

The elastomechanical properties of concrete expanded with aluminum nano-inclusions.

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Abstract

In recent years, nano-inclusion-reinforced concrete has gotten a lot of attention. Researchers have persistently examined the mechanical properties of concrete containing these inclusions. The aim of this research is to ascertain the mechanical properties of concrete augmented with nano-inclusions derived from aluminum waste. The Mori–Tanaka model is the method of homogenization used in this study. It is a common model for composites with spherical inclusions. The results show that the mechanical properties, such as the elastic modulus, shear modulus, and bulk modulus, are consistently getting better. This method gives experimental researchers a way to predict the acceptable volume fractions that can be added to concrete. This makes experiments more efficient and cuts down on unnecessary testing. To keep people safe, the maximum volume fraction is set at 30%.

Keywords: Nano-inclusions, Aluminum waste, Reinforced concrete, Mori–Tanaka model, Mechanical properties.

1. Introduction

Numerous studies have been conducted within the same research framework. Harrat et al. looked into how nanosilica could make concrete beams stronger. The agglomeration effect was the biggest problem that came up during the homogenization process. To fix this, they used a more advanced Voigt-based homogenization formulation [1]. Chatbi et al. also used a better Voigt homogenization method [2] to study how nanosilica sticks together in concrete slabs, both in the middle and at the corners. Benfrid et al. looked at concrete that was strengthened with glass powder. They used Eshelby's model to do a thermo-mechanical bending analysis of glass powder-reinforced concrete panels [3]. Dine El Hannani Soumia et al. performed an investigation on concrete beams fortified with highly sustainable alternatives that improve structural rigidity. A two-phase homogenization scheme derived from Eshelby's model was established [4]. Kecir et al. utilized Eshelby's theory to ascertain the stiffness matrix of concrete plates augmented with nano-inclusions in a separate study [5]. Chatbi et al. did an extra study on how concrete plates bend when they are on an elastic foundation and have nanoclay particles added to them. Eshelby's theoretical framework [6] was used for

the homogenization. Harrat Rabie also studied how adding tiny iron particles to concrete could make it stronger [7]. In another study, Benfrid et al. used Piggott's model to find out how plant-based nanofibers and gypsum composites work together [8]. Chatbi and others recently used a new way to mix things up to guess the mechanical properties of concrete that has nanoclay in it [9]. Using the Reuss and Maxwell–Eucken models, Benfrid et al. did a thermoelastic analysis of concrete panels that had nano-glass particles added to them [10].

The Mori–Tanaka model is frequently employed in scientific literature to achieve uniformity in materials containing nano-inclusions across two phases. Ketir et al. used this method to study lightweight concrete made from a gypsum matrix [11], and Melati used the same theoretical framework to make a steel–tungsten composite system more uniform [12]. Boukhari et al. utilized the Mori–Tanaka model to examine concrete integrated with nano-granite particles in a comparable fashion. Chatbi et al. used the Mori–Tanaka homogenization method to look at how well polymer composites with carbon nanotubes worked [14]. Yakro et al. also used similar homogenization methods to study eco-concrete that was made stronger with waste materials [15]. The Mori–Tanaka model provides a simple homogenization technique for composite materials composed of two phases, namely a matrix and reinforcing inclusions [16].

Wen Yu Xu and others say that adding up to 20% aluminum powder to fly ash can make concrete about 42% stronger when it is compressed. This means that adding aluminum powder to the composite material can make it work much better mechanically [17]. Fazel Azarhomayun and others found that adding a hydrophobic substance like calcium stearate makes cracks smaller, reduces free drying shrinkage, and reduces restrained shrinkage. On the other hand, adding aluminum powder to the mix almost completely stops free shrinkage. But restrained drying shrinkage does get a little bit bigger [18]. Hong Jiang and others looked into how to use secondary aluminum ash (SAA) in reactive powder concrete to recycle industrial waste and make it last longer. Their study shows that when SAA is exposed to NaCl and freeze-thaw cycles, it changes its mechanical properties and makes it less resistant to corrosion [19]. The research conducted by Mojtaba Fathi et al. on conductive concrete incorporating recycled aluminum waste, such as chips and aluminum powder, demonstrated enhanced electrical conductivity and thermal performance for deicing pavement applications [20].

This study tackles both environmental and technical issues by encouraging the recycling of aluminum waste and cutting down on the CO₂ emissions that come from making cement. The results show that adding 30% nano-scale aluminum powder as a partial replacement for cement reduces the amount of cement needed by 30% while still providing good mechanical performance. This way of doing things is better for the environment and uses materials more efficiently.

2. Methodology

We use the Mori–Tanaka homogenization method [16] to find the effective elastic modulus of a composite matrix that has spherical nanoparticles as dispersed inclusions. This method works best with materials that are not uniform, like

concrete, where the cementitious phase is the continuous matrix and nano-aluminum particles are used to strengthen it.

The combined volume of the fresh concrete matrix and the embedded nano-aluminum inclusions is called a representative volume element (RVE).

$$V_m = 1 - V_c \quad (1)$$

The bulk modulus, shear modulus, Young's modulus, and Poisson's ratio are all elastic constants that depend on each other. Mathematicians use their relationships to figure out the material's compressibility and shear parameters.

The composite material is made up of a concrete matrix with small, round bits of aluminum mixed in.

$$K_m = \frac{E_m}{3(1-2\nu_m)}, K_c = \frac{E_c}{3(1-2\nu_c)}, G_m = \frac{E_m}{3(1+2\nu_m)}, G_c = \frac{E_m}{2(1+\nu_c)} \quad (2)$$

The effective bulk modulus (compressibility) (k) and shear modulus (G) are expressed as follows:

$$\frac{K - K_m}{K_c - K_m} = \frac{V_c}{1 + V_m \left(\frac{K_c - K_m}{K_m + \frac{4}{3}G_m} \right)} \quad (3)$$

$$\frac{G - G_m}{G_c - G_m} = \frac{V_c}{1 + V_m \left(\frac{G_c - G_m}{G_m + f_1} \right)} \quad (4)$$

Where:

$$f_1 = \frac{G_m (9K_m + 8G_m)}{6(K_m + 2G_m)} \quad (5)$$

The effective modulus of elasticity E and Poisson's ratio ν are determined using the relation:

$$E = \frac{9KG}{3K + G}, \nu = \frac{3K - 2G}{2(3K + G)} \quad (6)$$

It is noted that:

E: Homogeneous Elasticity Modulus.

K: Homogeneous Compressibility Modulus.

G: Homogeneous Shear Modulus.

E_m: Matrix Elasticity Modulus.

E_c : Composite Elasticity Modulus.

K_m : Matrix Compressibility Modulus.

K_c : Composite Compressibility Modulus.

G_m : Matrix Shear Modulus.

G_c : Composite Shear Modulus.

V_m : Matrix Volume.

V_c : Composite Volume.

ν_m : Matrix Poisson's Ratio.

ν_c : Composite Poisson's Ratio.

3. Results

The volume fraction is limited to 30% for safety considerations, as exceeding this value leads to a reduction in the mechanical strength of the concrete. It is preferable to use this mathematical model without conducting experiments. The model allows researchers to analyze the material behavior and identify the optimal volume fraction. It is noted that the material is assumed to be homogeneous and isotropic. The Mori–Tanaka model was chosen due to its widespread use in the literature for predicting the effective properties of composite materials.

Table 1. The effective elasto-mechanical properties of new concrete.

V_c	K_{eff} (GPa)	G_{eff} (GPa)	E_{eff} (GPa)	ν_{eff}
0%	11.111	8.333	20.000	0.2000
5%	11.893	8.785	21.147	0.2037
10%	12.732	9.261	22.362	0.2073
15%	13.635	9.765	23.649	0.2109
20%	14.609	10.298	25.016	0.2146
25%	15.663	10.864	26.471	0.2183
30%	16.806	11.465	28.023	0.2221

Figure 1. The effective Young's modulus of nano-aluminum reinforced concrete versus inclusion volume fraction .

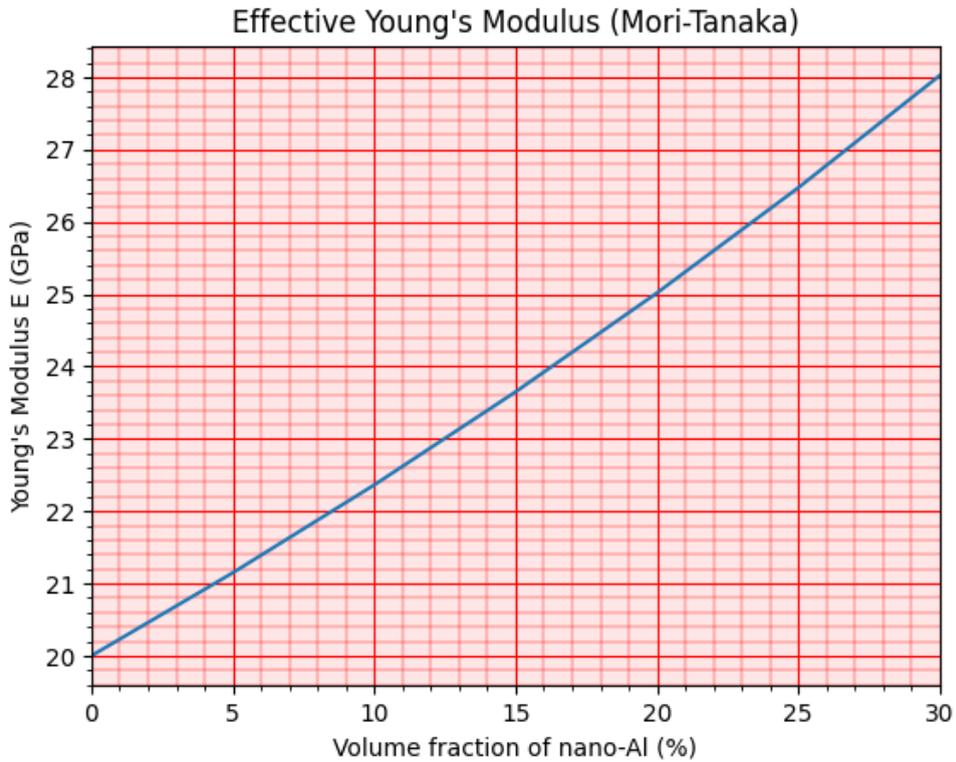


Figure 2. The effective bulk modulus new concrete.

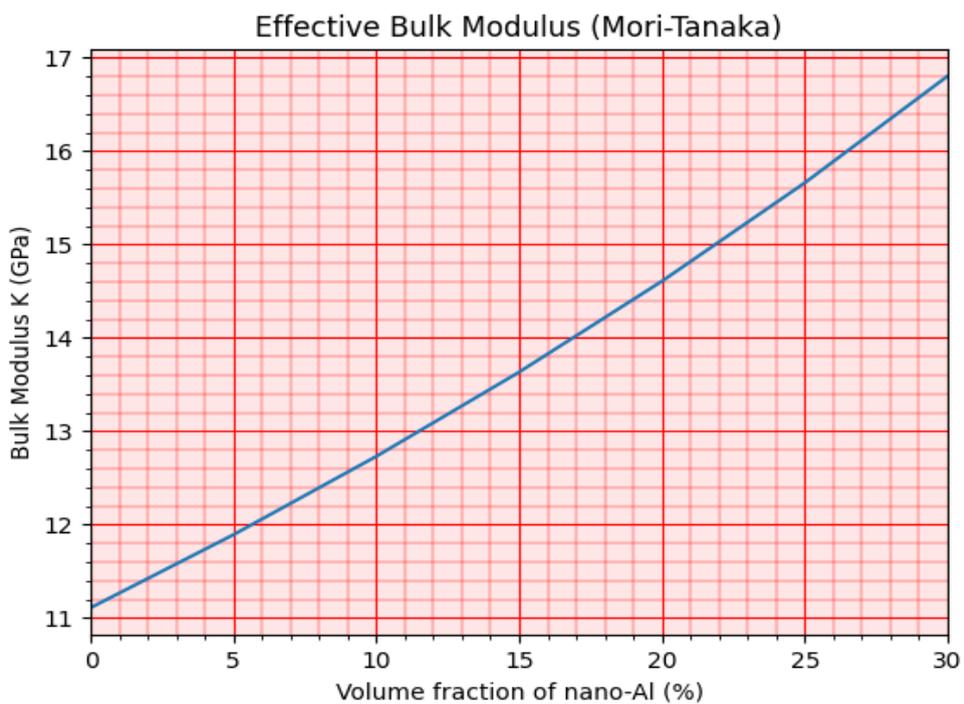


Figure 3: The effective shear modulus new concrete

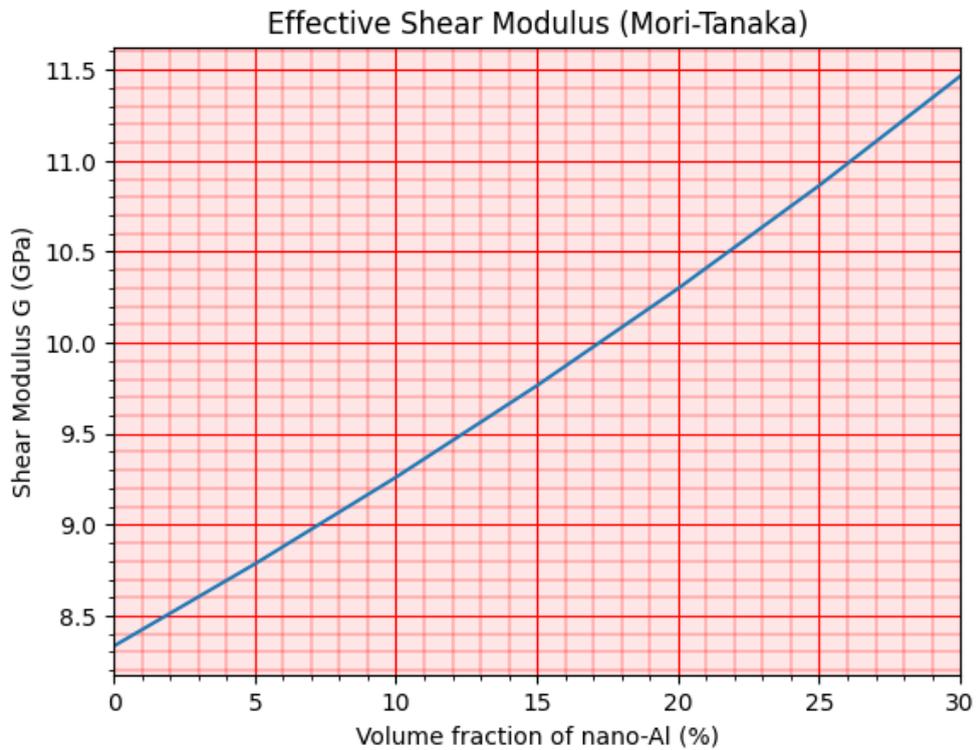
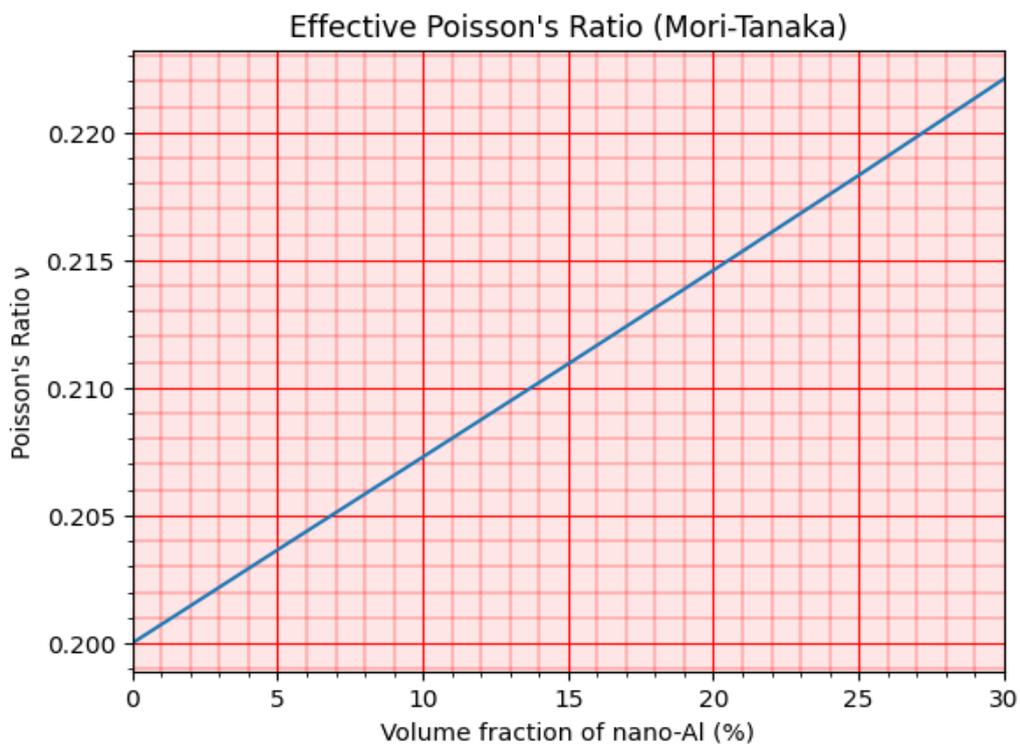


Figure 4. The effective Poisson's ratio in new concrete



4. Discussion

Table 1 and Figures 1–4 show that the Mori–Tanaka homogenization results show that the mechanical properties of concrete with spherical nano-aluminum inclusions get better and better as the volume fraction goes from 0% to 30%. Table 1 and Figure 1 show that the effective Young's modulus goes up by 40% from 20 GPa to 28.02 GPa. This shows that the aluminum phase, which is stiffer (70 GPa) [4], can easily transfer its stiffness to the concrete matrix (20 GPa) [1]. Table 1 and Figure 2 show that the bulk modulus goes up from 11.11 GPa to 16.81 GPa. This means that aluminum is less likely to change shape when you stretch it and more likely to stay the same shape. Also, Figure 3 and the numbers in Table 1 show that the shear modulus goes up steadily from 8.33 GPa to 11.47 GPa. This means that the material is less likely to bend and that the matrix and inclusions work better together. Figure 4 also shows that Poisson's ratio goes up a little, from 0.20 to 0.222. This means that the composite behavior is slowly becoming more like aluminum ($\nu = 0.3$), but it is still in the normal range for cementitious materials. The reinforcement is stable, the nano-inclusions are well spread out, and the Mori–Tanaka model's predictions match the physical properties of the particles in the concentration range we looked at, as shown in Figures 1–4 and Table 1. The linear behavior is valid only within the elastic range of the material. It is important to note that this model is purely based on mathematical homogenization.

5. Conclusion

The Mori–Tanaka model demonstrates that incorporating nano-aluminum spherical inclusions into concrete significantly enhances its mechanical properties. The effective Young's modulus, bulk modulus, and shear modulus all steadily increase as the volume fraction goes from 0% to 30%. This means that the material becomes more rigid and can resist both volumetric and shear deformation. Poisson's ratio goes up a little, but it's still in the range that is acceptable for cementitious materials. The Mori–Tanaka method is a good way to predict how nano-reinforced concrete composites will behave when they are stretched. In general, nano-aluminum works well as a reinforcing phase.

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