Toughness and Ultimate Compressive Strength of Bio-Based Raw Earth Concrete

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Abstract. Pollution is widespread around the world, and all the countries started looking for new and green alternative energies, or even started limiting the use of grey energy. Intensive grey energy is used nowadays to produce the modern construction materials made of concrete and steel. Therefore, new environmentally friendly and cost-effective building materials, so-called eco-building materials, are needed, which are mainly made of raw earth materials and have low energy consumption with respect to the modern materials.

However, the mechanical properties of silt-based clays need to be carefully studied and improved to achieve the best possible results with the lowest grey energy consumption, in order to become a better and competitive alternative to typical cement-based concrete. Some of the mechanical properties of this silt-based material have already been studied, such as its compressive strength [1] and ductility [2]. However, several other mechanical properties can also be used to investigate the mechanical properties of raw earth materials, such as deformation modulus and toughness. Generally, toughness is considered as the ability of a material to resist impacts and dynamic loads. It is considered in the literature, as the energy absorbed without cracking; or in other definitions, it is the energy required to slow the propagation of a crack before the material fails. With the exception of metals, studies on the toughness of materials have rarely been carried out, despite the important role they play in determining the energy a material absorbs under load before it breaks. This paper examines the toughness of this bio-based raw material and its relationship with its common known mechanical property: the ultimate compressive strength.

Keywords: Bio-based construction materials · Silt-based raw earth concrete · Stress-Strain curve · Strain Energy · Ultimate Compressive Strength · Toughness

1 Introduction

Raw earth has been used for thousands of years as one of the main building materials and remains usable until now. Raw earth is a material available all the time and everywhere. Its use as a building material exploits one of its properties, cohesion, which acts as

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S. Amziane et al. (Eds.): ICBBM 2023, RILEM Bookseries 45, pp. 310–323, 2023.
https://doi.org/10.1007/978-3-031-33465-8_25

a natural binder. There are various construction methods with an infinite number of variants that reflect the identity of places and cultures. Twelve methods of using earth in construction have been identified, six of which are very commonly used and constitute the major technical genres.

Recalling from the 17th century, in south China, the Hakka earth buildings (Kejia tulou) or the roundhouses were built from raw earth materials. These buildings were known by their enormous size and robust architecture with the ability to shelter hundreds of people within one stronghold. They were made of a mixture of earth, sand, lime, glutinous rice, bamboo and wood chips, with walls up to two meters thick [3].

Today, there are more and more modern raw earth buildings around the world. For example, the Chapel of Reconciliation in Berlin was built between 1990 and 2000 [4].

Recently, in 2014, a medical complex called Bayalpata Hospital was constructed in Achham, Nepal, built using rammed earth. It was built as replacement of an old and small hospital in the location, and now with this new building, the hospital will provide low-cost and high-quality care to 100,000 patients a year from Achham which is around more than its original capacity in the old building [5, 6].

Nowadays, the construction materials from concrete and steel need high and intensive grey energy causing high emission of greenhouse gases. These greenhouse gases are manipulating the climate to change on the world level, which gained the attention of all the countries around the world. Hence, a new eco-friendly and more economical construction material is essential to overcome these challenges. The best alternative for the present is the raw earth-based construction material which is considered to be eco-geomaterial with low energy consumption compared to the cement-based construction materials [7, 8].

Raw earth material has the upper hand, since it only requires 1% of energy to be produced with respect to that of the normal concrete [9]. Raw earth material are natural materials which makes them recyclable and reusable. Moreover, they are available everywhere and in large quantities having low and affordable cost.

Various studies were done to improve different properties of the raw earth material related to its mechanical strength, shrinkage and swelling properties, and hygro-thermal properties [10]. Raw earth alone is still not very compatible to be used alone, so, stabilizers such as lime, cement, and/or gypsum and reinforcement using fibers are added to the raw earth mixture enhance its performance [11].

Based on the used raw earth construction technique, adding a small quantity of binders; such as lime and/or cement can improve the material's compressive strength to a certain level in order to be accepted as a construction and building material [10, 12, 13].

The influence of increasing the percentage of flax fibers on the elastic modulus on earth concrete was studied by Kouta et al. 2021 [14]. Where they studied the influence of different proportions content using 0%, 3% and 4.5% and various lengths as12 mm, 24 mm and 50 mm of flax fiber added to earth mixture with constant lime and cement proportions of 3% and 8% respectively.

Imanzadeh et al. 2018 and 2020 studied the unconfined compressive strength of the raw earth material [1] and its ductility [2] and stated the influence of different substituents added in the mixture on these properties. With the help of the design of experiments, they were able to predict and find an optimal range of substituents used in the mixtures to have acceptable mechanical properties as a construction material. Then, to better enhance the mechanical properties of the raw earth and a better understanding with an optimal formulation, additional properties should be studied as toughness which is considered as interesting property to be shown in this paper.

Toughness of a material plays an important in terms of the energy a material can handle, few studies were done on fiber reinforced hydraulic lime mortar [15, 16] and fly ash concrete [17] but none is done on the raw earth concrete. Moreover, toughness is studied for reinforced concrete [18–22] highlighting the fact that adding fibers to a mixture can increase its energy absorption and improve the toughness index of the samples. Although reinforced concrete is a bit different from the raw earth material and can't be compared in terms of constituents, yet, the same definition of toughness referred to the reinforced concrete can be used for earth material too.

In this paper, the toughness of the material from the literature was taken into consideration with some modifications. This work concentrated on studying "toughness" for raw earth which is not done before for this material, to better understand the properties of this material and what ingredients can influence this property to reach to an optimal formulation. Moreover, to relate this toughness to a known mechanical property of the material, a relationship between the toughness of the raw earth concrete and its ultimate compressive strength was shown.

2 Materials

Raw earth concrete is a combination of several materials made of soil, flax fibers, water and binders: cement and lime. Natural silt was chosen as a building material for being plentifully available locally. According to the grading size distribution curve of the soil, its Atterberg limits, and based on the LPC-USCS (ASTM D2487-17e1) standards [23], this soil was categorized as silty sand (SM). Imanzadeh et al. 2018 described in details the properties of this silty sand [1].

The binders from cement and lime were used in the mixture of the raw earth concrete. The quantities of binders in the mixture was limited by 16% maximum for economical and ecological reasons. Where some detailed properties of these binders were well described by Eid 2017 [24].

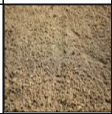
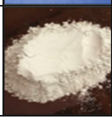
As the Normandy region is responsible for 55% of the total production of flax in France [25], these flax fibers were locally extracted and chosen to be added to the mixture. The fiber content in the mixture varied between 0.3% and 0.45% in mass.

Limited water content was considered in the mixture to minimize the shrinkage of the material. Additives as superplasticizer were added as an alternative to preserve the consistency during the manufacturing process of the concrete for a better workability of the material. These superplasticizers were used as lubrification of the solid surfaces and it decreases the friction stresses between particles [26]. 5 ml/m^3 of additives has been added for each sample preparation. A laboratory mixer of 4L capacity is used for the mixing procedure in order to obtain homogeneous samples with a random distribution of the materials. Additional details are mentioned by Imanzadeh et al.2020 [2].

2.1 Ranges for Mixing

Different constraints from economical, ecological, and environmental ones were respected constraints. As for the fundamental constraint, the summation of the mass of all constituents used must be 100% in the mixture. As explained before, binders were limited by maximum of 16% for economical and ecological reasons. Finally, the workability constraint which was assured for a better mechanical property [27] by including the fluidity conditions with the help of the concrete slump test fulfilling the S3 consistency condition following the standard NF EN 12350-8 [28]. Considering these constraints, the mixing range (lower and upper limit) of the constituents in the mixture is defined as follows in Table 1.

Table 1. Mixing range of each constituent

x_i	Photos	Lower Limit (%)	Upper Limit (%)
x_5: Silt		47	75
x_1: Fiber		0.3	0.45
x_4: Water		20	25
x_3: Cement		4	16
x_2: Lime		0	12

2.2 Formulations

Considering the mixing limits of the constituents used listed above, 25 different formulations were established varying all constituents at the same time respecting all the constraints highlighted before. Table 2 shows the four formulations that were considered in this study, where each one has different percentages by mass of the constituents.

Only four formulations were taken into consideration with different behaviors and various changes in their constituents. These various behaviors were considered as the most representatives to the main four behaviors that were realised through all the formulations that had been experimented. This collection of these four formulations is considered to be a good representative of all the other formulations.

Table 2. List of the considered formulations and their constituents

Formulation	Silt (%)	Fiber (%)	Water (%)	Cement (%)	Lime (%)
I	61.31	0.30	22.39	16.00	0.00
II	72.80	0.30	22.90	4.00	0.00
III	60.63	0.45	22.92	16.00	0.00
IV	59.43	0.45	24.12	11.21	4.79

3 Experimental Method

To study the ultimate compressive strength and toughness of the material, unconfined compressive strength test was performed as following:

3.1 Sample Preparation

The majority of the chemical reactions due to binders was ensured by curing the samples for 90 days by storing the produced specimens with a controlled relative humidity RH≈50% and constant temperature T≈22 °C. 75 specimens are produced in total, consisting of 3 trials for each of the 25 formulations considered with different mixing proportions.

3.2 Unconfined Compressive Strength Test

Following the NF P94–420 [29], NF P94–425[30] French standards, an axial Unconfined Compressive Strength test was performed on a 90 days-cured samples.

Imanzadeh et al. 2018 [1] stated in details the experimental device and the procedure. The force exerted on each specimen was recorded with its corresponding displacement using corresponding sensors. Where the axial strain is calculated by dividing the axial displacement recorded by the initial height of the specimen (Fig. 1) and its corresponding axial stress is calculated by dividing the force with the specimen's cross-sectional (Fig. 2).

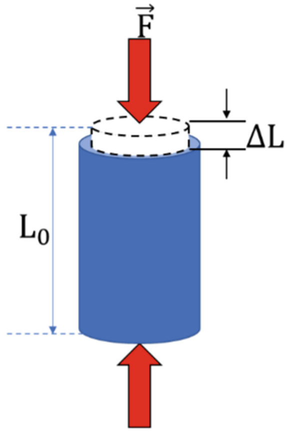


Fig. 1. Deformation of specimen due to applied axial load

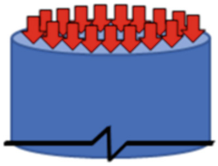


Fig. 2. The applied stress on the top of the specimen

4 Ultimate Compressive Strength (UCS)

Using this raw earth concrete, only nonreinforced structural elements subjected to axial compression [31–34] were intended to be constructed. Where the UCS is the maximum axial compressive stress that a specimen can withstand without applying any confining stress [35–37].

Hence, different parameters could be deduced from the applied axial stress versus axial strain curve obtained from the unconfined compressive strength test. An example of the stress-strain curve relationship is shown in Fig. 3.

In some trials the UCS (the maximum in the stress-strain graph) is not reached so this index couldn't be calculated and replaced by '/'.

5 Toughness

From the obtained stress-strain curves, a threshold of 15% of strength loss after reaching the peak (Fig. 4) is considered as enough to analyze the plastic behavior of the material Imanzadeh et al. 2020 [2]. Hence the study of toughness is done according to this threshold.

In general, toughness is the ability of the material to endure impacts and dynamic loads. It is defined as the energy needed to crack a material before fracturing, or in other

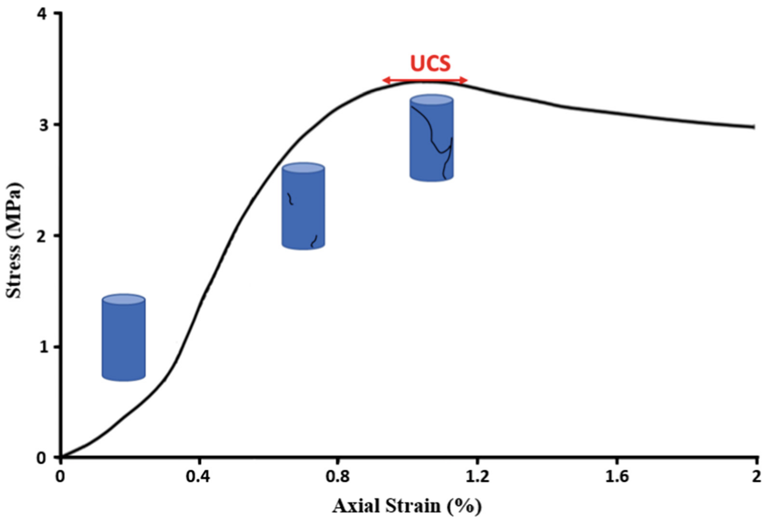


Fig. 3. An example of the stress-strain curve of raw earth concrete

words, it indicates the total amount of strain energy per unit volume a material can handle just before it fractures [38].

Toughness is the combination of strength and plasticity [39], where a tough material can take hard blows without rupturing. So, a material should withstand high loads and be strong and should have high deformations to be considered as plastic and ductile.

The toughness of the material was calculated as the area under the stress-strain curve until reaching the threshold of 15% of strength loss after reaching the maximum. This quantity represents the entire area under the stress-strain diagram presented in Fig. 4 considering the explained threshold.

As said before, in some trials the UCS is not reached and hence the threshold cannot be defined and hence, the toughness of these special trials couldn't be calculated and replaced by '/'.

6 Results and Discussion

Various behaviors of the raw earth material were studied (Fig. 5). Different behaviors could be seen between Formulations I and III even though they show a compatible toughness. Formulation I is considered as strong material with high ultimate compressive strength compared to the other formulations but more fragile. This causes the loss in toughness of FI compared to FIII. Hence, two specimens can have same toughness but one is stronger (FI – T1 = 93.7 kJ/m^3) while the other is more ductile (FIII – TIII = 98,3 kJ/m^3).

The importance of higher strength on the toughness is highlighted when Formulations I and IV are compared. Where, Formulation I has almost the double ultimate compressive strength compared to that of Formulation IV leading for FI to have a very much higher toughness.

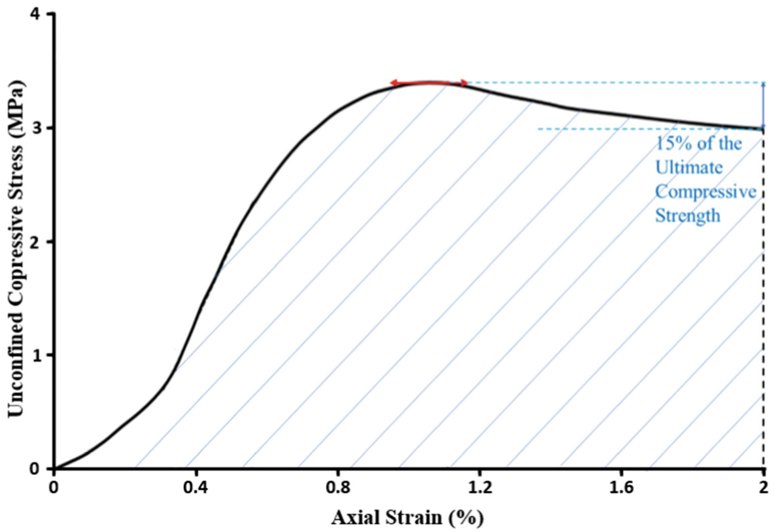


Fig. 4. An example of the raw earth material's stress-strain curve with threshold

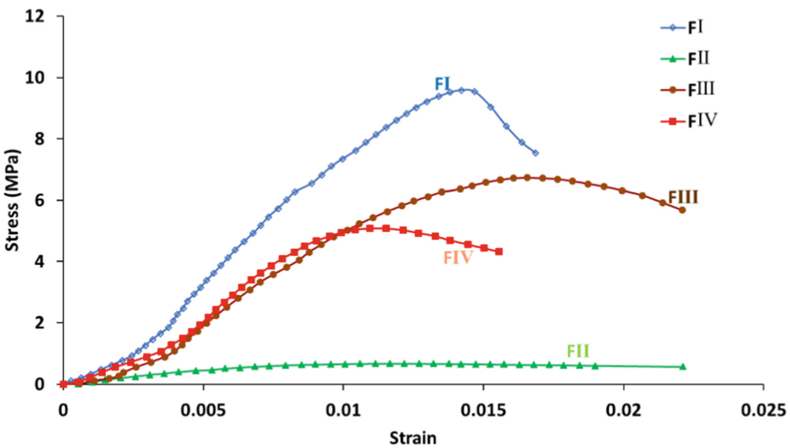


Fig. 5. Stress- strain curves of the Formulations 1, II, III, and IV

The UCS values of the three trials of the four considered formulations obtained from the stress-strain curves are presented in Table 3 with the mean value of the UCS for each specimen. In the same manner, the toughness obtained from the areas under the stress-strain curves for each of the three trials of each formulation is presented in Table 4.

Toughness of raw earth material ranges from 11.8 kJ/m^3 (for formulation with very low lime and cement contents and considered to be highly deformable) to 98.3 kJ/m^3 for 90 curing days period (Table 4).

Table 4 UCS of raw earth material ranges from 0.7 MPa (for formulation with very low binders' content and considered to be weak) to 9.2 MPa for 90 curing days period (Table 3).

Table 3. UCS Values for the 3 trials of the considered formulations

Formulation	UCS_1 [MPa]	UCS_2 [MPa]	UCS_3 [MPa]	MeanvalueofUCS [MPa]
I	8.9	9.2	9.6	9.2
II	0.7	/	/	0.7
III	6.7	/	6.7	6.7
IV	5.0	5.1	5.1	5.1

Toughness of raw earth material ranges from 11.8 kJ/m^3 (for formulation with very low lime and cement contents and considered to be highly deformable) to 98.3 kJ/m^3 for 90 curing days period (Table 4).

Table 4. Toughness values for the 3 trials of the considered formulations

Formulation	T_1 [kJ/m^3]	T_2 [kJ/m^3]	T_3 [kJ/m^3]	Meanvalueof$T$ [kJ/m^3]
I	90.5	103.6	86.8	93.7
II	11.8	/	/	11.8
III	101.5	/	95.1	98.3
IV	41.2	49.7	51.7	47.5

As expected, cement content has high influence on the UCS of the material. Figure 6 shows that as the cement content increases, the UCS of the raw earth concrete increases too. As a maximum amount of cement was used of 16% by total mass, two formulations are found to have different UCS (Formulation I has UCS of 9 MPa and Formulation III with UCS of 6.7 MPa). This shows that other constituents can affect the UCS of the raw earth at the same time, while increasing the cement content causes in high increase in the UCS.

As the water to cement ratio increases and by that the quantity of water increases in the sample, the UCS of the material decreases (Table 5). This is due to the increase in the fluidity of the material and hence decreases its strength to withstand the load applied. As this ratio increase to reach around 6, the UCS decreases to reach 0.7 MPa for a very weak material.

Material with very low cement content causes the material to lose its ability to withstand high loads and hence its toughness is very low as for Formulation II with T around 10 kJ/m^3 (Table 5). The higher the cement content, the higher the toughness of the material is. Until reaching the maximum cement content used of 16% due to the

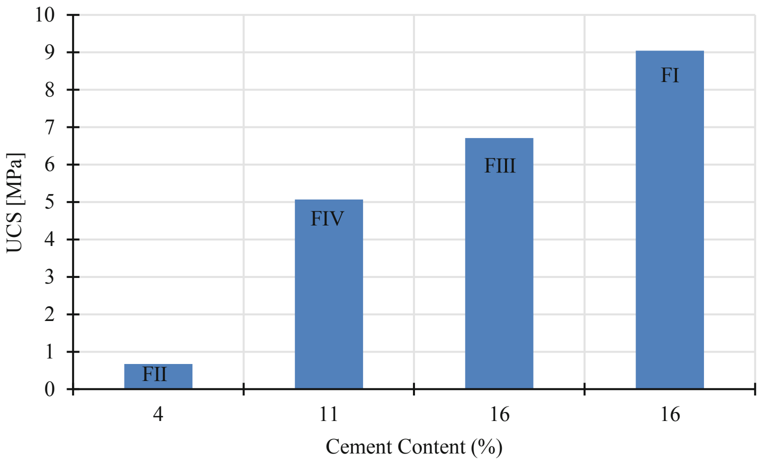


Fig. 6. UCS vs cement content

Table 5. Formulations and corresponding content and mechanical properties

Formulation	Fiber	Cement	Water/Cement	Density [kg/m^3]	UCS [MPa]	T [kJ/m^3]
I	0.0030	0.1600	1.3995	1390	9,05	88,67
II	0.0030	0.0400	5.7241	1397	0,67	11,81
III	0.0045	0.1600	1.4323	1387	6,71	98,29
IV	0.0045	0.1121	1.6626	1342	5,06	50,68

constraints considered, T reaches 98 kJ/m^3 for Formulation III showing that cement has high influence on this property but it is not the only influencing constituent.

As the water to cement ratio increases in the specimen, increasing the material's fluidity and hence losing its combined structure, causes the toughness to decrease. As this ratio is below 2, it gives a well combined structure having high toughness T above 50 kJ/m^3, whereas, the increase in this ratio where water is more than the cement, the material fluidity increases and decreases its toughness to reach a minimum of 10 kJ/m^3 for Formulation II having the value of water/cement ratio near to 6 (Table 5).

The UCS of the material can be related to the toughness of the material (Table 5). It is almost a linear relationship while the ability of the material to withstand higher deformations can increase the area under the stress-strain curve of the material leading to a higher toughness even though its UCS is not very high. As in the case of the Formulation III that has higher toughness (98 kJ/m^3) compared to formulation I (90 kJ/m^3) but it has lower UCS as explained before.

This means that withstanding higher deformations but with weaker material can give a higher toughness. A strong material means that the material is tough, but also a less fragile material but that can withstand higher deformations can mean the same thing. Hence a tough material can be strong and/or withstand high deformations.

Moreover, the density variation shows no clear information related to its influence on the studied parameters. Where both formulations I and II have close densities while the former has the highest toughness and the latter has the lowest one.

Additional study is considered which is the carbon intensity index related to the compressive strength of the material. This index is defined by Damineli et al. 2010 and 2013 [40, 41] as the total emitted CO2 to obtain a material compared to its strength or performance. To compare our material with the literature, the UCS is considered to define the material's performance rather than the toughness. Compared to the curve given by the Van Damme and Houben 2018 [42], the raw earth concrete studied lies down throughout different domains. This is due to the fact that in the literature, 40% of the carbon footprint of cement is not considered which changed their results compared to this material. As it can be seen that the raw earth material mixed with small amount of plasticizers, can decrease the footprint of CO2 emitted to manufacture the material and increases its performance which is its ultimate compressive strength in this case (Fig. 7).

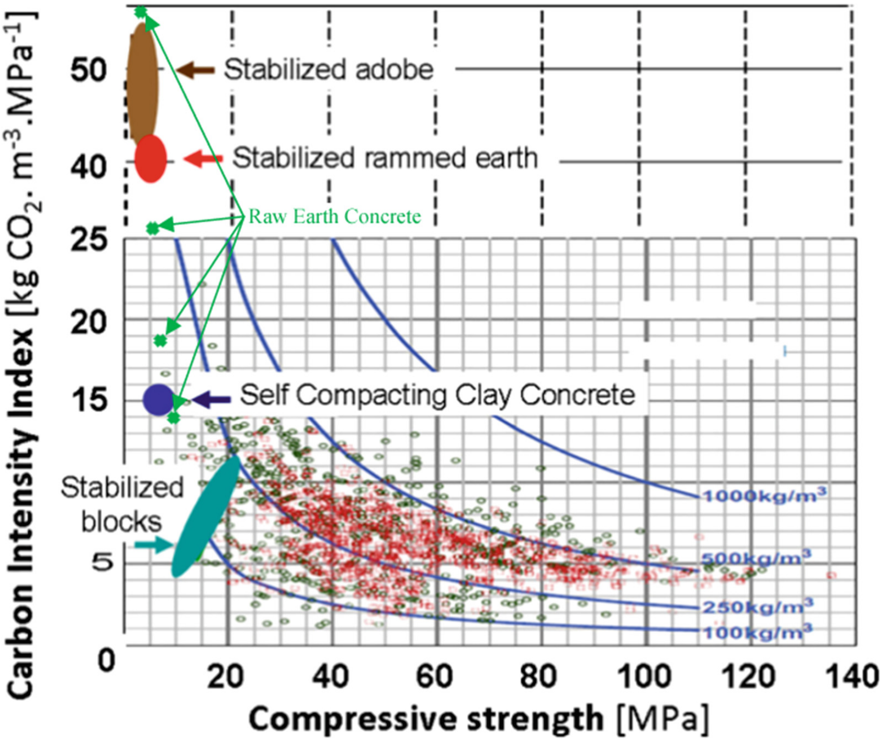


Fig. 7. Adjusted Carbon intensity index vs compressive strength [40, 42]

7 Conclusion

Toughness is an importantly significant characteristic that is needed to be studied for a construction material like raw earth concrete. The aim is to obtain a tough material that can withstand high loads and maintain its behavior at the same time at large strains. The durability of the material is ensured by its toughness. Varying the cement and water contents in the material, showed high effect on its toughness but should be verified with design of experiment that has been proved by other papers as suitable method to obtain optimal formulation having relatively good mechanical properties. All the data analyzed should be validated by the design of experiment to optimize the mechanical properties required.

Even though only four formulations were considered in our study, but these four formulations having different behaviors and difference in their constituents; it gave us an idea about the effect of some constituents on the UCS and toughness of raw earth concrete. These various behaviors considered, correspond to the main four behaviors we obtained through all the formulations had been experimented. Where we can say that this sample of the four formulations is quite representative for all other formulations.

It has been shown the positive effect of binders and specially cement on increasing the toughness of the material. On the other hand, water has a negative effect on this property specially when this content increases with respect to the cement content. Additional study is required with the use of Design of Experiments to have a better analysis of the effect of multiple constituents at the same time on one characteristic, and studying their influence on each other is interesting using a valid model for the toughness characteristic.

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