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Research Article

Determination of waste crushed baked clay aggregate concrete with granular composite material preparations

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ABSTRACT

Waste baked clay is an industrial waste that causes environmental pollution. Therefore, the possible utilization of this material would reduce environmental pollution. Utilization of baked clay as aggregate in concrete would have a positive effect on the economy. There are many studies on examining concrete as a granular composite. However, there are few studies on the examination of industrial or construction demolition wastes, which are used as aggregate in concrete, with granular composite models. This study was conducted to contribute to filling this gap in the literature. In concrete production, Portland cement, river sand, 4-32 mm in size crushed stone and crushed baked clay as coarse and medium aggregate in the replacement ratio of 0%, 50% and 100% were used. Compression tests were conducted on specimens. Stress-strain curves were drawn as a graph. Elasticity modulus were determined experimentally. Elasticity modulus were calculated using granular composite models. Experimental and calculated elasticity modulus were compared and examined. According to the results, it was determined that these wastes could be evaluated in concrete production and used in the elasticity modulus calculation of granular composite models.

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1. Introduction

Composite materials are created by combining two or more materials at a macro level to form a new, single material with improved properties. Composite materials are formed by combining matrix and reinforcement materials at an interface. Composite materials reinforced with particles (granular composites) are obtained by distributing the particles homogeneously in a matrix material (Yusuf 2022). Concrete can be given as an example of granular composites. Cement paste is used as matrix material in concrete, and aggregate is used as reinforcement material. The concrete components cannot show sufficient mechanical properties on their own. However, when these materials come together at an interface to form a composite material, the mechanical properties of the concrete improve. Aggregates used as reinforcement materials in concrete production are obtained from natural or artificial stones, ceramics, and organic materials. Examples of artificial aggregates include schists and clays, brick-tile pieces, and blast furnace slag (Ersoy 2001). With the increasing demand for new construction and the reconstruction of buildings to improve living standards, the reserves of natural aggregates have been rapidly depleted (Aboalella and Elmalky 2023; Mohamed et al. 2021). It can be used as aggregate in industrial waste. Studies on the utilization of industrial waste in the construction sector continue increasingly (Şengel et al. 2019, 2022a; Güler 2024). Lightweight concrete is produced by replacing normal-weight aggregate with a lighter aggregate to reduce the structure's weight (Mousa et al. 2018). Sustainable lightweight concrete production is aimed at using artificial aggregates in lightweight concrete production. Artificial aggregates such as crushed baked clay (CBC) reduce concrete density and prevent environmental pollution by using less natural aggregate.

In this study, normal aggregates and waste crushed brick and tile produced from baked clay were used as

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granular material. CBC can be used as artificial aggregate by crushing to appropriate particle size. Türkiye has a production capacity of 12.8 million m^3 of bricks in 163 factories and 307 million tiles in 36 factories. With the rising volume of waste, rapid environmental pollution poses a significant threat to biodiversity and human health. As a result, there has been an increase in research efforts on waste recycling, both in terms of study and implementation (Çelik et al. 2024; Şengel et al. 2022b; Canbaz et al. 2021). Large amounts of brick and tile waste are generated due to losses incurred during production, construction demolition works, and roof repairs (Zhang et al. 2020). Although these wastes do not contain environmentally harmful chemical waste, they cause environmental and visual pollution due to the large amount of waste and the need for extensive disposal areas (Zhao et al. 2018; Yang et al. 2020). Therefore, recycling and using this waste as raw materials for various industrial products is very important.

Klak et al. (2023) examined the recycling of CBC as fine aggregate in concrete and mortar. They used CBC as fine aggregate in different proportions in concrete production. They also examined compressive strength, splitting tensile strength, workability, dry and wet density, and absorption parameters. They stated that the compressive strength of concrete samples decreased.

Dang and Zhao (2019) produced clay brick concrete by replacing sand with CBC in specific proportions. They stated that the compressive strength of CBC concrete increases as the curing age increases. They concluded that the compressive strength was maximum in samples that did not contain extra water. The waste clay brick could absorb free water from the concrete mixture without additional water, reducing the w/c ratio effect. They stated they encountered a decrease at the same ratio when the elasticity modulus was examined.

Bektaş et al. (2009) produced recycled mortar by replacing sand with CBC. They stated that the compressive strength of the mortar produced with fine CBC increased with the curing age due to the pozzolanic effect. They found no significant difference between the compressive strength of the control mortar and the mortar prepared with fine clay.

Aliabdo et al. (2014) produced recycled mortar and concrete in various sizes using CBC. They stated that when CBC was used in certain proportions instead of cement, the compressive strength of the mortar decreased, and when it was used as an additive to cement, a slight increase in the compressive strength was observed. They found that the elasticity modulus decreased as the amount of CBC used increased.

In many studies, CBC has been used as a fine aggregate in different proportions, and many studies have been carried out on compressive strength. Depending on the usage ratios in the studies, a slight decrease in compressive strength and elasticity modulus was observed (Ge et al. 2015; Vieira et al. 2016; Dang and Zhao 2019; Olofinnade and Ogara 2021; Helmy et al. 2023).

This study aimed to produce concrete using CBC aggregates. First, an experimental study was carried out on the stress, strain, and elasticity modulus of the CBC concrete. Then, its mathematical application was made using different rheological models of granular composite materials. For this purpose, parallel phase model - Voigt model, series phase model - Reuss model, combined models, Hirsch-Dougill model, Popovics model, Illston model, Mehmel-Kern model, Bache and Nepper-Christensen model relations and elasticity modulus were found and compared.

The basic models of granular composites are parallel and series phase models that consider properties and volume ratios. Voigt's model called the parallel phase model, consists of parallel connected spring bodies. It predicts that both phases undergo elastic deformation similarly under tension (Voigt 1928). The Reuss model, which is a serial phase model, assumes that the phases that make up the composite will show different deformation under stress occurring in the body depending on the force that creates the composite (Kelly 1990). In the Hirsch-Dougill model, both phases are connected in series in the upper model of the unit element, and a series-connected structure is formed as a whole, with the section consisting of parallel connected phases in the lower part. The obtained formula consists of upper-bound Voigt model and lower-bound Reuss model relations. In the resulting formula, Voigt model values are used as the upper limit, and Reuss model values are used as the lower limit (Dougill 1962; Hirsch 1962). Popovics model consists of series and parallel phase models. In this model, one of the phases forming the composite is considered a serial phase, and the remaining part is considered a completely parallel phase (Popovics and Erdey 1970). The Illston and Mehmel-Kern models are similar. In the Illston model, a horizontal layered approach from the combined models is recommended, and in the Mehmel-Kern model, a vertical layered approach from the combined models is recommended. For both models, it is assumed that there is a square prism at the centre (Manns 1970). Another rheological model is Bache and Nepper-Christensen, which proposes elastic modulus equality depending on phase properties and volume ratios (Bache and Nepper-Christensen 1965).

2. Materials and Method

In concrete production, 4-16 mm and 16-32 mm aggregates were replaced with CBC at 0, 50 and 100%. CBC sizes 4-16 mm are coded "M", and 16-32 mm are coded "C". As seen from Table 1, 300, 350 and 400 cement contents were used in the produced concretes. The amount of water was kept constant at 190 kg/m^3. After one day, the produced samples were removed from the form and stored under standard curing conditions. 28-day compression tests were carried out according to EN 12390-3, and the elasticity modulus was calculated by drawing the stress-strain diagrams of each specimen.

Elasticity modulus was calculated based on the stress and deformations obtained from the compression test applied to the specimen prepared from each component used in production, and the results are given in Table 2.

Table 1. Mixture proportions of concrete.

Mixture, kg		Aggregate (0-4 mm)	Aggregate (4-16 mm - 16-32 mm)	
Cement	Water	Crushed stone	Crushed stone	Baked clay
300		739	581	443
350	190	721	568	434
400		705	555	424

Table 2. Elasticity modulus of ingredients.

	Matrix (binder)	Crushed stone	Baked clay
Elasticity modulus, GPa	7.5	12.27	1.6

Absolute volumes were determined depending on the density of the matrix and granular materials used. Volume ratios were calculated depending on their absolute volume and are in Table 3.

Elasticity modules were calculated mathematically using the elasticity modulus and volume ratios of the composite components in the formulas given in Table 4. Basic models Reuss and Voigt, combined models Hirsch-Dougill, Popovics, IIIston, Mehmel-Kern, and Bache-Nepper-Christensen models were used as calculation methods.

Table 3. Volume ratio of matrix and granular part of composites.

Volume ratio	Matrix	Baked clay	Crushed stone
C 300-0 M 300-0	0.570	0.000	0.430
C 300-50 M 300-50	0.560	0.117	0.323
C 300-100 M 300-100	0.552	0.233	0.215
C 350-0 M 350-0	0.579	0.000	0.421
C 350-50 M 350-50	0.570	0.114	0.316
C 350-100 M 350-100	0.562	0.228	0.210
C 400-0 M 400-0	0.589	0.000	0.411
C 400-50 M 400-50	0.580	0.111	0.309
C 400-100 M 400-100	0.572	0.223	0.206

3. Results and Discussion

The σ-ε diagrams related to the stress-strain of concrete specimens are given in Fig. 1. The use of CBC caused a reduction in compressive strength, as seen in Fig. 1. Compressive strength was decreased with the use of CBC at a cement content of 300-350 and increased at a cement content of 400. The fact that CBC's compressive strength is lower than the compressive strength of limestone-based aggregate caused a decrease in composite strengths. The increase in cement content and the resulting decrease in w/c ratio caused an increase in strength. Although strain values vary depending on the use of CBC, they generally increase. The low deformation stiffness of CBC was effective here.

Elasticity modulus of CBC concrete was found out by σ-ε diagram. Elasticity modulus was found for the concrete series produced by using granular composite material models as seen in Figs. 2–7. Comparison of experimental elasticity modulus and mathematical elasticity modulus are shown in these figures.

Experimental elasticity modulus was decreased with use of CBC and decrease in the amount of CBC used. This decrease ratio was reached 32% with the use of course CBC in 300 cement content concrete. CBC was less brittle material compared to crush stone for this reason strain was higher and also elasticity modulus of concrete was decreased. Experimental results of elasticity models were given closer results in experiments of 300 cement content 50-100 % course CBC concrete of Hirsch-Dougill model as shown in Fig. 2.

When Fig. 3 is examined, the experimental elasticity modules of 350 doses of concrete containing coarse CBC decreased by up to 36% as the coarse CBC content increased. Since they give similar results for this composite group, it is recommended that the parallel phase Voigt model be used for 50% CBC and the Bache-Nepper-Christensen model be used for 100% CBC.

Table 4. Formulas of granular composite models.

Models	Formulas
Paralell (Voigt)	$E_{c\,Voigt} = E_m \,.\, V_m + E_p \,.\, V_p$
Serial (Reuss)	$\frac{1}{E_{c\,Reuss}} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$
Hirsch-Dougill	$\frac{1}{E_{c\,Hirch-Dougill}} = 0{,}5\,.\left(\frac{1}{E_{c\,Voigt}} + \frac{1}{E_{c\,Reuss}}\right)$
Popovics	$E_{c\,Popovics} = 0{,}5\,.\left(E_{c\,Voigt} + E_{c\,Reuss}\right)$
IIlston	$E_{c\,Illston} = \left[\frac{1-\sqrt[3]{V_p}}{E_m} + \frac{\sqrt[3]{V_p}}{E_p\,.\sqrt[3]{V_p}^{\,2} + E_m\,.\left(1-\sqrt[3]{V_p}^{\,2}\right)}\right]^{-1}$
Mehmel-Kern	$E_{c\,Mehmel-Kern} = \frac{\sqrt[3]{V_p^{\,2}}}{\frac{\sqrt[3]{V_p}}{E_p} + \frac{1-\sqrt[3]{V_p}}{E_m}} + E_m\,.\left(1-\sqrt[3]{V_p^{\,2}}\right)$
Bache ve Nepper-Christensen	$E_{c\,Bache-Nepper-Christensen} = E_p^{\,V_p}\,.\,E_m^{\,V_m}$

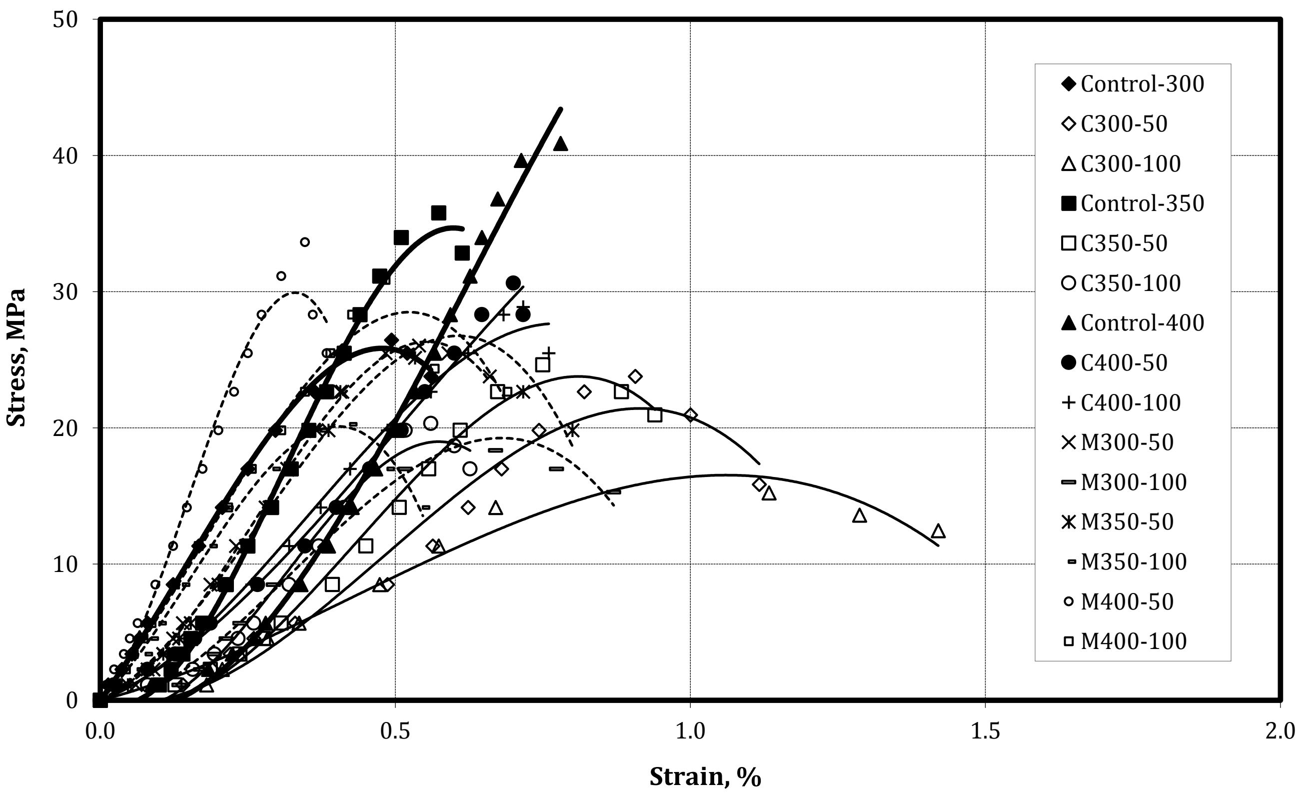

Fig. 1. σ–ε graphs of concrete containing baked clay.

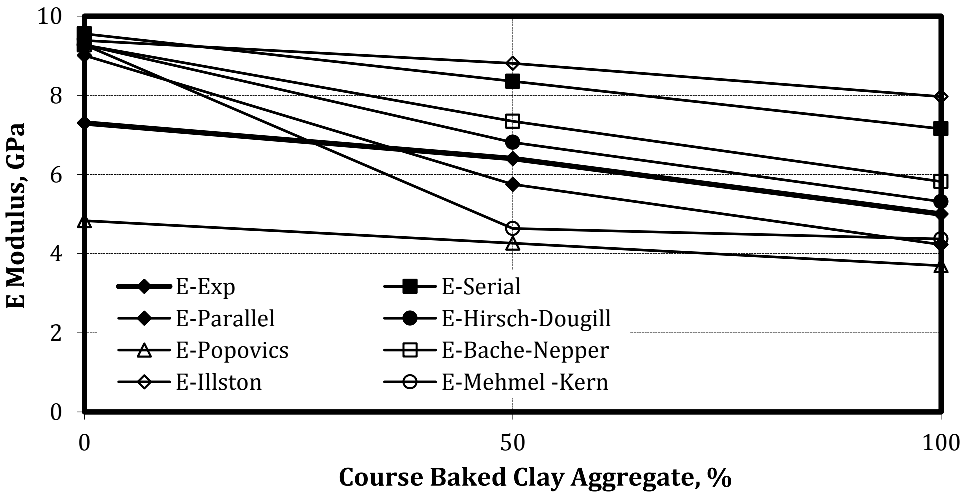

Fig. 2. Elasticity modulus of 300 cement content concrete containing course baked clay aggregate.

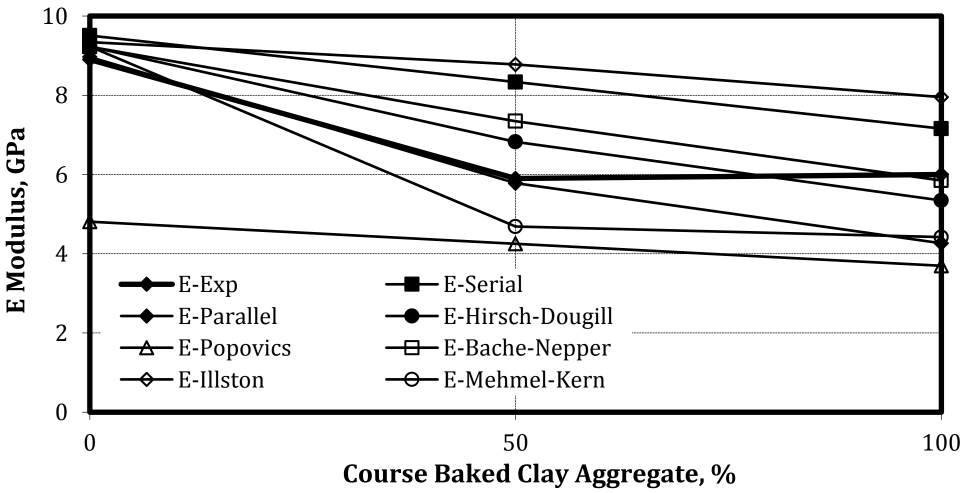

Fig. 3. Elasticity modulus of 350 cement content concrete containing course baked clay aggregate.

In Fig. 4, the experimental elastic modulus of 400 cement content concrete samples containing coarse CBC decreased by up to 29% as the coarse CBC content increased.

The study recommends using the Bache-Nepper-Christensen model for 50% CBC and the parallel phase Voigt model for 100% CBC as they provide similar results for this composite group.

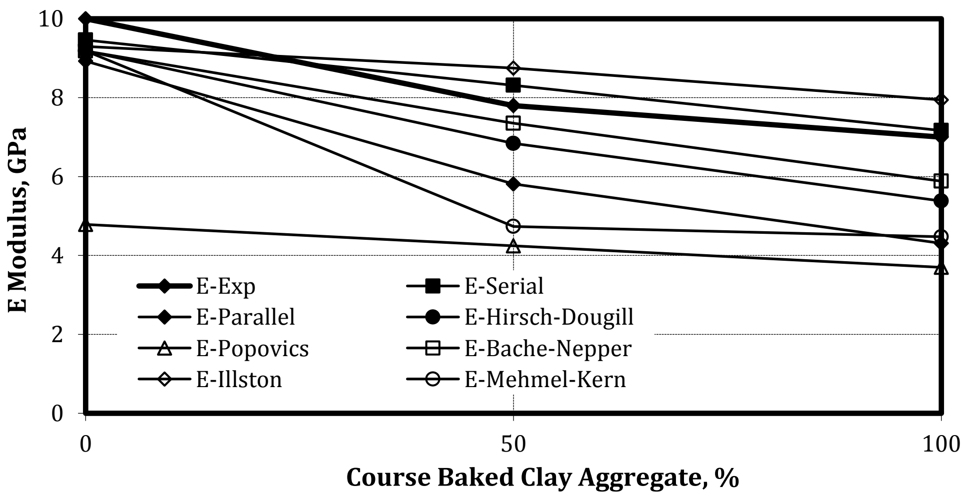

Fig. 4. Elasticity modulus of 400 cement content concrete containing course baked clay aggregate.

In Fig. 5, it was observed that the experimental elastic modulus of 300 concrete samples containing medium CBC decreased by up to 66% as the medium CBC content increased. The study suggests that the Popovics model for 50% and 100% CBC has similar results for this composite group.

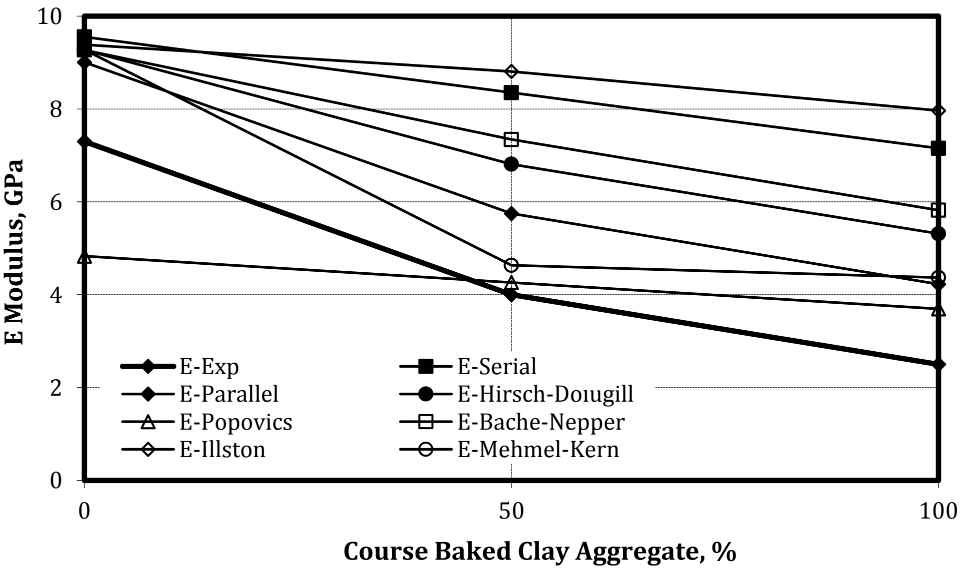

Fig. 5. Elasticity modulus of 300 cement content concrete containing medium baked clay aggregate.

In Fig. 6, the experimental elastic modulus of 350 concrete samples containing medium CBC decreased by up to 42% as the medium CBC content increased. The study recommends using the parallel phase Voigt model for 50% CBC and the Hirsch-Dougill model for 100% CBC as they provide similar results for this composite group.

When Fig. 7 is examined, the experimental elasticity modules of 400 doses of concrete containing medium CBC decreased by up to 36% as the medium CBC content increased. Since they give similar results for this composite group, it is recommended that the parallel phase Voigt model be used for 50% CBC and the Hirsch-Dougill model be used for 100% CBC.

The pointwise closest models of the experimental data obtained using different cement contents and CBC aggregate ratios are stated above. However, as a generalization, the parallel phase Voigt model is more suitable for 50% CBC use, and the Hirsch-Dougill model is more suitable for 100% CBC use. When CBC is coarse, the Hirsch-Dougill model would be more appropriate at low cement contents and the serial-phase Reuss model at high cement contents. When medium CBC is used, the Popovics model is more suitable for low doses, and the Hirsch-Dougill model is more suitable for high cement contents.

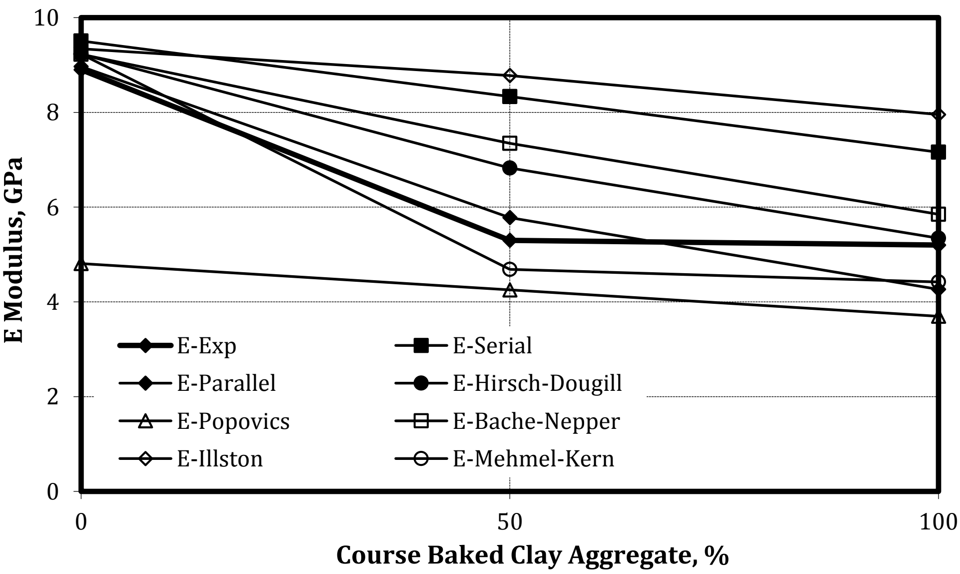

Fig. 6. Elasticity modulus of 350 cement content concrete containing medium baked clay aggregate.

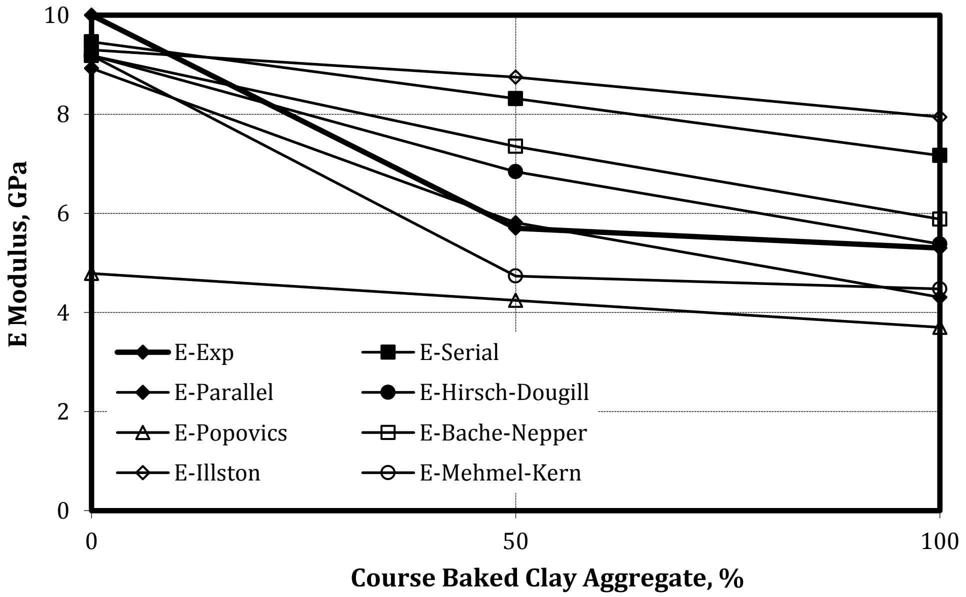

Fig. 7. Elasticity modulus of 400 cement content concrete containing medium baked clay aggregate.

4. Conclusions

The conclusions of the study are summarized as follows:

- As can be seen from the σ–ε graphs obtained from the compression test, while the compressive strength increased with the increase in cement content, it decreased as the use of CBC increased. It has been observed that CBC grains are very important in compressive strength. The use of 100% CBC is not recommended.
- In the specimens where CBC was used, the strength decreased, the deformation increased, and the elasticity modulus decreased compared to the control specimens. By increasing the cement content, the resistance of the binder matrix against deformation increases; thus, an increase in the elasticity modulus is observed.
- The pointwise closest models of the experimental data obtained using different cement contents and CBC aggregate ratios are stated above. However, as a generalization, the parallel phase Voigt model is more suitable for 50% CBC use, and the Hirsch-Dougill model is more suitable for 100% CBC use.
- When CBC is coarse, the Hirsch-Dougill model would be more appropriate at low cement contents and the serial-phase Reuss model at high cement contents. When medium CBC is used, the Popovics model is more suitable for low doses, and the Hirsch-Dougill model is more suitable for high cement contents.

The assessment of waste is crucial for sustainable environmental management. This study shows that the CBC waste generated during production, construction demolition works, and roof repairs can be used in concrete production. However, due to the negative effects of these wastes on mechanical properties, it is recommended to use them in non-load-bearing concrete. In addition, its potential to be used in load-bearing concretes by reducing its negative effects on mechanical properties by using lower ratios can be recommended for new research. It has been demonstrated in this study that granular composite models can also be suitable for concrete containing such wastes.

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Conflict of Interest

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Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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