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Effects of Macro-Synthetic Fibres Incorporation on the Dimensional Change Properties of Bacillus Subtilis Bacterial Concrete

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ABSTRACT: Immediate dimensional changes during loading are critical characteristics that must be thoroughly understood to ensure the long-term durability and performance of concrete. In the current study, the effects of fixed bacterial content and different macro-synthetic fibre mechanical properties and fibre percentages on concrete dimensional changes were evaluated using 34 mixed designs. The influence of low- and high-strength macro-synthetic fibre with nine contents ranging from 0% to 4% on M40 concrete was investigated with and without calcium carbonate precipitation of Bacillus subtilis activity at a cell concentration of 10^5 cells/ml. The ANSYS package was used to compute the homogenized properties of the composite materials, such as the elastic modulus, shear modulus, and Poisson's ratio. For validation, the numerical results showed good agreement with the analytical results of the dilute distribution model and the Mori-Tanaka model. Compared to the reference conventional concrete, The results showed that adding bacteria and 2% high-strength macro-synthetic fibre simultaneously improved elasticity, shear moduli, and Poisson's ratio by 17.89%, 15.16%, and 3.30%, however low-strength macro-synthetic fibres caused 3.54%, 1.32%, and 2.98% reduction, respectively. Overall, high-strength macro-synthetic fibre improves the properties of bacterial concrete composite for a variety of structural applications when compared to other traditional concrete.

KEYWORDS: composite materials; elasticity and shear moduli; numerical homogenized simulation; Poisson’s ratio; polyethylene fibre

LIST OF ABBREVIATIONS

CC	:	Conventional Concrete	BC	:	Bacterial Concrete
FRC	:	Fibre-Reinforced Concrete	FRBC	:	Fibre-Reinforced Bacterial Concrete
DD	:	Dilute Distribution	MT	:	Mori-Tanaka
FE	:	Finite Element	RVE	:	Repeated Volume Element

1. INTRODUCTION

Conventional concrete CC cracks can lead to steel reinforcement corrosion; however, bacterial concrete BC, also known as self-healing concrete, offers a solution by using bacteria to repair cracks and enhance the properties of fibre concrete (Chithambar Ganesh et al. 2019). The sustainable immediate self-repair of the formed micro- and macro-cracks can prevent crack growth by limiting the paths for liquids and gases that may contain harmful chemical substances (Hameed et al. 2023). Biogenic origins, such as ureolytic bacteria, can induce $CaCO_3$

precipitation, leading to the self-healing of cracks in concrete when exposed to different environmental conditions or mechanical loads (Rameshkumar et al. 2020). Bacillus subtilis embedded in BC can repair cracks and restore the original mechanical properties of concrete for up to 200 years (Jena et al. 2020). B. subtilis can repair a cement mortar crack width of 0.3 mm within 1-5 days in the laboratory (Vijay et al. 2017) and may take several weeks for the total rehabilitation of the macro-cracks up to 0.46 mm (Wiktor and Jonkers 2011) or 0.5 mm (Wang et al. 2014). This self-healing increased the compressive strength f_c' by an average value of 23% at 28 d, and the split tensile strength f_t improved in the range of 13.7 - 25.3% (Ghoneim et al. 2020). Moreover, self-healing can reduce porosity, increase durability, guarantee a reduction in degradation rates, lower repair frequency, minimize the costs of strength monitoring/damage detection, and extend the ultimate service life of concrete structures (Alshalif et al. 2020; Bhaskar 2021).

Incorporating fibres in concrete, which serve as reinforcement, improves the self-healing performance by bridging cracks and reducing the amount of healing product required (Zhang et al. 2020). Calcite sediment remediation techniques can fill inaccessible concrete pores caused by the use of fibres in concrete. Polypropylene fibres can prevent cracking, thereby affecting the dimensional changes and quality of the material (Tiwari and Singh 2024). The dimensional stability of concrete depends on the environmental conditions and applied loads; however, it is also related to the concrete mix components. This study demonstrates the effectiveness of a dual-component composite material consisting of randomly distributed fibres and bacteria in immediate elastic dimensional changes related to the applied loading of concrete. Because of their ease of application, low density, and non-breakability, synthetic fibres have been commonly considered for use in concrete. Macro fibres are defined as fibres with a diameter greater than 0.3 mm and a specific surface area of approximately 10 cm^2/g (Jawhar et al. 2024). Increasing the fibre content in fibre-reinforced concrete FRC to 4% strikes a balance between achieving maximum strength and maintaining workability (Hasan et al. 2019), while also improving ductility and toughness (Yoo and Moon 2018).

In addition, fibre-reinforced bacterial concrete FRBC is a composite material with greater stability over shelf-life and multiple significant environmental footprints. In the last 10 years, the major advantages of FRBC have been investigated by many researchers, as follows: (i) Crack bridging recovery, as provided by ESEM/XEDS microscopic images (Feng et al. 2019). (ii) Improving healing participation to fill the crack-controlled width pattern (Qian et al. 2009). (iii) Enhancing the ultimate load capacity and ductility (Hao et al. 2018; Ghoniem et al. 2021). (iv) Enhancing fibrous concrete porosity and extending the service life of the structure (Kua et al. 2019; Karimi and Mostofinejad 2020). (v) Recycling nonbiodegradable thermoplastic materials in fibrous concrete is an environmentally safe procedure (Merli et al. 2019). Understanding the concept of dimensional change in synthetic fibrous bacterial concrete requires an exploration of how fibres contribute significantly to the overall properties of the material, including reducing shrinkage and enhancing toughness, crack resistance, and flexural strength (Amjad et al. 2023; Damodaran and Thangasamy 2023).

Hence, the elastic dimensional change of synthetic fibrous bacterial concrete is a multifaceted topic that requires a thorough understanding of the composition of the material, the effects of synthetic fibres on bacterial activity, and influencing factors. The dimensional change properties have scarcely been investigated from a numerical analysis point of view to avoid time-consuming laboratory experiments. The main issue of numerical simulation is that the synthetic fibre diameter is a few micrometers, while the structural dimension is in meters. Therefore, the mechanical properties of such composites are a multiscale modelling problem (Geers et al. 2010; Montero-Chacón et al. 2019). There are two approaches to the numerical simulation of composite structures.

(1) The hierarchical approach is called the FE^2 approach because there is a separate microscopic finite element simulation for every integration point of the macroscopic finite element FE simulation. The stress and strain are computed in the smaller length scale and the averaged values are sent back to the larger length scale (Raju et al. 2021).

(2) The homogenization approach is called the unit cell approach, as it is the most popular approach to eliminate the scale problem in FE^2 analysis. The homogenization/unit cell approach for composite structure simulation has been described in the literature, in which the composite properties were averaged based on microstructure analysis rather than simulating the entire complex microstructure. Full-field approaches, based on periodic homogenization theory, estimate the overall behaviour of an equivalent homogeneous material by defining a repeated/representative volume element RVE (Naili et al. 2020).

An equivalent inclusion dilute distribution DD model can predict the effective bulk modulus K_{eff} and shear modulus G_{eff} of a composite in which a single inclusion/fibre is in an infinite elastic host material matrix (Eshelby 1957). The DD model is more suitable for small volume fractions of inclusions, where interactions between inclusions are negligible as they are far apart. Another widely used model is the Mori-Tanaka MT model, which is very close to the experimental results for the prediction of the effective bulk modulus and shear modulus. The MT model, based on the average matrix stress assumption, imposes an additional condition on the DD model to consider the effect of multiple inclusions by combining the DD theory with the effective field concept (Benveniste 1987).

The current study numerically investigated the composite properties by considering the unit cell approach of the composite structure simulated by ANSYS Material Designer as an integrated component system in the ANSYS software package. The elastic modulus, shear modulus, and Poisson's ratio were estimated to explore the synergistic effects of bacteria and fibres. The effects of high- and low-strength macro-synthetic fibres introduced by different volumes on the properties of concrete incorporating Bacillus subtilis bacteria at a concentration of 10^5 cells/ml in mixing water were evaluated. Finally, the gradual changes in the material properties obtained from the numerical results are compared with the analytical results of the dilute distribution model and the Mori-Tanaka model.

2. MATERIALS AND METHODS

Simulations were performed based on the known properties of their component base materials. The study material properties were chosen based on previous technical investigations and experiments to provide reliable inputs for the numerical models as follows: (i) Bacillus subtilis JC3 was identified as a spore-forming aerobic alkaliphilic bacterium. Peptone, NaCl, and yeast extract were used as growth media. The matrix characteristics for the control and bacterial concrete BC were developed at the age of 28 days, as shown in Table 1, with an optimum B. subtilis cell concentration equal to 10^5 cells/ml of mixing water (Rao et al. 2017).

Table 1. Plain and bacterial concrete characteristics.

Matrix Type	Control Concrete CC	Bacterial Concrete BC
Density (g/cm^3)	2300	2300
Elastic Modulus E (MPa)	32200	36700
Poisson's Ratio ν	0.18	0.18
Tensile Strength f_t (MPa)	4.51	5.13
Compressive Strength f_c (MPa)	52.01	61.06

(ii) The macro-synthetic polyethylene fibres have a unit diameter d_f, aspect ratio $AR_f = l_f / d_f$, density, elastic modulus E, Poisson's ratio v, and ultimate tensile strength as shown in Table 2. High-strength fibre/type 1 (M. Monishaa and Namitha 2017) and low-strength fibre/type 2 (Bentur and Mindess 2006) were provided. To investigate the target homogenized characteristics, the synthetic fibre matrix included different volume contents (V_f = 0.3, 0.5, 0.75, 1, 1.5, 2, 3, and 4%) for both the M40 control and bacterial concrete.

Table 2. Macro-synthetic fibre characteristics.

Fibre Type	Type 1	Type 2
Fibre Strength Type	High	Low
Diameter d_f (μm)	433	625
Aspect ratio AR_f	90	48
Density (g/cm^3)	0.97	0.94
Elastic Modulus E_f (MPa)	73000	5000
Poisson's Ratio ν_f	0.422	0.418
Ultimate Tensile Strength f_{tf} (MPa)	2580	600

The scheme of the specimen sets used to generate the RVE models is shown in Fig. 1. The generated 34 models were modelled to explore the synergistic effects of bacteria and fibres. For macroscopic simulation and computing the homogenized properties of chopped fibre composites, the study presents numerical RVE modelling of fibrous composite concrete modelled using ANSYS Material Designer integrated in the ANSYS software package, as shown in Fig. 2.

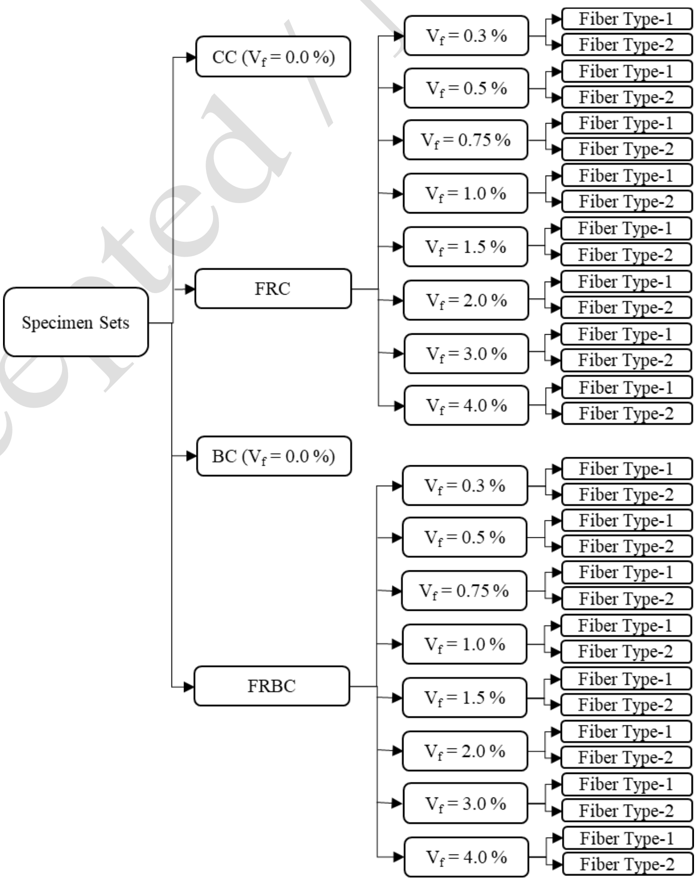


Figure 1. Scheme of the study specimen sets.

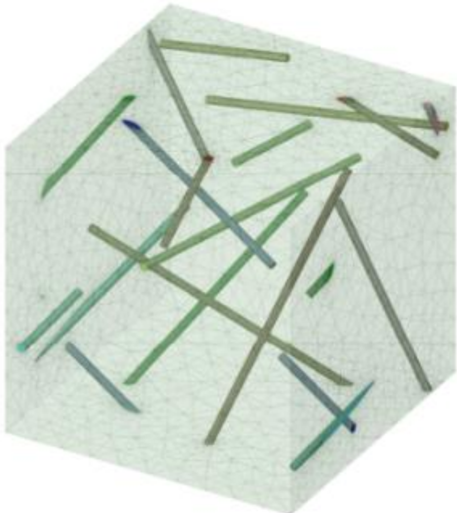


Figure 2. Meshed chopped fibre composites of ANSYS material designer typical RVE.

The Material Designer modelling procedure of a chopped fibre composite is summarized using different parameters until the geometric meshing of the internal shape, as follows: (1) The seed number against which the random fibre directions are calculated. (2) The repeat count specifies whether a given volume is sufficiently large to represent the number of fibres in the RVE. If the RVE size is insufficient, the software may fail to generate an RVE geometry with self-intersecting fibres that are longer than the RVE size. Consequently, increasing the variable size of the RVE is essential. Table 3 shows the actual numerically corrected size effects for various RVE models. (3) Tensor of symmetric fibre orientation. The initial fibre orientations were specified as uniform in all directions with diagonal values of 0.33,0.33,0.33 and zero values for the off-diagonal entries. Table 3 shows the actual values of the orientation tensor entries determined after generating the actual RVE geometry size and fibre fractions.

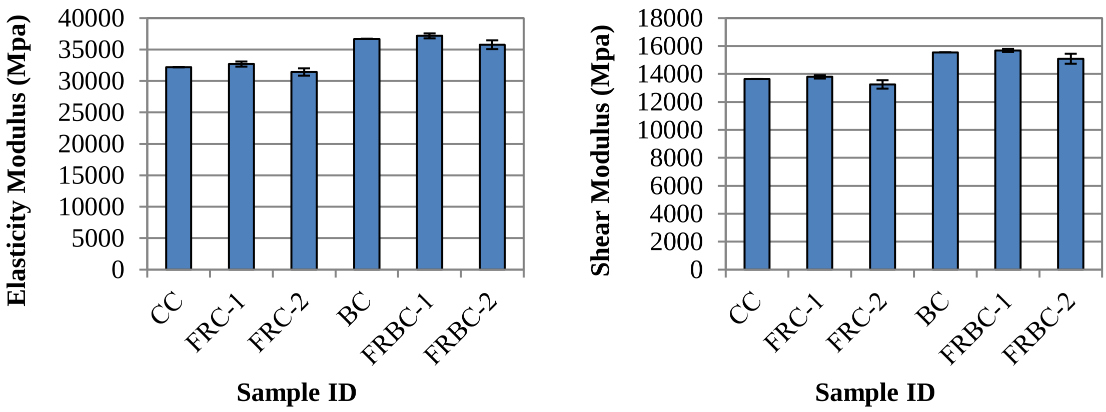
Table 3. Actual numerical entries and orientation tensor entries of RVE geometry.

The actual numerical entries for various RVE models						The actual orientation tensor entries of RVE geometry	
Fibre Type	**Volume Fraction V_f %**	**Actual V_f %**	**Seed**	**Repeat Count**	**No. of Fibres /RVE**	**Diagonal Values (a_{11}, a_{22}, a_{33})**	**Off-diagonal Values (a_{12}, a_{13}, a_{23})& (a_{21}, a_{31}, a_{32})**
	0.0	-	-	-	-	-	-
	0.3	0.3131	1	4	12	0.2632, 0.2502, 0.4866	-0.03205, 0.01635, -0.09209
Type 1	0.5	0.5044	1	4	9	0.3616, 0.2778, 0.3606	-0.07518, -0.01506, -0.1615
	0.75	0.8246	1	4	8	0.3191, 0.2141, 0.4668	0.01058, -0.05301, -0.1623
	1	1.11	1	4	7	0.1123, 0.2199, 0.6677	0.039, -0.07615, -0.1813

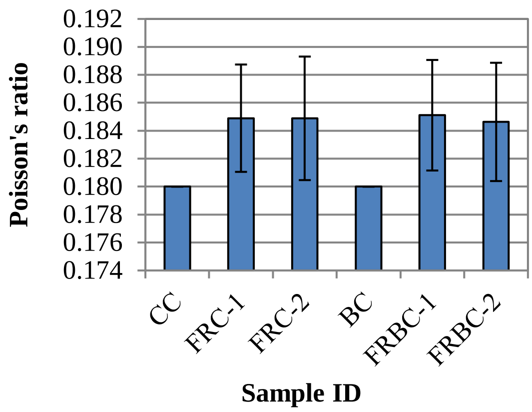
	1.5	1.641	1	5	11	0.2887, 0.2881, 0.4232	0.083, -0.06024, -0.2119
	2	2.066	1	5	9	0.1458, 0.2446, 0.6096	0.06223, -0.1672, -0.1258
	3	3.17	8	6	13	0.3567, 0.2763, 0.367	0.06598, 0.02428, -0.05158
	4	4.131	10	6	11	0.2648, 0.4444, 0.2908	-0.05631, 0.01301, -0.2039
	0.0	-	-	-	-	-	-
	0.3	0.3296	1	3	10	0.3147, 0.3333, 0.352	-0.04782, -0.02756, -0.05366
	0.5	0.5673	1	3	8	0.3417, 0.3304, 0.3278	-0.03748, -0.1053, -0.0703
	0.75	0.7694	1	4	14	0.2839, 0.2198, 0.4963	-0.01388, -0.07003, -0.04152
Type 2	1	1.015	1	4	12	0.2819, 0.2261, 0.492	0.02245, -0.03927, -0.08307
	1.5	1.511	8	5	19	0.3634, 0.3177, 0.3189	0.04143, -0.04234, 0.03576
	2	2.082	8	5	17	0.4302, 0.2271, 0.3427	0.0165, -0.0994, 0.03733
	3	3.15	8	5	14	0.3587, 0.3012, 0.3401	0.008798, -0.205, 0.03489
	4	4.156	8	5	12	0.2957, 0.402, 0.3024	0.09896, -0.02228, 0.1095

3. RESULTS AND DISCUSSION

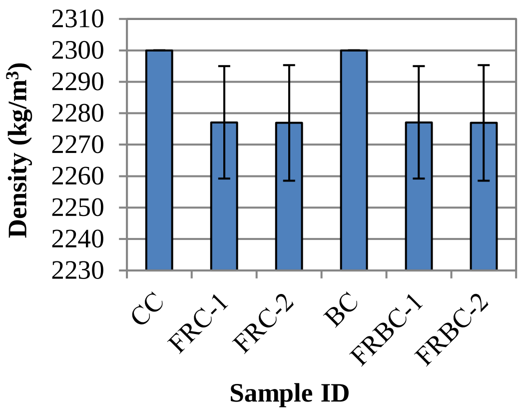
The dimensional change in fibrous bacterial concrete affects the performance and service life of structures. Excessive loading can lead to cracking, reduced serviceability, and compromised durability, while unexpected cracks can result in structural damage and loss of functionality. A numerical RVE model was used to study the improvement of certain properties, such as the elasticity modulus E_y, shear modulus G_{yz}, Poisson's ratio ν_{xz}, and density ρ. The mean and standard deviation SD of results are displayed in Fig. 3 with SD below 2.14%. The target samples were mentioned as "matrix type - fibre type".



(a) (b)



(c)



(d)

Figure 3. Concrete properties of the study samples: (a) elasticity modulus, (b) shear modulus, (c) Poisson's ratio, and (d) density.

With respect to plain concrete, high-strength fibre reinforced concrete FRC-1, bacterial concrete BC, high-strength fibre reinforced bacterial concrete FRBC-1, and low-strength fibre reinforced bacterial concrete FRBC-2, the mean values of elasticity modulus E_{eff} and shear modulus G_{eff} increased by 1.52% and 1.11%, 13.98% and 13.98%, 15.46% and 14.97%, and 11.09% and 10.60%, respectively. The mean values decreased by 2.39% and 2.85% for the low-strength fibre reinforced concrete FRC-2. Detailed improvements in elasticity and shear moduli for both the fibrous concrete FRC and fibrous bacterial concrete FRBC relative to the M40 conventional concrete are illustrated in Fig. 4. The target samples mentioned as “matrix type - fibre type - homogenized moduli”.

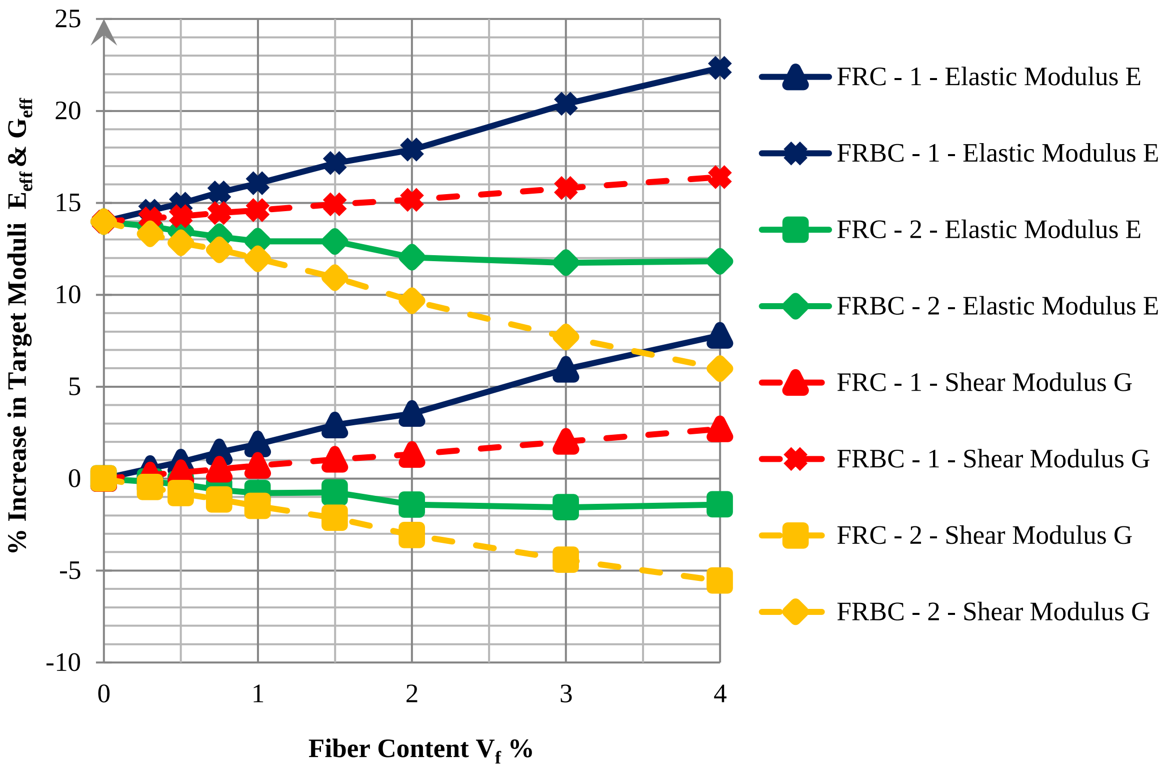


Figure 4. Enhancement in the target numerical elastic and shear moduli.

The elastic and shear moduli for both the FRC and FRBC increased with the high-strength fibre content, whereas the enhancement in the homogenized moduli decreased with the low-strength fibre content. This innovative result supports the fact that high-strength fibres improve ductility because fibre pull-out is the desired failure mode for dissipating energy in the matrix (Richardson 2005; Khan and Ayub 2016). Polyethylene macro-synthetic fibres can enhance the pre-peak elastic modulus of an element, causing an increase in flexural strength and shear capacity (Pantazopoulou and Zanganeh 2001; Majdzadeh et al. 2006). Bhosale et al., 2019 concluded that increasing the energy-absorbing capability during fracture improved post-peak ductility (Bhosale et al. 2019). Polyethylene macro-synthetic fibres provide post-cracking tensile resistance across cracks (Yıldırım et al. 2015).

With respect to plain or bacterial concrete, both high- and low-strength fibre-reinforced concrete and fibre-reinforced bacterial concrete mean values of density decreased by 1%. While high-strength fibre reinforced concrete FRC-1, low-strength fibre reinforced concrete FRC-2, high-strength fibre reinforced bacterial concrete FRBC-1, and low-strength fibre reinforced bacterial concrete FRBC-2, mean values of Poisson's ratio ν_{eff} increased by 2.72%, 2.71%, 2.84%, and 2.57%, respectively. The detailed enhancements in Poisson's ratio for fibrous concrete FRC and fibrous bacterial concrete FRBC compared to conventional concrete are illustrated in Fig. 5. The Poisson's ratio enhancement increased with the content of high-strength or low-strength fibres in both fibrous concrete and fibrous bacterial concrete, indicating improved crack formation arrest and post-peak strength (Tiberti et al. 2014).

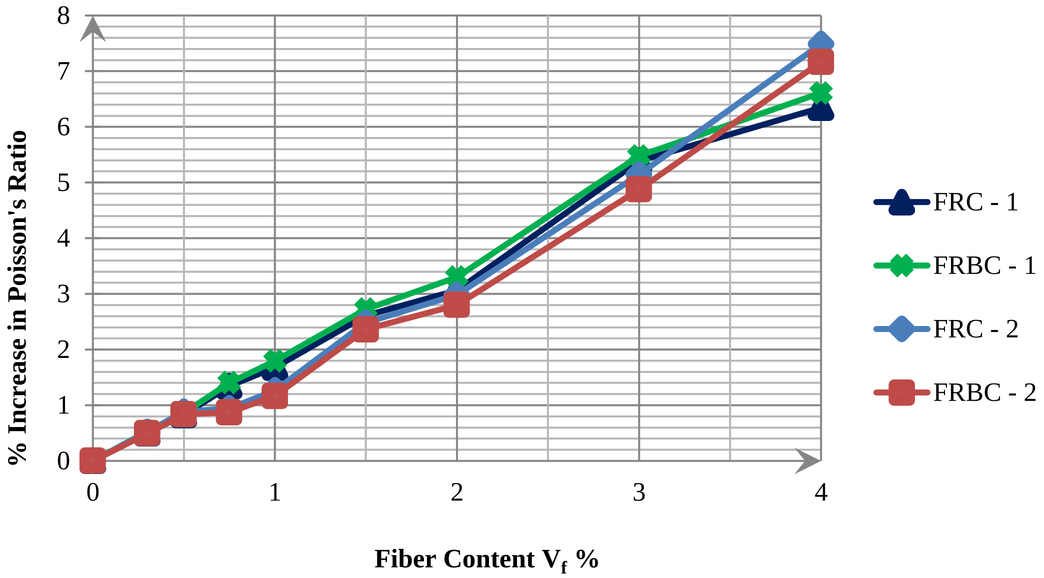


Figure 5. The enhancement in the target numerical Poisson's ratio ν_{eff}.

Related to the reference conventional concrete, the results indicated that the inclusion of high-strength fibre from 0% to 2% and constant content of Bacillus subtilis bacteria increased the elastic modulus, shear modulus, and Poisson's ratio in the range of 13.98 – 17.89%, 13.98 – 15.16%, and 0 – 3.30%, respectively. However, the inclusion of only high-strength fibre from 0% to 2% without Bacillus subtilis bacteria increased the elastic modulus, shear modulus, and Poisson's ratio in the range of 0 –3.54%, 0 – 1.32%, and 0 – 2.98%, respectively. Hence, the contribution of Bacillus subtilis bacteria distinguished in concrete mixtures with different fibre percentages from 0% to 2% was in the ranges of 13.98 – 14.35%, 13.98 – 13.84%, and 0 – 0.32% for the elastic modulus, shear modulus, and Poisson's ratio, respectively.

One of the current research objectives is to verify the numerical bulk modulus and shear modulus results using the analytical DD and MT models. As depicted in Fig. 6 and 7, the homogenized numerical results are in good agreement with the analytical results for the bulk and shear moduli. The target samples are mentioned as “matrix type - fibre type - modelling method”. In addition, the statistical hypothesis factorial ANOVA test in SPSS V25 software was used to compare the effect of analysis methods on composite moduli, finding no significant differences between the numerical and analytical results, and no significant differences between FRBC and FRC in terms of Poisson’s ratio, but significant differences among different matrix types in elastic and shear moduli.

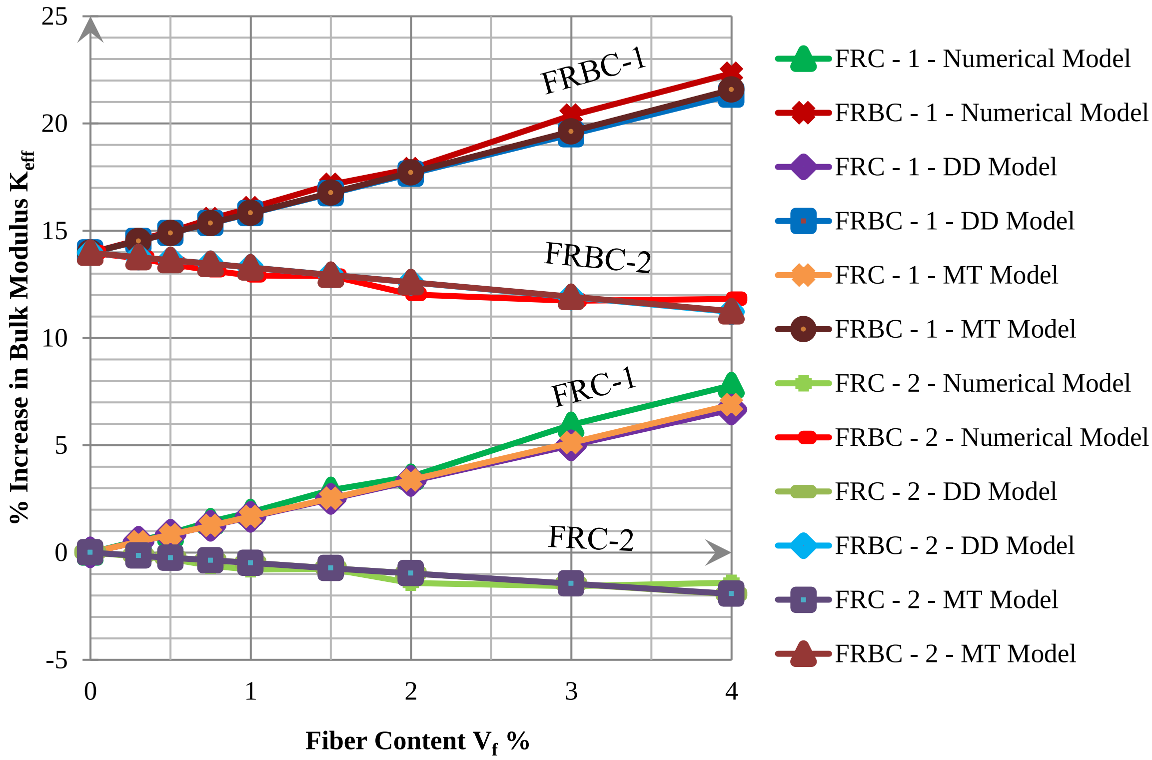


Figure 6. Validation of target bulk modulus, K_{eff}.

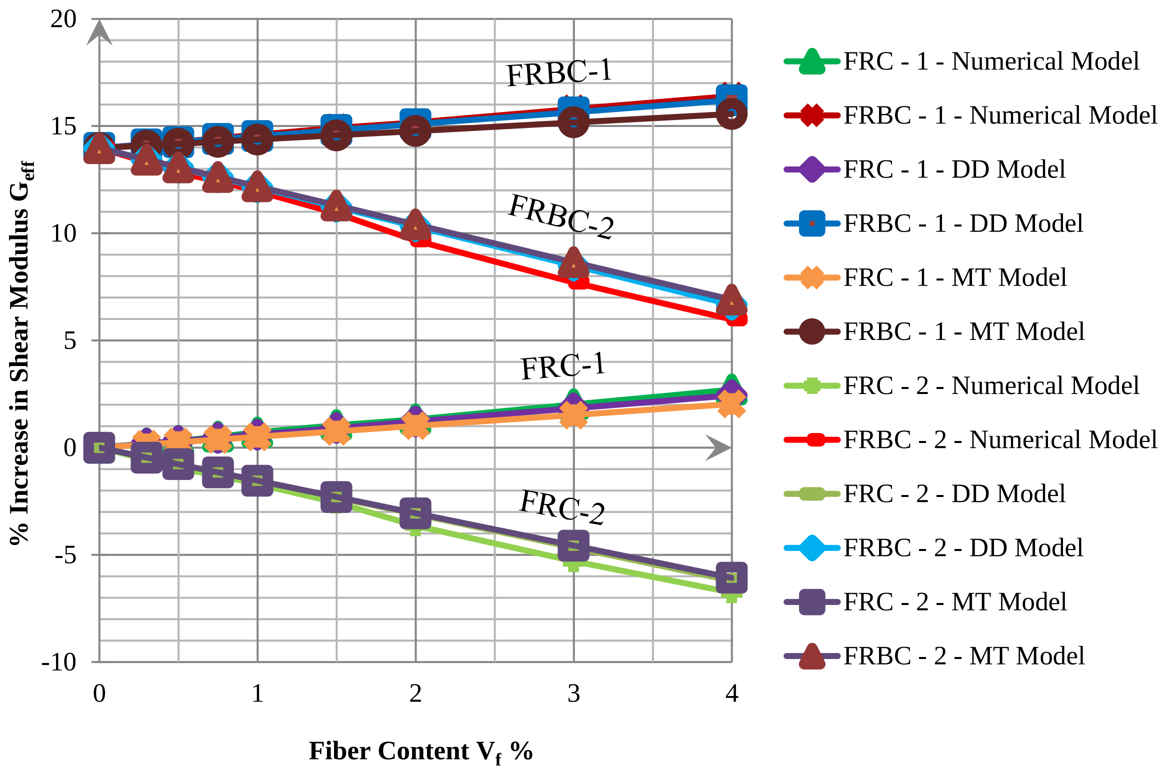


Figure 7. Validation of target shear modulus, G_{eff}.

Fig. 8 shows target composite properties E_{eff}, G_{eff}, *and* ν_{eff} that equals -0.5%, -1%, and 2.75% for FRC, 13.98%, 13.98%, 0% for BC, and 13.25%, 12.75%, 2.75% for FRBC, respectively, with 99% confidence level. The mean values show that fibrous FRBC and non-fibrous BC had better elasticity and shear moduli than traditional concrete. The biological self-repairing concept of traditional concrete has more effective advantages, and the addition of high-strength fibres only slightly enhances these properties. This result is broadly consistent with the major trends of other studies, in which the initial tangent modulus E_{it} changed slightly with the addition of fibres (Ezeldin and Balaguru 1992; Algihwel 2018).

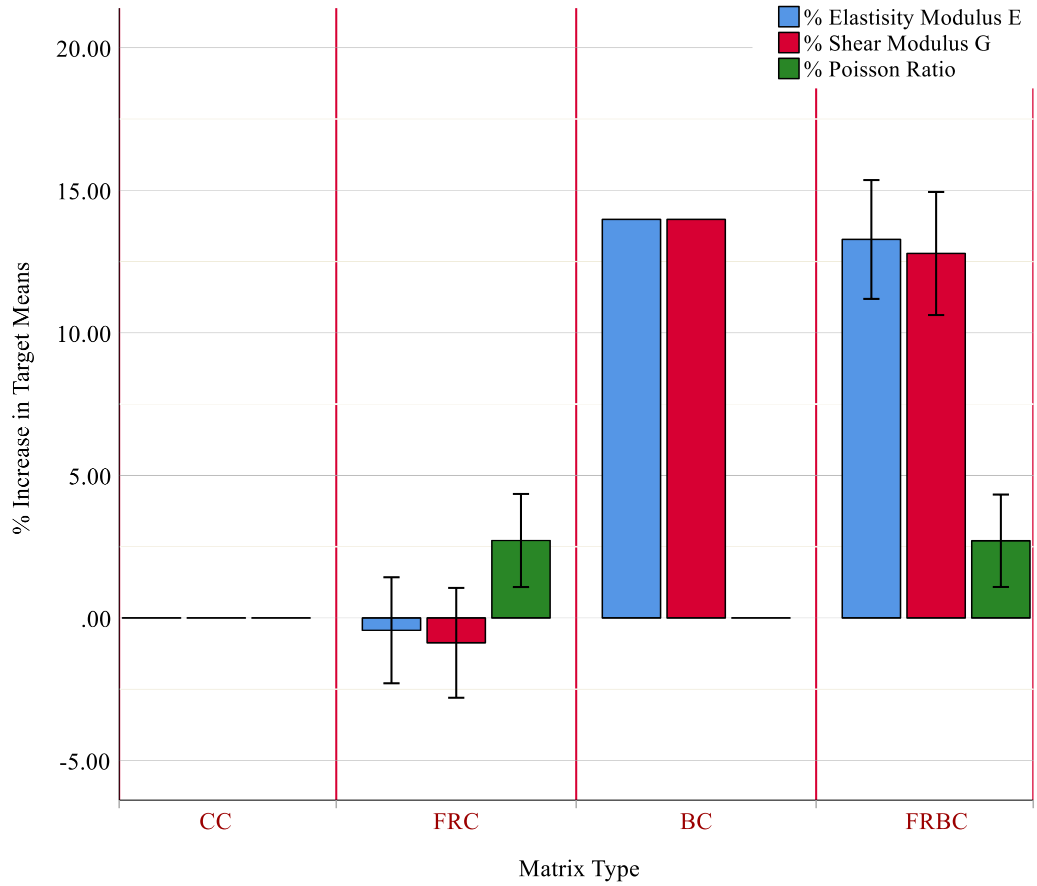


Figure 8. Enhancement of the properties of different matrix types.

Fibrous bacterial concrete mitigates dimensional changes through the network incorporation of high-strength fibres, which reduces strain and restrains the concrete matrix. The bacterial components in synthetic fibrous bacterial concrete, such as calcium carbonate-producing bacteria, play a vital role in mitigating dimensional change cracks by producing calcite crystals as fillers in the microstructure. The controlled crack pattern in synthetic fibrous bacterial concrete improves the bond strength between the fibres and the low-porosity matrix, resulting in enhanced flexural strength and shear capacity. As a result, the biological self-repairing concept of traditional and fibrous concrete achieved more effective advantages for the elastic and shear moduli. These findings are consistent with those of previous studies (Qian et al. 2009; Hao et al. 2018; Feng et al. 2019; Kua et al. 2019; Karimi and Mostofinejad 2020).

Despite its inherent benefits, fibrous bacterial concrete can undergo long-term dimensional changes owing to environmental conditions, chemical reactions, and material properties. Factors such as high temperature, humidity, and exposure to aggressive chemicals can accelerate the growth of bacteria, leading to an increase in the production of calcite crystals, resulting in dimensional changes. Therefore, laboratory testing techniques, including strain gauges and expansion tests, can help researchers understand the behavior of the material and develop predictive models. Furthermore, as the scope of the investigation expands beyond the prediction of linear elastic properties of composites, the limitations of numerical models become more apparent in modelling post-failure behaviour and predicting damage and cracking patterns. Future studies will focus on other dimensional changes of concrete related to the applied loadings as creep deformation or related to environmental aspects, such as early thermal expansion/contraction and swelling/shrinkage, which account for the majority of cracking in concrete structures. The fibre parameters, matrix grades, and self-repair techniques require further investigation. In addition, the macroscopic stress, strain distributions, and failure responses require intensive surveys. More data are required to facilitate the design and production of FRBC.

4. CONCLUSION

The current study investigated the dimensional change properties of concrete that included macro-synthetic fibres and Bacillus subtilis bacteria, such as Poisson's ratio, elasticity, and shear moduli. Proper incorporation of fibres and bacteria, coupled with careful mixture design and construction practices, can effectively manage immediate dimensional changes, mitigate long-term dimensional changes, and ensure the optimal performance and longevity of structures constructed using this innovative material. The main findings are as follows: (1) Using high-strength macro-synthetic fibres instead of low-strength synthetic fibres improves the concrete target properties. (2) It is essential to acknowledge that the process of bacterial-induced calcite precipitation BICP involves the conversion of the calcium lactate or urea present in the concrete mixture into calcite, effectively counteracting dimensional changes. The bacterial strain treatment combined with macro-synthetic fibre inclusion increased the conventional concrete homogenized elastic modulus, shear modulus, and Poisson's ratio properties by 13.25%, 12.75%, and 2.75%, respectively, according to the statistical analysis, regardless of the content and mechanical properties of the fibre. Ongoing research has direct positive effects on the design of practical structural elements by developing stronger synthetic fibres and optimizing bacterial activity to further enhance the performance of fibrous bacterial concrete with respect to dimensional changes.

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