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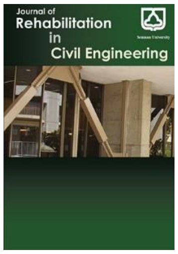

Evaluation of Recycled Materials as Aggregate of End Bearing and Floating Stone Columns: a Comparative Study

Abdolhosein Haddad [1], Mohsen Shahverdi [2]

1. Associate Professor, Faculty of Civil Engineering, Semnan University, Semnan, Iran
2. Graduate student, Faculty of Civil Engineering, Semnan University, Semnan, Iran

Corresponding author: *Haddad@semnan.ac.ir*

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ABSTRACT

The object of this research is to compare the behavior of floating and end bearing stone columns made of recycled aggregates of building debris with natural aggregate. To do so, both types of stone columns were constructed by crushed concrete and crushed brick as recycled aggregates and compared with the same models made of gravel as natural aggregates. All the columns were constructed with the same size, density, and grading in a clay bed. To evaluate the initial quality of materials of the stone columns, the index tests including aggregate impact value test and aggregate crushing value test were performed. The results of such tests illustrated the less resistance of recycled materials in comparison to the natural materials; On the contrary, according to the results of the index tests, crushed bricks are not recommended to construct stone columns. Despite the index tests, results of loading on a floating column filed with natural and recycled aggregate were approximately the same, approximately five times the unreinforced bed, while the bearing capacity of the end bearing column made of natural aggregates was 35% more than the same model made of recycled aggregates.

1. Introduction

Columns have been employed for various applications in soils: (a) support of superstructures including embankments, walls, buildings, etc. (b) lateral support, (c) stabilisation of slopes and (d) containment of water and pollutants. In such applications, columns are used to reduce settlement, increase the bearing capacity, provide lateral support, and enhance slope stability, drainage

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and containment. Rigid columns such as concrete columns known as piles and flexible columns such as stone columns are the most common methods to improve beds of structures. Such two types of columns can be evaluated in terms of bearing capacity and drainage. When it comes to the former, it is stiffness of piles that plays a significant role for piles to take advantage over stone columns, while in terms of drainage, granular materials can serve as drainage paths to soft soil. This property of stone columns can increase the acceleration of consolidation of soft clay soil, leading to saving time and cost for constructing embankments, buildings and so on. Therefore, when time and cost of construction of structures over soft clay soil need to be saved, flexible columns (stone columns) take preference over rigid columns (piles) .Numerous research has been done to assess the impacts of stone columns on the amount of the clay bed improvement [1-7]. In most of these studies, a type of aggregate was utilized in the construction of stone columns with various dimensions. In practice, natural aggregates of mines around the project are used in constructing stone columns. In addition, an enormous amount of natural aggregates are consumed to construct the stone columns. Given that natural resources such as gravel and sand are becoming scarcer [8] and the volume of landfills is increasing, the use of recycled aggregates rather than natural aggregates for stone columns can be a golden opportunity [9].

Many research has also been conducted to evaluate the use of recycled materials such as crushed brick and crushed concrete for stone columns. Theories taking account of the effect of using recycled aggregates on the column design process have been presented by Jefferson et al [8]. Furthermore, in the study of Serridge [10], the use of crushed concrete and recycled railway ballast was proposed to replace the natural aggregates for stone columns. Experimental models of end bearing columns making of a combination of crushed concrete, crushed brick ,and incinerator bottom ash aggregate were evaluated by Amini [11], resulted in a good response of the stone columns. Moreover, experimental studies conducted by Demir et al [12] showed that floating columns filled with recycled and natural aggregates had a bearing capacity close to each other.

Studies on the use of tire chips as an alternative to the main materials for the aforementioned columns were also conducted; research of Ayothiraman and Soumya [13] demonstrated that replacing 40% or 60% of tire chips instead of natural aggregates resulted in the same bearing capacity as stone columns made of natural aggregate. In addition, Mazumder et al [14] also achieved good loading results in terms of the encased stone column made of 100% tire chips in comparison to natural aggregate. The assessment of the combination of recycled material and natural aggregates for floating stone columns also was carried out by Shahverdi and Hadad [15]. Their results showed that using a kind of material was far better than the compound of them.

The goal of this experimental study is to compare the bearing capacity of end bearing columns made of a kind of recycled aggregate and natural aggregate with the results of floating columns tests of Shahverdi and Hadad's research [15] to better understand the behavior of building debris under different conditions. Moreover, to compare the behavior of such materials when they are used in a scaled model with index tests, in this study, aggregate index tests recommended by standard BRE [16](2000) including the aggregate impact value(AIV) test and the aggregate crushing value(ACV) test were performed to assess the quality of the materials of the columns. Then, according to the experiment plan of constructing stone columns presented in Table (1), seven loading plate tests were performed on the models. Single columns constructed in two types of floatation and end bearing were modeled. Crushed brick and crushed concrete (recycled aggregate) and gravel (natural aggregate) were utilized as filler material of the columns.

Table 1. Summary of the Laboratory programs

Test series	Kind of column	Materials of column	relative density Dr(%)
1	Unreinforced clay	—	—
2	Float	Gravel	٧٥,٢
3	Float	Crushed Concrete	٧٤,٢
4	Float	Crushed Brick	٧١,٢
5	End bearing	Gravel	75/2
6	End bearing	Crushed Concrete	74/2
7	End bearing	Crushed Brick	71/2

2. Experimental plans

2.1. Aggregate impact value test

AIV test was done to evaluate the behaviour of materials under the influence of impact forces on the basis of the Standard BSI [17]. AIV is calculated using equation 1, where M_1 is the total mass of the sample in grams and M_2 is the mass of the material passing 2.36 mm sieve in grams.

$$AIV = \frac{M_2}{M_1} * 100 \qquad 1$$

Standard BRE [16] recommends the maximum of AIV =30% (maximum 30% of aggregates pass 2.36 mm sieve) for the acceptance index. Table 2 presents the results of the AIV tests on gravel, crushed brick, crushed concrete; in the AIV test; the crushed brick had more crushing than the other materials, and even crushing of the crushed brick exceeded the maximum recommended value of BRE did not satisfy the required criterion to be used in stone columns.

Table 2. Summary of the AIV tests

Material	AIV (%)	AVI value limited
Gravel	15.2	
Crushed Brick	31.7	<30
Crushed Concrete	26	

2.2. Aggregate crushing value test

ACV test is also another recommendation of the standard BRE [16] to evaluate the behavior of materials used in stone columns. This test was conducted in accordance with Standard BSI [18]. ACV can be calculated using equation (2); which M_1 is the total mass (grams) and M_2 is the mass of the aggregate passing 2.36 mm (grams).

$$ACV = \frac{M_2}{M_1} * 100 \quad 2$$

Table (3) provides the results of the ACV tests on gravel, crushed brick, and crushed concrete. According to the results of the ACV tests, unlike gravel and crushed concrete, the crushed brick.

Table 3. Summary of the ACV tests performed

Material	ACV (%)	ACV value limited
Gravel	23.2	
Crushed Brick	45	<30
Crushed Concrete	27.7	

2.3. Materials and dimensions of the model

The clay soil of the local area was used as a footing bed of the experiments. The soft clay bed was so poorly prepared that construction of stone column models becoming easy. Table 4 presents the properties of the soft clay. After being done a laboratory vane shear test, the undrained shear strength of the clay bed was got approximately 5 kPa .

The particle materials of both types of stone columns separately were gravel (natural aggregate), crushed brick, and crushed concrete (recycled materials) with the varying sizes ranging from 2 to 9.5 mm along with a uniformity coefficient of 1.7 (Fig. 1). The waste concrete and brick of building debris were crushed with mechanical equipment. All materials of the columns were classified as poorly graded gravel (GP) in terms of ASTM D2487-06[19]. Furthermore, the maximum and minimum density of the aggregates were obtained by ASTM D-4254 [20] and ASTM D-4253 [21] tests and the relative density of materials are presented in Table 5. The aforesaid materials were then compacted in a dense density. By the direct shear test at 75.2 relative density, the internal friction angle of gravel was obtained 45 °.

Table 4. Properties of clay

Parameters	Value
Test bed moisture content	39
Optimal moisture (%)	18
Plastic limit (%)	22
Liquid limit (%)	51
Plasticity index (%)	29
Specific gravity	2.69
Bulk unit weight at 39% moisture (kN/m^3)	17.2
dry density in the densest state (kN/m^3)	15.3
USCS classification symbol	CL
Undrained shear strength (kPa)	4.5-5

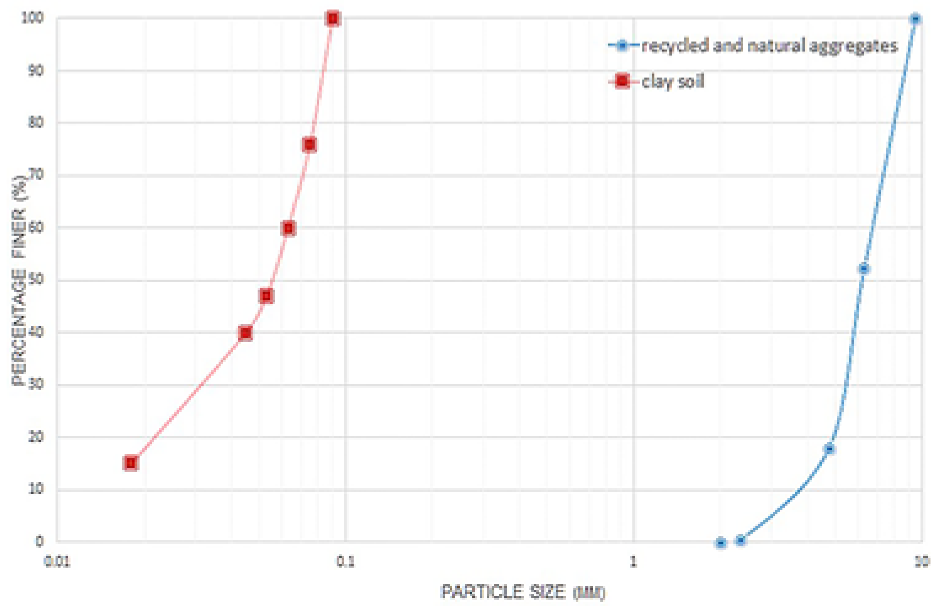

Fig.1. Particle size distribution curve of materials

Table 5. The density of the material of columns

Type of Material	Pmax (kg/m3)	Pd (kg/m3)	Pmin (kg/m3)	Rc(%)	Dr(%)
Crushed concrete	1367	1313	1180	96.1	74.4
Crushed brick	1007	950	836	94.4	71.2
Gravel	1695	1642	1500	96.9	75.2

The dimensions of both end bearing and floating columns were identical meaning that length and diameter of columns were L = 360mm and d = 60mm respectively, presenting an optimal length ratio of L / d = 6. This optimal length ratio resulted in a bugling failure in stone columns [1, 2, 6]. A rigid circular footing with a diameter of 1.6 times the diameter of the columns was used for both kinds of the columns. These dimensions lead to an area replacement ratio (column area/footing area) of Ar = 0 36, lying in the range of the best area replacement ratio which is between 30% and 40% [4].

2.4. Modeling considerations

Dimensions of the test tank should be chosen in such a way that the effect of the loading stresses of the test is similar to that of the actual conditions. The space between the tank walls should be large enough to prevent the formation of buckling phenomenon during soil settlement, and the effect of induced stresses on the tank boundaries should be negligible [22]. Therefore, in order to assess the impacts of the stresses on the test tank walls, an equivalent footing at two-thirds of the length of the column is assumed. The stress distribution for a footing with a diameter of 100 mm and a column with a length of 360 mm has been demonstrated in Fig. 2 which is a schematic view for the floating stone column and the end bearing stone column. This equivalent footing distributes the induced stresses with a 2:1 ratio in the depth of the box. As it has been shown in Fig. 2a and 2b , a tank with a height of 660 mm and a diameter of 580 mm for the soil bed of the floating columns was used, by which the effect of the distributed stresses on the bottom of the tank is negligible (≈4%), Moreover, a cylinder tank with a height of 360 mm and a diameter of 580 mm was used for end bearing columns tests. In practice, stone columns are built with a diameter in the range of Dp = 0 .6-1 m and the grains size in the range of ds = 25- 50mm, thus that the ratio Dp / ds is usually between 12 and 40 [23]. In this modelling (Dm = 60mm, dm = 2-9.5mm), this ratio varied from 6 to 30.

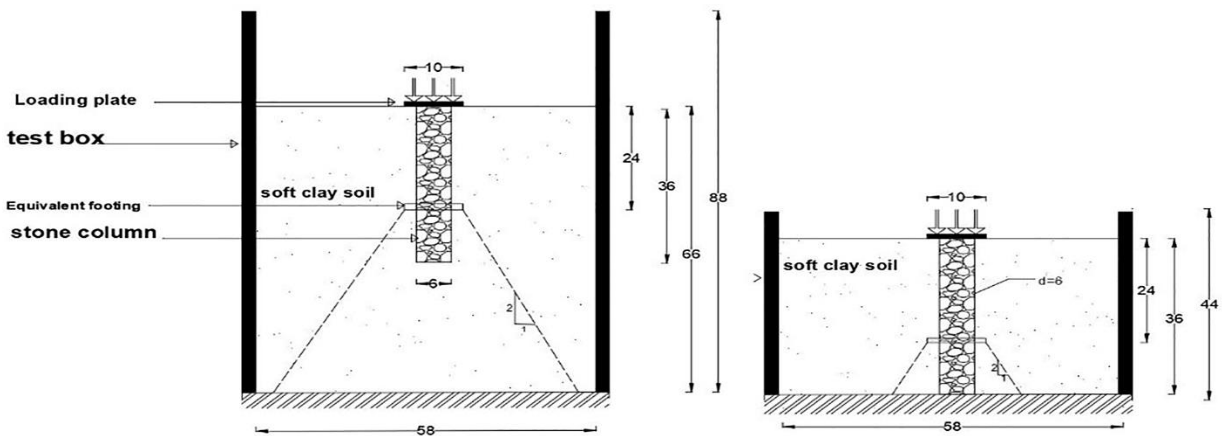

Fig. 2. Schematic view for (a) floating stone column; and (b) end bearing stone column

2.5. The procedure of the test

2.5.1. Clay bed preparation:

At first, in order to lessen the friction between the soil sample and wall of the tank during the settlement, silicone grease was used to lubricate the internal wall of the test tank. The vane shear test and the Proctor compaction test were conducted to distinguish the moisture content corresponding to 5 kPa undrained shear strength of the soil. Next, the clay paste with determined moisture was placed in the test tank in 100mm thick layers and each one was compacted with a 3-kg rode. Finally, on the clay bed surface, a thick plastic was laid and left for a week to bring the entire soil mass to a uniform moisture content.

2.5.2. Stone columns:

In order to construct the end bearing and floating and stone columns by the replacement method, first, the inner and outer walls of the casing pipe were lubricated with silicone grease so it could penetrate without difficulty into the clay bed. After being pushed the pipe in the center of the clay bed to a depth of 360 mm, the soil within the pipe was taken out with a long spade. The next step was to charge the aggregates into the pipe. To construct all the floating and end bearing stone columns with the same relative density (dense) and grading, the weight of the materials was measured before being charged the materials into the pipe. The aggregate of the materials inside the pipe then was compacted in layers with a thickness of 50 mm with a 2-kg rod.

Next, the pipe was slowly lifted up to achieve a maximum overlap of 25 mm between the surrounding soil and aggregates. Finally, this process was proceeded until the measured materials of the column were thoroughly used on the bed surface. A typical scheme of the constructed stone column is shown in Fig. 2 After being constructed the column, for 4 hours, a 2.5-kPa surcharge was deployed to load the total area of the bed. This loading was performed to reach uniformity in the test bed by eliminating the local disturbances [24].

2.5.3. Loading:

The loading of the surrounding soil and the column was performed with a steel plate with a thickness of 10 mm and a diameter of 1.6 times the diameter of the column. This compressive loading was used with a hydraulic jack in a strain-controlled manner at a rate of 2 mm/min. Such a fast loading rate would make the friction angle of clay approach to nought, which leads to soil with poor resistance to be simulated [6]. The footing load was applied until a settlement of 40 mm was obtained.

Fig. 3 depicts the equipment used for loading and measuring the settlement. The loadings of hydraulic jack transmitted to the footing were recorded with a load cell placed on the footing. Then, two transducers on the loading plate to measure the settlement of the rigid footing were used. Loading and movement information was saved by a computerized data acquisition system. This device recorded data at a speed of 1 second. All of the instruments were calibrated before being tested and finally were connected to a laptop computer.

Fig. 3. photograph of the experimental setup

3. Result and discussion

In this part, first, the data of loading the floating and end bearing columns made of a kind of material are separately compared. Then, the outputs of the loaded floating columns, constructed of both natural and recycled materials, are evaluated and compared together and this procedure is also applied to all of the end bearing columns.

3.1. Stone columns constructed of natural materials

The results of bearing pressure-settlement of the footing reinforced with both floating and end bearing stone columns made of gravel (natural aggregate) and unreinforced bed have been shown in Fig. 4. Reported settlements (S / D) are the average readings of two L.V.D.Ts. In general, both types of columns have resulted an increase in the bearing capacity of the clay bed. In the initial strains, theses gravelly columns have behaved similarly, on account of the characteristic of initial interlocking of the compacted materials together. Then, with increasing stress, the slope of the bearing pressure curve for the floating column has reduced in contrast to the end bearing column.

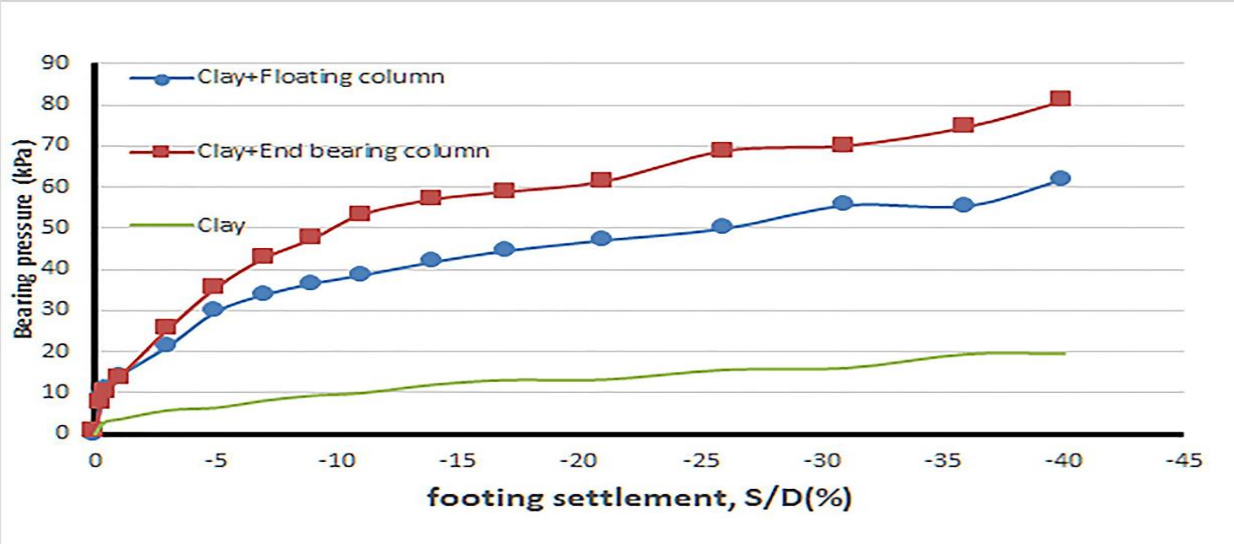

Fig.4. pressure-settlement curves of the clay beds with columns made of Gravel aggregate.

The results show that the end bearing column has a bearing capacity greater than that of the floating column. As can be seen, almost at the strain of 10 %, the clay bed reinforced with floating and end bearing stone columns had a bearing capacity of up to 38 kPa and up to 50 kPa, respectively. The rationale for such a difference can be attributed to the different placement conditions of the two columns towards the loading. Because the presence of a rigid bed in contact with the tip of the end bearing column has caused the end bearing column to have a higher bearing capacity than the floating stone column. Despite this, in stone columns constructed with an L / d ratio greater than or equal to 4 or 6, of both floating and end bearing types, a bulging failure occurs [25]. Not having a tip bearing, the wall friction of the floating columns with the soil resistance due to the bulging of the column have less impact than the bearing of the tip of end bearing columns.

3.2. Stone columns constructed of recycled materials

The response of bearing pressure-settlement of the footing reinforced with end bearing and floating columns filled with crushed brick and crushed concrete are respectively presented in Figs. 5 and 6. Regardless of the index properties of the material and the type of column, both types of columns made of crushed bricks and concrete have improved the bearing capacity of the clay bed. In terms of low stresses, the behavior of both the end bearing and floating columns is similar, but with increasing stress, the settlement of the end bearing columns increases. In contrast to the end bearing column, the curve of the bearing capacity of the floating column has become horizontal after the settlement of approximately 11% for the crushed brick-constructed columns and 5% for crushed concrete-constructed columns and it can be said that the floating column has suffered a failure. The rebounding curve slope can be due to the rearrangement of the material of the columns and the remobilization of the shear resistance of the soil.

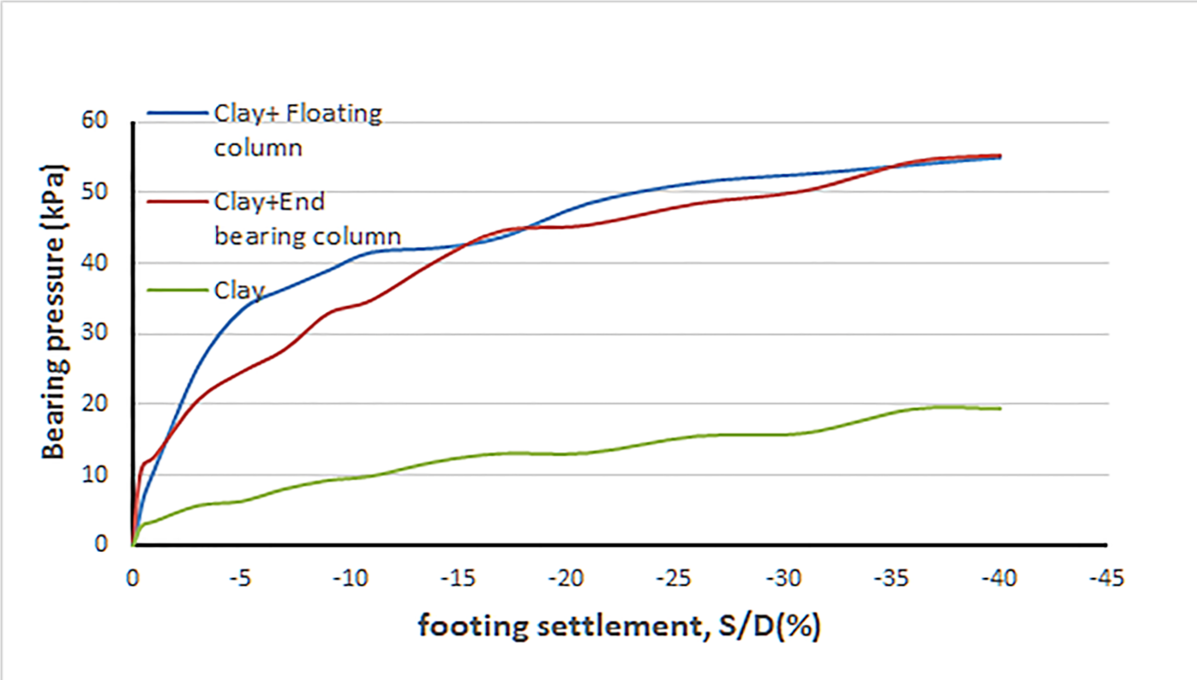

Fig. 5. pressure-settlement curves of the clay beds with columns made of crushed brick.

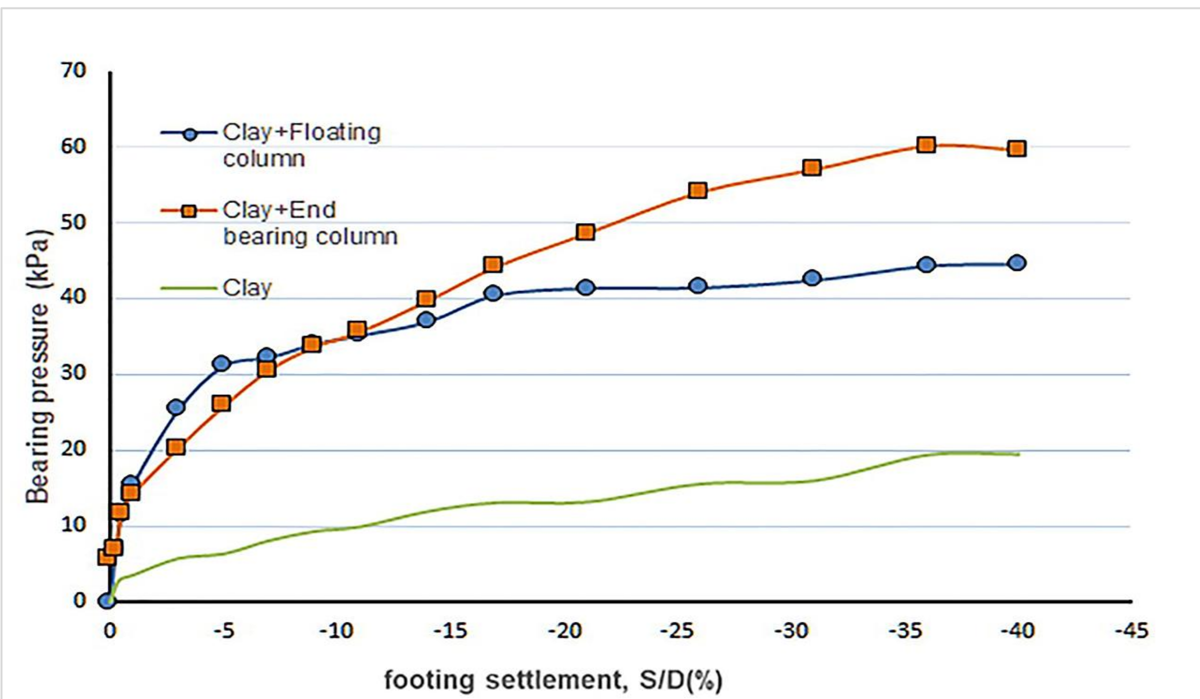

Fig. 6. pressure-settlement curves of clay beds with the stone columns made of crushed concrete.

Figs. 5 and 6 show that, with the same type of recycled material, the floating columns have more bearing capacity than the end bearing columns have. This reaction can be due to the fact that in end bearing stone columns, a portion of the compressive stresses is tolerated by the tip of the column, resulting in the materials of the end bearing columns undergoing more compression. Given the results of index tests of AIV and ACV, naturally, crushed brick and crushed concrete are crushed more and sooner in end bearing columns. Thus, the presence of fines reduces the angle of internal friction, decreases bearing capacity, and increases settlement [10, 26].

3,2, Floating columns

By comparing the loading response of the floating columns with the natural and recycled materials through non-dimensional factor, IF, a clearer comprehension of the behavior of these materials towards the loading can be obtained. The proportion of bearing capacity on the bed reinforced with stone columns to without stone columns at the same settlement is defined as the bearing capacity improvement factor (IF). Variations of IF with the settlement of the clay bed reinforced with floating columns constructed of crushed brick, crushed concrete, and gravel aggregates have been demonstrated in Fig. 7. All of the beds reinforced with a floating column has endured more bearing pressure than the unreinforced bed due to an increase in bed stiffness, leading to improving bearing capacity. When the stress of columns reaches the yield strength, the gradient of the column's IF is reversed, meaning that the stresses are transferring from the column to the surrounding soil. Then, Because of the rearrangement of the materials of the column and soil after displacement, the curve experiences oscillations in the increase the bearing.

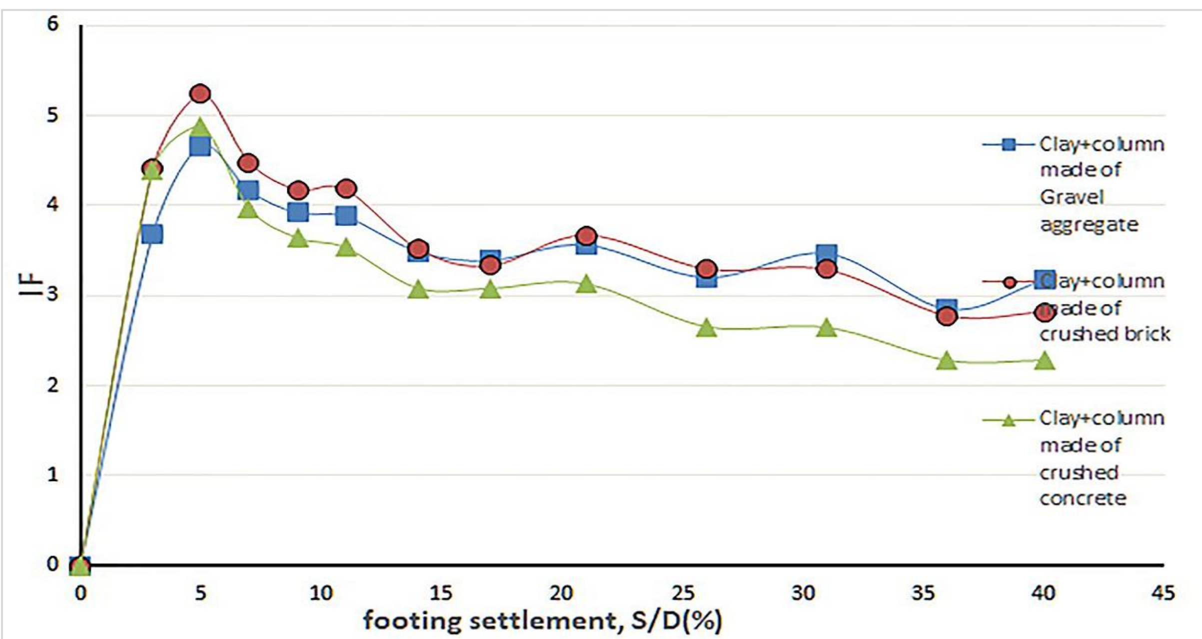

Fig. 7. Variation of bearing capacity of beds with floating columns.

Based on the Fig 7, the maximum improvement of the bed reinforced with the floating columns constructed with crushed brick, crushed concrete, and gravel aggregates, has been nearly five times of the unreinforced bed. This shows that the loading conditions that dominate throughout the index tests on materials are different from the loading conditions of the floating stone columns. This being the case, the bed reinforced with the column made of crushed brick has a slightly higher bearing capacity than those with the other columns. This may be due to the fact that the contrast between the minimum and maximum density of the crushed brick is less than that of other materials (according to Table (3)). Therefore, the interlocking of such the materials during the loading is mobilized and the strength of the materials is activated sooner. Then, because crushed brick is brittle, interlocking among materials breaks and the column is dilated sooner. By and large, the mechanism that mainly leads stone columns to improve is the bulging of columns [25]. The weakness of the crushed brick causes the crushed brick to tend to have a lateral bulging in deeper depth compared to the other materials. While depth increases, the pressure of soil and passive resistance of the surrounding soil enhance. Given this, when the column tends to the bugle out in deeper parts of the bed, more passive resistance of the soil is activated which results in an improvement in the bearing capacity of the bed.

3,3. End bearing columns

Fig. 8 illustrates the response of variations in the IF with the settlement of the clay bed reinforced with end bearing columns made of crushed brick, crushed concrete, and gravel aggregate. In general, in spite of the type of materials (recycled or natural), all of the end bearing columns increase the bearing capacity of the clay bed. Considering the yield strength of the end bearing columns in the settlement, which is equivalent to 5% of footing diameter, the end bearing stone column made of gravel (natural materials) has the highest bearing capacity compared to the other columns made of the recycled materials. According to the index tests, gravel aggregates have a higher resistance to crushing and impact than recycled materials, causing that end bearing stone column made of gravel experience further increase in bearing capacity compared, more than 35%, with columns made of crushed brick or crushed concrete and recycled materials are crushed leading to low bearing capacity due to their poor resistance.

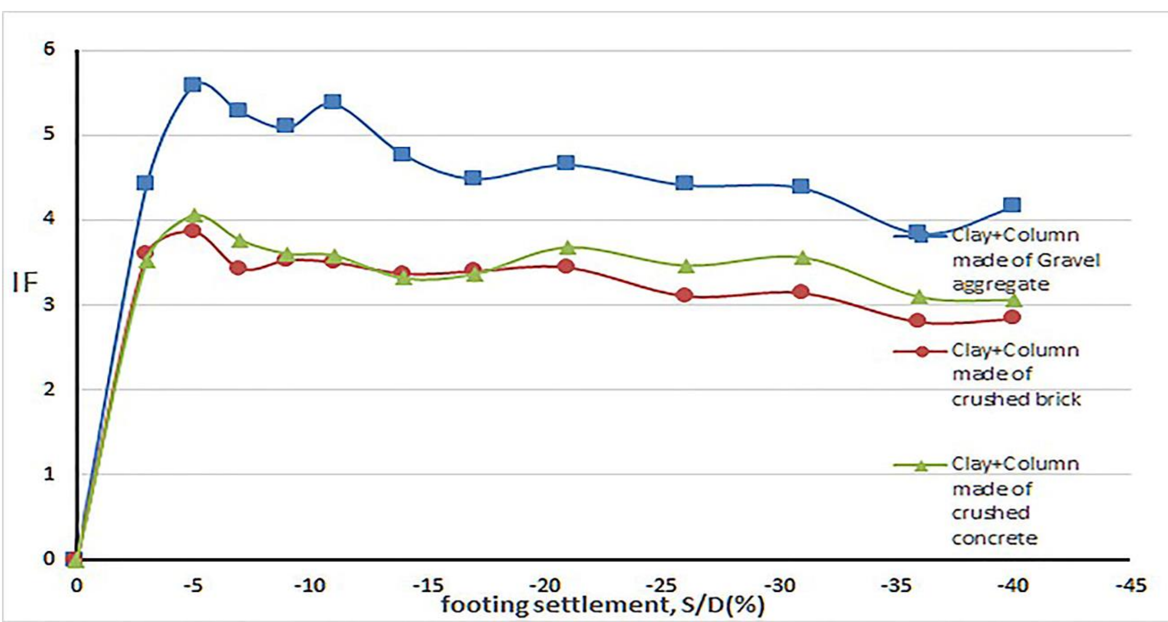

Fig. 8. Variation of bearing capacity of beds with end bearing columns.

4. Conclusion

The findings of the experimental investigation into the behavior of recycled aggregates, of building debris, in floating and end bearing stone columns are briefly summarized as follows;

• According to index tests of aggregates, recycled materials have proved a poor performance, and the use of crushed brick to construct stone columns is not recommended

• Broadly speaking, the strength of clay beds reinforced with both types of columns made of recycled materials has increased.

• An end bearing stone column filled with natural aggregate has higher bearing capacity (more than35%) than the same columns made of crushed brick and crushed concrete,

• This reaction demonstrates that the resistance of aggregate, in terms of crushing, has a significant impact on the performance of end bearing stone columns.

• A floating stone column filled with recycled materials has the same bearing capacity as the floating one filled with natural aggregate and about five times an unreinforced bed, indicating that the behavior of materials in floating stone columns is different from their behavior of materials in the index tests. This may be because the bulging of floating stone columns has a larger contribution than the strength of the materials to increase the bearing capacity of columns.

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