International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

عدد خاص بالمؤتمر الليبي الدولي للعلوم التطبيقية و الهندسية دورته الثانية
LICASE -2
2024 / 10 / 30-29

المجلة الدولية للعلوم والتقنية
International Science and Technology Journal
ISTJ

تم استلام الورقة بتاريخ: 15/ 9/2024م
وتم نشرها على الموقع بتاريخ: 18/10/2024م

Theoretical Estimation of Young's Modulus for Concrete with Glass Powder.

http://www.doi.org/10.62341/abmb1118

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Abstract:
This work compares three theoretical models with experimental results to identify the most accurate model for estimating the effective modulus of elasticity (Eeff) of eco-concrete made with glass powder. The models are Ruess-Voigt, mixture law, and Ishai and Cohen. Validation is based on scientific studies of this eco-concrete. The study concludes that glass powder can replace 20% of cement, with the Ruess-Voigt model being the most accurate. If glass powder replaces up to 30% of fine aggregates, both the Ruess-Voigt and mixture rule models are closely accurate.

Keywords: Homogenization, Effective Elasticity Modulus, Glass Powder. Ruess/Voigt Model. Mixture Law Model. Ishai and Cohen model.

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استخلاص معامل الليونة الافتراضي للخرسانة المحتواة على مسحوق الزجاج الناعم

عبد المطلب بن فريد، محمد بشير بويجرة
مخبر الهياكل والمواد المتقدمة في الهندسة المدنية والأشغال العمومية جامعة جيلالي اليابس سيدي بلعباس الجزائر
الجمهورية الجزائرية

الملخص:

يهدف هذا البحث إلى مقارنة ثلاثة نماذج نظرية مع النتائج التجريبية لتحديد النموذج الأكثر دقة في تقدير معامل المرونة الفعّال (Eeff) للخرسانة البيئية المصنوعة من مسحوق الزجاج. النماذج الثلاثة هي: نموذج Ruess–Voigt، نموذج قانون الخليط، ونموذج Ishai و Cohen. بالإضافة إلى ذلك، تعتمد عملية التحقق من هذه النماذج على الدراسات العلمية التجريبية التي تركز على هذا النوع من الخرسانة البيئية. وقد تم الاستنتاج أن مسحوق الزجاج يمكن أن يحل محل 20٪ من الأسمنت، وأن النموذج الأكثر دقة هو نموذج Ruess–Voigt. يمكن لهذا المسحوق أيضًا أن يحل محل ما يصل إلى 30٪ إذا استبدل الركام الناعم؛ وفي هذه الحالة، يوجد نموذجان قريبان: نموذج Ruess–Voigt ونموذج قانون الخليط.

الكلمات المفتاحية: التجانس، معامل المرونة الفعّال، مسحوق الزجاج. نموذج رويس/فويت Ruess–Voigt . نموذج قانون الخليط. نموذج هايشاي وكوين Ishai و Cohen.

Introduction

Glass recycling is of significant importance in civil engineering, as experimental studies have shown that glass powder can effectively replace a substantial portion of cement, providing both ecological and environmental benefits. Mansouri Khelifa et al., in their 2021 doctoral thesis, reported the parameters for glass powder particles as follows: modulus of elasticity (Eg) of 64 GPa, Poisson's ratio (ng) of 0.3, and density (rg) of 2.54 g/cm³ [1]. For concrete incorporating glass powder, the comparison parameters are: modulus of elasticity (Em) of concrete with 0% glass powder (either Eij or Eexp), Poisson's ratio (nm) of 0.3, and density (rm) of 2.5 kg/m³. The Voigt model, Reuss model, Voigt-Reuss model (first model), Reuss-Voigt model (second model), Ishai and Cohen model, and the Mixture Rule are well-defined homogenization models as detailed in reference [2]. The code for reinforced concrete at limit states (1991/99) [3] is the most commonly used regulation for calculating reinforced concrete in North Africa , Southern Europe and southern Europe . In their 2018 study, Wasan I. Khalil and Nazar F. Al-Obeidy explored the use of glass waste to formulate concrete, replacing 10%, 15%, 20%, 25%, and 30% of the cement with glass powder (75 µm). Their results indicated that glass powder acts as a pozzolanic material, enhancing mechanical properties, with the maximum improvement observed at 15% glass powder [4]. In 2017, Dalia Shakir Atwan

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prepared concrete using glass waste with three different diameters (600 µm, 2.36 mm, and 4.75 mm) to replace fine aggregates at rates of 10%, 20%, and 30%. She found that strength improved when the glass waste was very fine, like powder [5]. Comparing our models with the results obtained from glass powder (300 µm) at 28 and 90 days of age is therefore relevant. Mohamed Mahir Yassen et al. (2019) investigated concrete with glass powder, replacing 10%, 15%, 20%, and 25% of cement with powder ranging from 75 µm to 300 µm. They concluded that both concrete strength and elastic modulus improved, with the optimal value at 20% glass powder [6]. Arwa Gazi Naje et al. (2019) studied the behavior of concrete incorporating glass waste, replacing 10% to 30% of sand with crushed glass (less than 5 mm). They found that replacing up to 30% of sand with glass waste increased the mechanical properties of the concrete [7]. It should be noted that the resistance reported was for concrete cubes of size 10×10×10 cm.

1. Homogenization models

Considering that eco-concrete is a bi-phase material, with reference concrete as the matrix and glass powder as the reinforcement.
Knowing that:
M: Matrix (ordinary concrete).
g: Particulate of glass (glass powder).
V: Volume.
E: Elastic's Modulus or Young's Modulus.
P.V: % of glass powder
Fc: Stress of compression.
The Ishai & Cohen, Ruess-Voigt, Voigt, Ruess, Voigt-Ruess, and Mixture laws models are theoretical frameworks used to analyze the mechanical behavior of composite materials.

$$V_g + V_m = V \tag{1}$$

I. REUSS Homogenization Model [2]:

$$\frac{1}{E_r} = \frac{1-V_g}{V*E_m} + \frac{V_g}{V*E_g} \tag{2}$$

II. Voigt Homogenization Model [2] :

$$E_v = \frac{E_g*V_g}{V} + \frac{E_m*(1-V_g)}{V} \tag{3}$$

III. Voigt-REUSS Homogenization Model [2] :

$$E_p = E_m + V_g^{\frac{2}{3}}(E_g - E_m) \tag{4}$$

$$\frac{1}{E_{vr}} = \frac{1}{E_m} + V_g^{\frac{1}{3}}\left(\frac{1}{E_p} - \frac{1}{E_m}\right) \tag{5}$$

IV. REUSS-Voigt Homogenization Model [2] :

$$\frac{1}{E_s} = \frac{1}{E_m} + V_g^{\frac{2}{3}}\left(\frac{1}{E_g} - \frac{1}{E_m}\right) \quad (6)$$

$$E_{rv} = E_m + V_g^{\frac{1}{3}}(E_s - E_m) \quad (7)$$

V. (Reinforced concrete at limit states)

The (Reinforced concrete at limit states) (1991/99) rule [3] defines the following two modules**:**

$$E_{ij} = 11000 * f_{cj}^{1/3} \quad \text{(MPa)} \quad (8)$$

$$E_{vj} = \frac{E_{ij}}{3} \quad \text{(MPa)} \quad (9)$$

VI. Model loi de mélange (Law mixture) [1] :

The first approximation is expressed as follows:

$$E_{mix} = V_m * E_m + \sum V_g * E_g \quad (10)$$

For a biphasic system:

$$E_{mix1} = \frac{E_g * E_m}{V_g * E_m + V_m * E_g} \quad (11)$$

VII. Model d'ISHAI & COHEN [1] :

Assumptions: It is assumed that, under a state of stress, the matrix and reinforcement are macroscopically homogeneous, and that adhesion is perfect.

In the case where the stress is uniform, the elastic modulus of the particle composite is expressed, at the upper limit, as follows:

$$\frac{E_c}{E_m} = 1 + \frac{1 + (\delta - 1) * V_g^{\frac{2}{3}}}{1 + (\delta - 1) * (V_g^{\frac{2}{3}} - V_g)} \quad (12)$$

In the case where the stress is uniform, the elastic modulus of the particle composite is expressed, at the lower limit, as follows:

$$\frac{E_c}{E_m} = 1 + \frac{V_g}{\frac{\delta}{(\delta - 1) - V_g^{\frac{1}{3}}}} \quad (13)$$

when :

$$\delta = \frac{E_g}{E_m} \quad (14)$$

2. Results and comparisons

Table 1. Comparaison entre (Eeff, Eexp et Eij) obtenus à partir des résultats à 60 jours par Wasan I. Khalil et Nazar F. Al-Obeidy.

P.V	Fc60	Eexp60	Ei60	Erv	Emix	Eish-coh
0%	64.7	45.1	44.16	44.16	44.16	44.16
10%	66.1	46.9	44.48	44.55	44.57	45.75
15%	73.3	48.8	46.05	45.92	46.31	46.61
20%	67.5	45.6	43.88	45.5	47.08	47.50

Table 2. Comparison between (Eeff and Eij) Obtained from Results at 28 Days by Dalia Shakir Atwan.

P.V	Fc28	Ei28	Erv	Emix	Eish-coh
0%	30.68	34.43	34.43	34.43	34.43
10%	32.77	35.20	34.99	36.1	36.46
20%	34.23	35.71	35.5	36.99	37.6
30%	36.40	36.45	36.13	37.94	38.80

Table 3. Comparison between (Eeff and Eij) Obtained from Results at 90 Days by Dalia Shakir Atwan.

P.V	Fc90	Ei90	Erv	Emix	Eish-coh
0%	33.18	35.35	35.35	35.35	35.35
10%	34.71	35.88	35.89	37.05	37.34
20%	35.97	36.31	36.39	37.89	38.46
30%	37.26	36.74	37.01	38.42	39.64

Table 4. Comparison between (Eeff and Eexp) Obtained from Results at 28 Days by Mohamed Mahir Yassen et al..

P.V	Eexp	Erv	Emix	Eish-coh
0%	19.75	19.75	19.75	19.75
10%	20.63	20.44	21.22	21.76
15%	20.4	21.04	22.03	22.99
20%	20.39	21.76	22.91	24.33

Table 5. Comparison between (Eeff and Eij) Obtained from Results at 14 Days by Arwa Gazi Naje et al.

P.V	Fc14	Ei14	Erv	Emix	Eish-coh
0%	9.1	22.96	22.96	22.96	22.96
10%	11.3	24.68	23.64	24.54	25.06
20%	11.8	25.04	24.24	25.41	26.31
30%	17.7	26.32	24.96	26.34	27.67

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Table 6. Comparison between (Eeff and Eij) Obtained from Results at 21 Days by Arwa Gazi Naje et al.

P.V	**Fc21**	**Ei21**	**Erv**	**Emix**	**Eish-coh**
0%	10.3	23.93	23.93	23.93	23.93
10%	12.5	25.52	24.61	25.53	26.05
20%	13.6	26.27	25.20	26.41	27.30
30%	15.2	27.24	25.92	27.36	28.66

3. Discussion of the results

The Ruess-Voigt model demonstrates a strong alignment with the effective interaction modulus Eij when cement is replaced with glass powder of particle size 75 µm. This observation indicates that the model accurately reflects the mechanical behavior of the composite material, suggesting that the integration of glass powder at this size may enhance the properties of the cement matrix. However, it is noteworthy that the experimental modulus Eexp does not correspond closely with any of the three models considered for this particular replacement. This discrepancy may arise from variations in the processing conditions, particle distribution, or the intrinsic properties of the glass powder that are not fully captured by the theoretical models. The insights are illustrated in Tables 1 and 2, which detail the relationships between the models and their respective experimental outcomes.

In cases where fine aggregates are substituted with glass powder of larger particle size (300 µm), the Ruess-Voigt model again stands out as the closest match to Eij , as shown in Table 3. This consistency further reinforces the reliability of the RUESS-VOIGT model for predicting the effective modulus in scenarios involving glass powder, regardless of particle size. The continued success of this model suggests that it can be a useful tool for engineers and material scientists looking to optimize composite mixtures in construction applications.

Moreover, when examining the replacement of cement with glass powder across both 75 µm and 300 µm sizes, the Ruess-Voigt model emerges as the most accurate representation of the experimental modulus. improvements in the overall performance of concrete mixtures, making this approach a viable alternative for sustainable construction practices.

Finally, when considering the replacement of sand with glass waste (particle size less than 5 mm in diameter), the Mixture Rule model exhibits the closest alignment with Eij,as presented in Tables 5 and 6. This model accounts for the contributions of each constituent material in the composite, demonstrating its applicability for mixtures involving larger aggregates. The ability of the Mixture Rule model to effectively predict the mechanical properties in this scenario illustrates its versatility and reliability, making it a valuable resource for developing innovative construction materials that incorporate recycled glass waste.

In summary, the analysis reveals that the Ruess-Voigt model consistently provides accurate predictions for the effective modulus when incorporating glass powder into

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cement matrices, while the Mixture Rule model is more appropriate for mixtures involving larger glass waste aggregates. These findings underscore the importance of selecting the right model based on the specific material replacements being considered, ultimately aiding in the design of more efficient and sustainable construction materials.

4. Conclusion

The Ruess-Voigt model is the most accurate for the homogenization of eco-concrete incorporating glass powder with a diameter between 75 µm and 300 µm. This model is applicable for up to 20% glass powder replacement if the glass powder substitutes part of the cement, and can be extended to 30% if the powder replaces fine aggregates. Additionally, the mixture rule model is also effective if the glass waste (less than 5 mm) replaces sand. The Ruess-Voigt model provides a very high level of reliability; therefore, it is essential to first anticipate effective results on pozzolanic powder, regardless of its type, without wasting time on laboratory tests. While there are colleagues working in the experimental field, the validation and creation of empirical formulas should be based on homogenization laws. Homogenization is the key to future technical regulations that are more precise and reliable.

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