fact that they require constant maintenance [32]. The disadvantageous aspects of conventional surface treatments necessitate the development and optimisation of bacterial concrete. Overall, the results concerning capillary water uptake and gas permeability obtained for bacterial concrete were similar to those obtained with regular water replants, such as silanes [32]. Further experimentation into how these substances affect the properties of concrete needs to be conducted in order to evaluate their use confidently.

In comparison, calcium nitrite and surface treatments are more efficient at inhibiting corrosion in concrete than bacteria, genus *Bacillus*. However, whilst the implementation of calcium nitrite and surface treatments only serve to decrease the corrosion of the concrete, the addition of bacteria offers wider ranging enhanced properties.

Durability

The durability of concrete can be defined as its ability to last for a prolonged time without significant deterioration. One factor that increases the durability of bacterial concrete is the fact that it consumes oxygen during the conversion of calcium lactate to $CaCO_3$, which – given oxygen is an essential element in the process of corrosion – reduces corrosion [8]. The durability of a material negatively correlates with its coefficient of permeability: as the coefficient of permeability decreases, the material becomes less permeable and is, therefore, more durable. Hence, a lower coefficient of permeability is desirable which is a property of bacterial concrete.

The term ‘durability’ also covers the ability of a material to withstand harsh conditions, such as acidic conditions. Srinivasa Reddy *et al*. performed an acid durability test by exposing normal and bacteria-treated specimens to a 5% solution of H_2SO_4 to determine their resistance to an aggressive environment [22]. Their results showed that the bacteria affected the concrete’s resistance to the acid. After 90 days of immersion, the grade M80 control specimen suffered a ~4% loss in mass and an ~11% loss of its compressive strength, whereas its bacteria-treated counterpart only underwent a ~3% loss in mass and a ~6% loss in compressive strength. For every grade, the bacteria-treated concrete endured on average ~20% lower loss in mass and ~40% less of a decrease in compressive strength. Therefore, bacterial concrete is more durable in terms of its ‘Acid Durability Factor’ than conventional concrete. This is an important quality because acid rain, which has a pH of 4.0, is relatively common and is especially prevalent in the North-Eastern parts of the United States [33]. This property is essential to ensure that the concrete can withstand these harsh conditions.

The durability is also increased due to the porosity of the concrete being decreased. The less porous concrete is, the harder it is for harmful chemicals to flow through the concrete. Achal *et al.* observed a 50% decrease in the porosity of concrete treated with *Bacillus sp. CT-5*, and Fares *et al.* also observed a decrease in porosity [21, 34]. This decrease in porosity is caused by the pores in bacterial concrete being plugged by the calcite deposits, meaning that the flow of oxygen and nutrients to the bacteria stops, eventually causing the bacteria to die or turn into endospores. The increase in the matrix strength therefore would have resulted in less expansion on average, overall increasing the durability and performance of the concrete [19].

Concrete must endure extremes in temperatures so its resistance to freezing is vital for its use in cold areas. Muynck *et al*. tested the resistance of regular concrete and concrete treated with *Bacillus sphaericus* by subjecting the specimens to 21 cycles of freezing and thawing, each consisting of 24 hours of exposure to temperatures between 10°C and −15°C, followed by 10 hours of exposure to temperatures at −15°C. The bacterial specimens showed increased resistance to freezing and thawing as shown by their higher splitting tensile strengths after the freezing and thawing test when compared to that of regular concrete [35].

In summary, the durability of concrete is enhanced through the addition of bacteria as shown by its increased acid durability factor, its increased resistance to freezing and thawing, and its decreased porosity. This property means that bacteria-treated concrete can last longer and under harsher conditions than conventional concrete.

Strength

From an engineering viewpoint, strength refers to the ability of a material to withstand an applied load without failure or plastic deformation. With 20% of bacterial concrete being made from clay, a material absent from the composition of regular concrete, the strength of concrete is significantly impacted [8].

Compressive Strength

Compressive strength is one of the most important measures of strength when discussing concrete as it measures the ability of a material to withstand loads that will decrease its size. With many applications of concrete being large structures that must endure stress (e.g., multi-story car parks and dams), it must have high compressive strength.

Many organic bio-cement precursor compounds have been tested, but the introduction of, for example, yeast extract into the cement resulted in a decrease of around 50% in the compressive strength [16]. However, the use of calcium lactate ($C_6H_{10}CaO_6$) caused a 10% increase in the concrete's compressive strength, which contrasted with all of the other bio-cement precursors compounds tested [16]. Srinivasa Reddy *et al.* investigated this further by testing the compressive strengths of cement specimens with different cell concentrations of the alkaliphilic microorganism, *Bacillus subtilis*, aged 7 and 28 days [22]. Results from these tests identified 10^5 cells/ml as the optimum concentration of the bacteria within the concrete matrix as it caused a ~21% increase in the compressive strength. The compressive strength of the control and bacterial concrete specimens were tested, it was found that the strength improved by an average of ~23% [22]. Subha *et al.* also observed that concrete's compressive strength increased significantly by 42% for the concentration of 10^5 cells/ml [36]. Furthermore, Shashank *et al.* observed a ~36% increase in the compressive strength of concrete with a concentration of 10^6 cells/ml of an unidentified culture of bacteria [37]. In addition to this, Porto *et al.* detected a 31% increase in the compressive strength upon the addition of *Bacillus subtilis* [38]. The compressive strength increases due to mortar being deposited on the cell surfaces of the microorganism and within the pores of the cement-sand matrix. These results demonstrate that bacterial concrete has higher compressive strength, meaning that more pressure must be applied to the concrete for cracks to form, making it safer for applications such as foundations or motorways. The extent to which the compressive strength increases depends on the concentration of cells and the type of bacteria employed within the matrix; it also relies heavily on the bio-cement precursor compound used.

Tensile Strength

Concrete has a comparatively low tensile strength, or ability to withstand tension. Although tensile strength is, in relative terms, a less crucial quality than compressive strength; it is still important as many cracks form due to tensile stress because concrete structures are vulnerable to tensile cracking due to various effects and applied loading [40]. Verstraete *et* *al.* found that the tensile strength of concrete with *Bacillus sphaericus* was 0.007 N/mm^2, whilst the tensile strength of conventional concrete is so negligible that it is often referred to in literature as 0 N/mm^2 [40]. The split-tensile strengths of regular concrete and bacterial concrete were tested in an experiment conducted by Gandhimathi *et al.* after curing for 7, 14, and 28 days [41]. Testing the split tensile strength is an indirect method of testing the tensile strength by subjecting the concrete cylinders to a compressive force, a method selected due the challenge of directly measuring the tensile strength of concrete [42]. From these results, it can be concluded that the split-tensile strength of the concrete increased by an average of ~7% when it contained the bacteria *Bacillus sphaericus* [41]. Subha *et al*. also found that for the concentration of 10^5 cells/ml, the tensile strength of the concrete increased by 63% after 28 days [36]. Shashank *et al.* observed a ~29% increase in the split-tensile strength of concrete with the alkaliphilic microorganism *Bacillus sphaericus* added to it in the concentration 10^7 cells/ml [37]. This is because the activity of the bacteria causes $CaCO_3$ precipitation in the cement-sand matrix, increasing the load resisting capacity of the concrete. Albeit, due to the differences in bacteria and concentrations used there are apparent differences in the recorded increases, the overall improved tensile strength in bacterial concrete is useful as it means that cracks are less likely to occur, so the concrete will last longer.

Stress-Strain Behaviour

The stress-strain behaviour of a material can be modelled into a stress-strain curve, producing a visual representation of the material's resistance to deformation. Reddy *et al*. tested the stress-strain behaviour of conventional concrete and concrete containing the bacteria *Bacillus subtilis* to derive toughness [43]. This test was performed on cylindrical specimens prepared in a universal testing machine of 3000 KN capacity. Overall, their results were in line with those of Shashank *et al.* and indicated that the bacterial concrete showed improved stress-strain behaviour [37]. For instance, at a stress of 61 MPa, the bacterial concrete showed a ~13% decrease in its level of stress [43]. The stress-strain data was then used to calculate the toughness, which refers to the ability of a material to counteract crack propagation by distributing the deformation energy. Their results showed that bacterial concrete had a ~21% increased modulus of toughness, meaning it is better at spreading deformation energy than conventional concrete and has improved stress values for the same levels of strain when compared to those of the controlled concrete specimens [43]. In other words, comparatively more force must be applied to the bacterial concrete in order to fracture it.

The modulus of elasticity, which is the ratio between the stress in a system and the strain applied to it, can also be derived from the stress-strain behaviour of materials. According to Shashank *et al*., the modulus of elasticity is increased by ~31% when a concentration of 10^6 cells/ml of the bacteria *Bacillus sphaericus* is added into the concrete matrix [38]. Porto *et al.* also reported an improved modulus of elasticity of approximately 25 GPa and Belie *et al*. observed a modulus of elasticity of 31.8 GPa [38, 40]. This implies that bacterial concrete displays higher resistance to elastic deformation when stress is being applied to it [44].

However, few tests on the stress-strain behaviour of concrete have been conducted. Therefore, further experimentation must be done so that the true stress-strain behaviour of bacterial concrete can be obtained.

CONCLUSION

The performance of concrete is not solely determined by whether or not it contains bacteria. It is also dependent on the grade of concrete used, which is determined by the ratio of cement to sand to aggregate used. The grade also partially defines the price of concrete (with other factors including distance from the source and how easy the construction site is to access), with higher grades being more expensive due to their larger cement content [45]. Grade M60 concrete is ~41% more expensive than grade M20 concrete [17]. Lower grades of concrete that are treated with bacteria could potentially be used to replace higher grades of non-bacterial concrete due to the improved properties that adding bacteria provide. For example, M60 bacterial concrete could replace M80 conventional concrete as it has a higher compressive strength [22]. Additionally, M20 bacterial concrete has higher compressive strength than the required 30 MPa for grade M30 concrete [22].

Even in applications where the concrete does not encounter severe compressive stress, it may still be worthwhile to invest in a lower grade concrete containing bacteria due to the improvement of its other properties. For example, the split tensile strength of bacterial concrete is also improved due to the calcite deposits in the concrete's pores, increasing its load resistance capacity. Adding bacteria also leads to a proportionately larger decrease in the coefficient of permeability. In fact, M20 bacteria-treated concrete outperforms M80 conventional concrete, in terms of their coefficients of permeability [20]. This decrease originates from the reduced porosity of the bacterial concrete matrix.

However, regarding durability, the benefits of the bacteria are not as significant. For example, M60 bacterial concrete underwent less mass loss than M80 normal concrete when in contact with sulfuric acid. Nevertheless, when using HCl instead of H_2SO_4, the improvement had through the addition of bacteria was far smaller [22]. This, combined with the fact that it is extremely rare for concrete to encounter such prolonged low pH conditions, means that lower grades of bacterial concrete are potentially still durable enough to replace higher grades of regular concrete. Therefore, lower grades of bacterial concrete are a viable candidate to replace higher grades of conventional concrete.

The improved properties of bacterial concrete do, however, have an associated increased cost per m^3 due to the more intricate manufacturing steps, although its ability to self-heal makes it cheaper to maintain. For certain applications, this balance of performance, cost to buy, and cost to maintain can mean bacterial concrete is a practical investment, especially for applications where performance and maintenance are critical, such as dams and bridges. The higher initial cost of bacterial concrete could also be offset by downgrading the base grade of concrete due to its improved properties. A switch to lower grade bacterial concrete could have many advantages. For example, lower grades of concrete contain less cement, therefore if they were replaced by concrete of a lower grade, the global demand for cement would decrease, hence decreasing anthropogenic CO_2 emissions. Extremely high-grade bacterial concrete (e.g. M90 or M100) could potentially even be used to replace even stronger or rarer materials, such as granite, which would help reduce costs for businesses.

Given the advantageous properties of bacterial concrete, there is a need for further research into the optimum concentration of cells/ml as this value varies between literature. It is apparent that different species of the *Bacillus* bacteria confer different advantages through their variation in properties. It would be important to assess whether particular species of *Bacillus* (e.g., *Bacillus sphaericus* and *Bacillus subtilis*) have a greater effect on certain properties which would be more useful in specific applications to optimise the performance of bacterial concrete based on its purpose. Assuming the data collected through laboratory experiments are reproducible in industrial settings, to assess the practicality of bacterial concrete more data needs to be collected to validate whether as the use of bacterial concrete is scaled up, it is still economically sustainable in the long term. Together, this could pave way for a more sustainable path for civil engineering through the use of bacterial concrete.

CONFLICT OF INTEREST STATEMENT

Katie Molyneux is, at the time of publication, the Lead Copy-Editor for the Youth STEM Matters Journal. The double-blind editorial process has, however, ensured that the Reviewers were unaware of this fact. No other conflicts of interest are declared.

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