

Sustainable materials used as stone column filler: A short review

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Abstract. Stone columns (also known as granular piles) are one of the methods for soft soil stabilization and typically used to increase bearing capacity and stability of slope.; Apart from decreasing the compressibility of loose and fine graded soils, it also accelerates the consolidation effect by improving the drainage path for pore water pressure dissipation and reduces the liquefaction potential of soils during earthquake event. Stone columns are probably the most “natural” ground treatment method or foundation system in existence to date. The benefit of stone columns is owing to the partial replacement of compressible soil by more competent materials such as stone aggregate, sand and other granular materials. These substitutes also act as reinforcement material, hence increasing overall strength and stiffness of the soft soil. Nowadays, a number of research has been conducted on the behaviour and performance of stone columns with various materials utilized as column filler replacing the normal aggregate. This paper will review extensively on previously conducted research on some of the materials used as stone column backfill materials, its suitability and the effectiveness as a substitute for regular aggregates in soft soil improvement works.

1. Introduction

A great deal of previous research in soft soil improvement has been found to employ the stone column method with their primary focus engaging towards settlement and deformation behaviours. The aim of stone column construction are to improve the soil characteristics, support the structure and infrastructure overlying both in very soft to firm cohesive soils and also loose silty sands having greater than 15% of fine aggregates [1]. Most of the stone columns analysed in this study are found to utilize normal aggregate as column filler. Column filler materials normally consist of stone aggregates between 20 to 75 mm, gravel and sand are compacted into a vertical hole generally of 0.6 to 1.0 meter in diameter and 15 to 20 meters deep. Crushed stones or gravel for column backfills should be clean, hard, and unweathered—free from organics, trash or other deleterious materials. Three main criteria are taken into consideration when selecting an efficient backfill material, i.e. availability, suitability, and economy. A mixture of crushed stone and sand might also be used in the proportion of 1:0.2 to 0.5 by volume [2]. When columns are formed with granular fill, their load capacities become highly dependent on the strength of the fill material and the confining stress of the surrounding soil [3]. To create required strength capacity with stone columns, the granular materials consisting of stone or stone sand should be



compacted [4]. Generally stone columns constructed using ramming or vibro-replacement method either by wet process or dry process, depends on the availability of equipment and its application.

2. Stone Column

According to Han and Ye, stone columns and sand compaction columns have relatively lower load capacities and stiffness compared to rigid columns (e.g., vibro-concrete columns) and as such they are categorized as flexible columns. Granular columns have excessive bulging problem especially at low confining stress near ground surface, which makes it unsuitable for very soft soil with undrained shear strength lower than 15 kPa. The bulging will occur within 2.5 to 3 times the length of column, measured from the top of the stone column [5]. The problem can be solved by using geosynthetic-encased granular columns where the geosynthetic increases the stiffness of the columns thus improving the soft soil behaviour in term of deformation and strength. However, the geosynthetic is more expensive and takes time to be installed as compared with granular columns without encasement. Several other researches have already been published on encased granular columns, either using geosynthetic, geotextile, etc. However, the stone column design method is still in empirical phase, where based on past experiences and in need of few field trials before any further execution [6]. Hence, no well-defined or well-structured guidelines and/or codes are available to date.

Nowadays, various potential materials have been identified and studied to be adopted as column fillers. It requires further evaluation to validate the performance of the stone columns in soil treatment. For example, quarry dust was selected as a filler material in stone columns to improve clayey soils, however, its performance was not as good as that of gravel. The materials used in stone column construction are required to be free-draining, hard, and inert and comply with acceptable criteria in terms of material type, grading, hardness and chemical stability. In pursuing environmental sustainability in ground treatment, there is an increasing desire to use recycled materials for vibro-stone column techniques [7]. For example, recycled materials can be classified as Recycled Aggregate, from the processing of construction waste materials or Secondary Aggregates, from the bi-products of industrial processes [8]. These aggregate sources have been used historically for lower grade applications such as bulk fills and hard standing, which require low levels of specification. However, after processing, recycled aggregate materials could be utilized for higher grade applications such as stone column construction. Readily available recycled materials in construction industries such as crushed concrete, recycled aggregates, tyre chips, railway ballast and crushed glass, have big potential to be used in stone column construction. More recent studies have also incorporated materials such as PFA, fly ash, bottom ash, and quarry dust as column filler materials in the performance evaluation of stone columns that will be used for soft ground treatment.

3. Previous researches on stone column filler materials

Many researches have been performed to evaluate the effectiveness of other materials either manufactured or recycle materials to substitute the normal aggregate in stone column construction. Apart from the type of material used, it is important to adopt proper and effective compaction technique and equipment that match with the selected granular backfill material to achieve the highest relative density and thus optimum improvements effects.

The research conducted by Juran *et al.* provided a preliminary basis for a fundamental understanding of the cementation effect on the performance of the granular column and a qualitative evaluation of the group effect on the settlement response of the reinforced soil [9]. Triaxial compression tests were conducted on composite-reinforced soil samples made of annular, normally consolidated kaolin representing the soft soil, reinforced by both cemented and untreated columns of river sand. In addition to that, Daya D. and Niranjana K. evaluated the influence of column material in the performance of stone column made up of conventional aggregate and gravel through numerical analysis using PLAXIS 3D software [10]. The results are then have been validated through load tests and show clear improvement in the load carrying capacity of the column when gravel is used. Some studies on the effectiveness of gravel as stone column filler were carried out by many researchers such as Tander Y.

K. *et al.*, A. Marto *et al.*, A. Zahmatkesh & A.J. Choobbasti, Mahmoud Ghazavi & Samira Ebrahimi and many more [11][12][13][14].

In the meantime, Andreou *et al.* conducted a study on the influence of several controlling parameters, which are the drainage conditions, grain size of the stone column materials, the confining pressure of the soil, and the rate of deformation in the design of stone columns through a series of laboratory experiments on two types of material; sand and gravel. The experimental results showed the advantages of this ground improvement technique, particularly on the strength characteristics of the foundation soil, even with a relatively low replacement factor compared with that used in practice. The study found that as the confining pressure increases, the improvement in the specimen with the sand column is more pronounced [15].

The consolidation effect of sand and aggregate as stone column filler material under distributed load has been evaluated using a unit cell [16]. An axisymmetric consolidation model using Plaxis software simulation was used to compare the increasing rate of consolidation for both materials. The study found that sand can be considered a suitable filler material to increase the consolidation rate, thus shortening the time of the consolidation process. Therefore, the desired settlement and bearing capacity can be achieved in a short time. Meanwhile, the study conducted by Shadi S. Najjar found that the drained shear strength parameters unaffected by the sand column reinforcement, except for fully penetrating columns with high area replacement ratios. The study was performed using consolidated undrained triaxial tests on normally consolidated kaolin specimens based on various parameters such as diameter and height of the sand columns, the type of columns geotextile encased versus non-encased and the effective confining pressure [17]. In addition, the research conducted by A. Namur K.S. *et al.* revealed that for both floating and end bearing types, the sand columns at low relative density exhibited higher bearing improvement ratios and lower settlement reduction ratios compared to stone columns. On the other hand, a reverse behavior was noticed, when the backfill material was placed at "dense state" soil condition [18].

Other than sand and gravel, Silica-Manganese slag which is a by-product from ferro-alloy industries also can be used as the stone column material. In the study conducted by Prasad *et al.* on marine clay stabilized by stone column filler, load carrying capacities of the floating stone columns reinforced with circular discs placed at $D/2$ spacing showed better performance than the columns with discs placed at D spacing, where D is column diameter. The circular discs were placed at two different spacing (D and $D/2$) over varied reinforcement depths ($0.25L$, $0.5L$, $0.75L$ and L) [19].

Pulverised fuel ash (PFA), is a by-product of pulverised fuel (typically coal) fired power stations and can be used as engineering fill and as a component for concrete. Several researchers established the study on PFA as stone column material to stabilized soft clay and peat soil. A. Muntohar *et al.* conducted a study on peat soil treated by PFA column using two types of models; Model A and Model B, where Model A represents geometrical block while Model B, column group. Soil and soil-column parameters have been back-calculated using numerical analysis based on the field static loading test. It was found that both models used in the study are reliable in simulating the field static-loading test for column-treated peat. Essentially, Model B shows higher stability to failure if compared to Model A. The effects of PFA on strength behaviour of stone column also investigated by M. Shakri *et al.* and found that PFA really helps in process of increasing the unconfined compression strength of columns [20]. A laboratory study on bearing capacity of treated stone column with PFA as filler material has been performed by Nazaruddin A.T. *et al.* through UCT test and Plate Loading Test and concluded that the used of PFA mixture on stone column also improve the bearing capacity and reduce settlement on soft soil [21].

A series of experimental study were conducted to understand the behaviour of a group of three columns and seven columns built using six different filler materials including clay, quarry dust, sea sand, river sand, gravel, and stones, besides observing the influence of these column materials to stone column performance [22]. Finite element analysis using 15-noded triangular elements via the Plaxis software package was carried out to compare the load settlement behaviour with the developed test model. From

the study, the researcher concluded that among the different stone column materials, stones are found to be more effective from both the single column test and group column test. Moreover, the study found that quarry dust is also effective in improving the load deformation characteristics of the soil. Therefore, quarry dust can also be used as an alternative material to construct stone column fillers, which is in fact efficient and economical as it is cheap and easily available.

Apart from that, the performance of stone column constructed with two different filler materials (gravel and quarry dust) have been evaluated through Priebe's method by using the unit cell concept [23]. Researchers found that load bearing capacity increases by 14% when gravel is used as a reinforcing material as compared to that of quarry dust for a given stone column dimension. The improvement factor obtained from the study was also higher when gravel is used as reinforcing material, than when quarry dust is used. The improvement factor determination was also established by Pivarc using the values calculated from numerical and laboratory models, which were then compared with the improvement factors as acquired from Priebe's theory [24]. The stone column filler used in the study was made from gravel or crushed stones arranged by a vibrator. The study concluded that the agreement of the results between the improvement factor calculated through Priebe's method, the FE method, and the laboratory experiments, is evidently satisfactory.

Spent Railway Ballast is high quality aggregate (typically granite or limestone) taken from beneath railway tracks, when excessive fines occur after continued attrition under repeated railway carriage loads. The study on the mechanisms and interactions of granular material "ballast" in isolated or grouped stone columns with the surrounding ground has been investigated by Baba *et al.* [25]. The settlement performance of various configurations of columns beneath rigid square footing was examined using finite element modelling and found that the column material properties (stiffness, friction angle), which is influenced by column arrangement (column position), and the behaviour law obeyed by both columns and soils, increase the settlement reduction factor. The study also proved that the column spacing is more relevant, such that when floating columns reach critical length, their behaviour become similar to end-bearing columns.

Stone columns were constructed to improve the deformation characteristics of treated soil especially to reduce primary settlement, whereby limestone quarries ranging from 2.50 to 10 mm in size were used as column filler materials. In this study, Jadid managed to use the calculated modulus value within a depth of approximately six meters from the existing grade and the information obtained from the post-improved CPT test results for more than six meters deep, to estimate the allowable bearing pressure for the planned shallow foundations. This approach ultimately reduced foundation settlement and improved bearing capacity, hence reducing footing size requirements, which enabled shallow footing construction and stabilization of the slope [26]. Meanwhile, Xueyi Liu *et al.* focused towards investigating the stress concentration ratio on stone columns of different backfill materials modified by sand, lime and cement under confined conditions using model tests of stone column performed inside cylindrical container of 300 mm in diameter and 350 mm in height. The results revealed that the values of stress concentration ratio, ranges from 4 for columns with crushed stone as backfill material, to 7.6 for columns with crushed stone stabilized with 5% cement. However, the presence of dry lime did not show any significant increase in the stress concentration [27]. In addition, the study on the behaviour of geosynthetic encased quarry waste column has been conducted by K.Balan *et al.*, P. Ancy Genu C George, K. Beena, D. Isaac and S. Siva Gowri Prasad [28][29][30][31][32].

Stone dust is a multipurpose material and well suited to a yard or passageway surface. It is also a great choice for the sub-base in laying paving blocks and slabs, and for jointing natural stone, such as slate. The study on stone dust utilized in stone column construction has been performed by S. Rani and P. Kumar [33]. The properties of stone dust in this study is similar to normal aggregate, therefore it is suitable to use as stone column filler and found to be acceptable in soil improvement work, where the soil bearing capacity tend to be increased.

Many studies focused on the better way to expand the usage of industrial by-products to alleviate disposal problems such as steel slag, bottom ash, PFA and so on. Large quantities of steel slag were deposited in yards, causing environmental pollution. Like other metallurgical slags, steel slags exhibit a great potential to be used as aggregate in highway construction. The physical properties of steel slag were found to be acceptable and meet the aggregate standard specifications for Malaysian road works [34]. A Vibro-flotation and stone column application is the latest application of steel slag [35]. Steel slag has been used in stone column construction in Saudi Arabia since 1995. The stone column constructed using steel slag need to extend down to considerable depth (end bearing) or hard stratum, which means that this kind of materials are not suitable for floating columns [36]. Steel slag has an extensive record of use as a material in the sand compaction pile (SCP) by vibration compaction as a marine construction method, mainly for ports and harbours. The study conducted by K. Onda *et al.* summarized that steel slags are satisfactory for use in the sand compaction pile method by static compaction for liquefaction countermeasures [37]. There is a weakness in the use of steel slag because of this material is quite abrasive and could lead to increase the maintenance cost of vibro equipment. In addition the expansive potential issue also should be noted.

Coal bottom ash (CBA) is the waste from coal burning and possesses similar properties to sand, making it a suitable stone columns filler material. The excess bottom ash production in Malaysia lead to several environmental problems due to the high production of electricity [38]. A research on CBA used to improve the shear strength parameters of clay soil was conducted through Consolidated Undrained Triaxial Tests with pore pressure measurements by A. Marto *et al.*. Results indicated that the installation of CBA columns in clay specimens increased the apparent cohesion but did not show any significant difference in effective friction angle. The apparent cohesion of soft clay reinforced with partially penetrating columns is higher than that of fully penetrating columns. It was also found that during consolidation, the dissipation of pore water pressure accelerated due to the presence of bottom ash columns, which draws the conclusion that consolidation and shear strength of soft clay could be improved by installing bottom ash columns [39].

On the other hand, shear strength improvement of soft clay reinforced with encapsulated single bottom ash column was also proven from the Unconfined Compression Test in a laboratory. A Polyester Non-woven Geotextile Needle-punched Fabric (MTS 130) was used to encase the bottom ash reinforced kaolin clay column. This encasement significantly improved the overall shear strength of the specimens [40]. The investigation on bearing capacity of soft clay installed with singular and group of encased bottom ash columns also has been done by A. Marto *et al.*, V. R. Raju and M. Hassan *et al.* [41][42][43].

Other materials tested for its effectiveness as stone column material is crushed polypropylene (PP). The use of PP as stone column material was investigated by Muzamir *et al.* [44]. Since PP is a definite waste material, currently disposed in large quantities into landfills, the cost of soil improvement can be reduced significantly. A total of 28 unconfined compression tests were conducted on kaolin samples reinforced with crushed polypropylene. In brief, shear strength parameters are affected by the diameter and height of the columns, and in the case of PP being introduced into the column, it brings better improvement to the shear strength.

Shredded waste tyres were also proposed as an alternative to normal aggregates in constructing stone columns as described in the research conducted by Ayothiraman and Soumya . Different mix proportions of stone aggregates and tyre chips were considered in this study. The study involved several series of triaxial tests on samples of 50 mm diameter and experiments onto physical stone column model of 1/12 scale factor installed in a kaolin clay bed of uniform consistency. This clearly shows that waste tyre chips can be used as partial replacement of stone aggregates up to approximately 60% in stone columns [45][46]. In the meantime, the investigation on strength improvement of stone columns using tyre chips and aggregates through plate load test was carried out by A. Akhitha and found that the lesser the amount of stone aggregate used the more it will reduce the overall cost of a stone column and incite better waste utilisation and preservation of natural resources [47]. Hence, tyre chips are indirectly proven

to cost less aside from being environmental friendly. However, these findings need to be further verified on a full-scale environment, to develop design guidelines before implementing the use of tyre chips in the field.

The use of fly ash aggregate as replacement for conventional aggregate material was investigated through consolidation tests in order to evaluate the suitability of fly ash aggregate as column filler material in problematic clays. From the experiment, it was found that the time required for 90% consolidation of stone aggregate and fly ash aggregate column in soft clay are comparable regardless of pressure increment and number of columns. Hence it can be concluded that fly ash aggregate may be effectively utilized as column material in the place of conventional coarse aggregate for improving soft clay. Research on evaluation of fly ash aggregate as stone column materials for soft clay improvement also has been done by S. Vidhyalakshmi *et al.* and Saravanan [48][49][50][51].

Vibro-stone columns are a common form of ground improvement technique that typically utilizes primary aggregates but in recent years, due to sustainable practices, recycled aggregates have been used as an alternative. Some of the recycled aggregates and secondary aggregates available to date have been the focus of interest, especially for its suitability in the construction of vibro-stone columns. These include steel slag, spent railway ballast, crushed concrete, demolition materials and 'waste' rock. However, Serridge has the opinion that crushed concrete and recycled (spent) railway ballast offer the greatest potential for use in vibro-stone columns [52]. In the research conducted by Amini, a selection of primary (granite) and three recycled aggregates (crushed concrete and brick, incinerated bottom ash aggregate type 1 and 2), which are commonly used in the construction of vibro-stone columns, were compared in the actual context of the installation and loading of a single stone column in soft clay [53]. The findings showed that despite the various results given by the aggregate index tests, the recycled aggregates can still be used as stone column fillers. The crushing of the aggregates during the installation can affect the behaviour of the column even more than during loading. Also, the contamination of the column material with fines can significantly reduce the performance of the stone columns under static loading. The installation time for each layer of aggregates should be reasonable to allow the aggregates to be sufficiently compacted, while retaining the aggregates from damage by crushing or affected by overtreatment. The use of recycled concrete aggregate can be considered in the construction of granular columns and play an important role in sustainable geotechnical design as proved by S. Demir *et al.*, C. Serridge and T. Robert *et al.* [46][47][48].

Other waste materials such as crushed concrete and crushed glass, or manufactured materials such as lightweight expanded clay aggregate can indeed become secondary aggregates, which are prospective materials for replacing regular aggregate in stone column construction. Many researchers have explored the potential of crushed waste glass as a replacement for sand in concrete. However, this material has never been found to be used as a stone filler. Crushed glass of 20/40 mm grade in vibro-stone columns would still have sharp edges that may cause problems in handling and instigate potential health and safety issues [54]. Recycled glass characteristics indicate that it is suitable to be used as a fill (backfill) material in structural and geotechnical applications. Recycled glass on its own or in a mixture with natural or recycled aggregates (such as crushed rock and crushed concrete) can be used in a range of road work applications including sub base, embankments material and drainage media in roads [55]. Nevertheless, this material still needs to be further examined in order to verify its suitability as stone column filler materials. The manufactured material that is similar to normal aggregate in terms of their physical properties such as lightweight expanded clay aggregate (LECA) tend to be more appropriate as stone aggregate replacement in stone column construction. Furthermore, many studies have been performed to evaluate the potential use of LECA in Geotechnical applications, especially in embankment and bridge construction, road and highway pavement, slope filling and so on [56][57][58][59][60]. However, it is worth noting that no studies have been found using this material as stone column fillers replacing the conventional aggregate. A summary of previous studies conducted to evaluate the performance of granular materials as a filler of stone column replacing the normal aggregates is shown in Table 1.

Table 1. Previous studies conducted to evaluate the performance of granular materials as a filler of stone column replacing the normal aggregates.

Researcher, Year	Filler material	Finding
Andreou <i>et al.</i> , 2008	Comparison between sand and gravel	As the confining pressure increases, the strength characteristics improvement in the specimen with the sand column is more pronounced.
Dipiy Sarin Isaac, 2009	Comparison between clay, quarry dust, sea sand, river sand, gravel, and stones	Stones are found to be more effective from both the single column test and group column test
Shadi S. Najjar, 2010	Sand	The Undrained strength significantly improved even for area replacement ratios less than 18%, while drained shear strength parameters were found to be relatively unaffected by the sand column reinforcement, except for end bearing columns with high area replacement ratios.
Nannur K.S. Al Saudi <i>et al.</i> , 2016	Sand	The sand columns at low relative density exhibited higher bearing improvement ratios and lower settlement reduction ratios, while a reverse behaviour was noticed, when the backfill material was placed at "dense state"
Jayalekshmi <i>et al.</i> , 2010 K.Balan <i>et al.</i> , 2013 A Genu C George, 2016 S. Siva Gowri Prasad, 2016	Comparison between gravel and quarry dust	Load bearing capacity increases and soil improvement factor was higher when gravel is used as a reinforcing material as compared to that of quarry dust.
Ismail <i>et al.</i> , 2011	Sand	The consolidation rate increased.
Pivarc, 2011	Crushed stones (gravel)	Improvement factors was higher for $s/d=2$, followed by $s/d=3$ and 4, where s and d is spacing and diameter of stone column, respectively.
Ayothiraman & Soumya, 2011 A. Akhitha, 2017	Tyre chips	Strength improved, however, need to be verified on a full-scale environment.
Nazaruddin A.T. <i>et al.</i> , 2013 Muntohar <i>et al.</i> , 2013 Shakti M.S. <i>et al.</i> (2014)	PFA	Improve the bearing capacity and reduction of soft soil settlement.
Prabhu, 2013 S. Vidiyalakshmi <i>et al.</i> , 2009 Saravanan, 2013	Fly ash aggregate	Compression index and coefficient of volume compressibility found to be lower than that of clay without column, thus improved the settlement of soft soil.
Daya D. & Niranjana K., 2017	Comparison between normal aggregate and gravel	The column made up of gravel giving more load carrying capacity compare to conventional aggregate column

Tandel Y. K. <i>et al.</i> , 2012 A. Marto <i>et al.</i> , 2013 A. Zahmatkesh & A.J. Choobasti, 2010	Gravel	Improved bearing capacity and reduced settlement of soft clay.
Prasad <i>et al.</i> , 2015	Silica-Manganese slag	Reinforced with circular configuration placed at D/2 spacing showed better performance than the columns with discs placed at D spacing, where D is stone column diameter.
Amini, 2015	Recycle aggregate	Can be used as column filler but not very good due to construction and handling problem
A. Marto, 2014	Coal bottom ash	Consolidation and shear strength of soft clay could be improved by installing bottom ash columns
A. Marto <i>et al.</i> , 2016 M. Hassan <i>et al.</i> , 2016 M. Hassan <i>et al.</i> , 2015	Coal bottom ash	Bearing capacity improved
	crushed polypropylene (PP)	Shear strength parameters are affected by the diameter and height of the columns.
K. Onda <i>et al.</i> , 2014	Comparison between Steel slag and natural sand	In comparison with natural sand, which is used in conventional SCP, the improvement effect and workability (diameter of pile, construction time) of these steel slags were similar and comparable to those of natural sand.

4. Conclusion

The partial replacement of compressible soil with more competent and promising materials such as stone aggregate, sand, and other granular materials, presents several benefits in the construction of stone columns. It also acts as reinforcing materials that increase the overall strength and stiffness of soft soils. Until now, a number of researches have been accomplished pertaining to stone column behaviour and performance with various materials used as column fillers. Most of the alternative materials used as stone column fillers or backfill materials can be produced from waste and recycled materials. These materials have been established based on experiments, numerical analysis and/or physical modelling as conducted in a laboratory. Therefore, the findings need to be further verified in a full-scale environment, to develop design guidelines, specifications and QA testing, prior to implementing any of these replacement materials to be conventionally utilized as stone column fillers. If this is fulfilled, then these materials could offer excellent and sustainable solutions by utilizing potential wastes effectively while reducing demands for primary aggregates. These alternative materials for stone column fillers offer high efficiency apart from being economical, as the materials are cheap, easily available and environmental friendly.

From this review paper, materials such as fly ash, coal bottom ash, crushed polypropylene (PP), recycled aggregate, tyre chips, Pulverized Fuel Ash (PFA), Silica-Manganese slag, quarry dust, stone dust, limestone, river sand, etc. have all been recognized to be utilized as stone column materials replacing its traditional aggregate materials. Nonetheless, no study or research has been found with respect to the usage of crushed waste glass and lightweight expanded clay aggregates (LECA), which are categorized as alternative granular materials to be used as stone column backfills. Therefore, it is suggested that studies can be made to assess the effectiveness of these two materials in the stone column construction as one of soft soil improvement method.

References

- [1] Barksdale, R.D. and Bachus R C 1983 Design and construction of stone columns *FHWA/RD-83/026, Federal Highway Administration, Washington, D.C.*
- [2] Vahedian a., Mahini S and Aghdai S a. 2014 A Short State-of-the-Art Review on Construction and Settlement of Soft Clay Soil Reinforced with Stone Column A Short State-of-the-Art Review on Construction and Settlement of Soft Clay Soil Reinforced with Stone Column *International Journal of Engineering and Technology* **6** 420–6
- [3] Han J 2015 *Principles and Practice of Ground Improvement* (John Wiley & Sons, Inc. Hoboken, New Jersey)
- [4] Dheerendra Babu M R, Nayak S and Shivashankar R 2013 A Critical Review of Construction, Analysis and Behaviour of Stone Columns *Geotechnical and Geological Engineering* **31** 1–22
- [5] Das B M *Principles of Foundation Engineering, SI ed 7th Edition* (USA: Cengage Learning)
- [6] Ambily A P and Gandhi S R 2004 Experimental and Theoretical Evaluation of Stone Column in Soft Clay *Icgge* 201–6
- [7] Serridge C J 2005 Achieving sustainability in vibro stone column techniques *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* **158** 211–222
- [8] Tranter R, Jefferson I and Ghataora G 2008 The use of recycled aggregate in vibro-stone columns - A UK perspective *GeoCongress 2008: Characterization, Monitoring, and Modeling of GeoSystems, March 9, 2008 - March 12, 2008* 630–7
- [9] Juran B I and Riccobono O 1991 Reinforcing Soft Soils With Artificially Cemented Compacted-Sand Columns *Journal of Geotechnical Engineering* **117** 1042–60
- [10] Daya Dath N K 2017 A Study On Conventional Aggregate And Gravel As Columnar Inclusions In Clay *International Conference on GEOTECHNIQUES FOR INFRASTRUCTURE PROJECTS* (Thiruvananthapuram) pp 1–5

- [11] Tandel Y k., Solanki C H and Desai A K 2012 Numerical modelling of encapsulated stone column-reinforced ground *International Journal of Civil, Structural, Environmental and Infrastructure Engineering* **2** 82–96
- [12] Aminaton Marto Farshad Helmi, Nima Latifi, Mohsen Oghabi R M 2013 Performance analysis of reinforced stone columns using finite element method *Electronic Journal of Geotechnical Engineering (EJGE)* **18 B** 315–23
- [13] A. Zahmatkesh A J C 2010 Settlement Evaluation Of Soft Clay Reinforced By Stone Columns, Considering The Effect Of Soil Compaction *International Journal of Research & Reviews in Applied Sciences* **3** 159–66
- [14] Ghazavi M and Nazari Afshar J 2013 Bearing capacity of geosynthetic encased stone columns Geotextiles and Geomembranes 38 26–36
- [15] Andreou P, Frikha W, Frank R, Canou J, Papadopoulos V and Dupla J-C 2008 Experimental study on sand and gravel columns in clay *Proceedings of the Institution of Civil Engineers - Ground Improvement* **161** 189–98
- [16] M. A. Mohamad Ismail L. K. Ng and N.A. Ramli H M Y 2011 Consolidation of Sand and Aggregate as Stone Column Material *Electronic Journal of Geotechnical Engineering (EJGE)* **15** 2705–11
- [17] Shadi S. Najjar Tarek Maakaroun S S 2010 Effect of Sand Columns on the Undrained Load Response of Soft Clays *JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING* **136** 1263–77
- [18] Namur K.S. Al Saudi Nawres A.A. Rajab, G Tanyrbergenova A G 2015 Sand and stone columns in soft soil at different relative densities *Japanese Geotechnical Society Special Publication* **2** 2121–6
- [19] Siva S, Prasad G, Harish Y and Satyanarayana P V V 2015 Stabilization of Marine Clays with Geotextile Reinforced Stone Columns Using Silica-Manganese Slag as a Stone Column Material *ISSN // International Journal of Computational Engineering Research* **9** 2250–3005
- [20] Shakri M S, Hafez M A, Adnan M A and Nazaruddin A T 2014 Effects of use of PFA on strength of stone column and sand column *Electronic Journal of Geotechnical Engineering* **19 L** 3745–55
- [21] Nazaruddin A.T. Hafez M.A. S M S 2013 Laboratory Study on Bearing Capacity of Treated Stone Column *Electronic Journal of Geotechnical Engineering* **18** 5871–80
- [22] Dipty Sarin Isaac G M S 2009 Suitability of Different Materials for Stone Column Construction *Electronic Journal of Geotechnical Engineering (EJGE)* **14** 1–12
- [23] Jayalekshmi S. Harish Paravastu S V 2010 Ground Improvement using Stone Columns for Infrastructural Development *CISTUP @ CiSTUP 2010* (Bangalore: Indian Institute of Science)
- [24] Pivarc J 2011 Stone columns – determination of the soil improvement factor *SLOVAK Journal of Civil Engineering* **19** 17–21
- [25] Khadija.Baba Latifa.Ouadif N N 2015 Stone Columns In Silty Clay Soil: A Numerical Model *3rd Turkish Conference on Earthquake Engineering and Seismology* 1–10
- [26] Jadid M N 2013 A Practical Approach For Computing Soil Bearing Capacity Under Shallow Foundations Using Vibro-Replacement Method *International Refereed Journal of Engineering and Science (IRJES)* **2** 54–62
- [27] Xueyi Liu ; A. M. Shubber Ammar ; Hongsong Lin J R 2009 The Stress Concentration Ratio of Stone Columns under Confined Condition *Second International Conference on Transportation Engineering* 4247–55
- [28] K. Balan P K J and S T 2015 “Studies on natural geotextile reinforced quarry waste columns for soft soil stabilizatio *Indian Journal of Geosynthetics and Ground Improvement* **4** 3–11
- [29] Ancy Genu C George P K C 2016 Studies On Natural Geotextile Reinforced Quarry Waste Column For Improving Soft Soil *International Journal of Science, Engineering and Technology Research* **5**

- [30] Siva Gowri Prasad S and Satyanarayana P V V 2016 Improvement of soft soil performance using stone columns improved with circular geogrid discs *Indian Journal of Science and Technology* **9**
- [31] Beena K S 201AD Ground Improvement using Stone Columns *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. (California: Scholars' Mine) pp 1–7
- [32] Isaac D S and Girish M S 2009 Suitability of different materials for stone column construction *Electronic Journal of Geotechnical Engineering* **14 M** 1–12
- [33] Rani S S and Kumar P S P 2015 A Study of Behaviour on Stone Column in Homogenous Soil *International Journal of Science and Research (IJSR)* **5** 1215–9
- [34] Oluwasola E A, Hainin M R and Aziz M M A 2014 Characteristics and utilization of steel slag in road construction *Jurnal Teknologi* **70** 117–23
- [35] Holiday, K. A 1997 Steel Slag-The High Performance Industrial Aggregate. *Proceedings of the XIIth World Meeting of the International Road Federation* (Toronto)
- [36] Wang G C 2016 *The Utilization of Slag in Civil Infrastructure Construction* (Woodhead Publishing)
- [37] Onda K, Honda H and Yoshitake H 2014 Examination of application of steel slag to sand compaction pile method *JFE Technical Report* **19** 41–8
- [38] Ramzi N I R, Shahidan S, Maarof M Z and Ali N 2016 Physical and Chemical Properties of Coal Bottom Ash (CBA) from Tanjung Bin Power Plant *IOP Conference Series: Materials Science and Engineering* **160** 12056
- [39] Aminaton Marto Masayuki Hyodo, Ahmad Mahir Makhtar M H 2014 Shear Strength Parameters and Consolidation of Clay Reinforced with Single and Group Bottom Ash Columns *Arabian Journal for Science and Engineering* **39** 2641–2654
- [40] Muzamir Hasan Mohd Nor, Suzillco Suki N P 2016 Shear Strength Of Soft Clay Reinforced With Single Encased Bottom Ash Columns *ARPJ Journal of Engineering and Applied Sciences* **11** 1562–9
- [41] Muzamir Hasan Norhayani Pangee N A H 2016 Strength Of Soft Clay Reinforced With Square And Triangular Pattern Encapsulated Bottom Ash Columns *Second International Conference on Science, Engineering & Environment*
- [42] Aminaton Marto Choy Soon Tanb, Fauziah Kasima, Nor Zurairahetty Mohd Yunusa, Razieh Moradia N A R 2016 Bearing capacity of soft clay installed with singular and group of encased bottom ash columns *Jurnal Teknologi (Sciences & Engineering)* **78** 105–110
- [43] V R Raju 2011 Ground Improvement Using Vibro Techniques in FlyAsh Deposits *National Conference on Recent Advances in Ground Improvement Techniques* pp 0–12
- [44] Muzamir Hasan Noor Amirah Noor Shahrudeen, Anas Mohammed Husian Kassim N Y 2015 Strength of Soft Clay Reinforced with Group Crushed Polypropylene (PP) Columns *Electronic Journal of Geotechnical Engineering (EJGE)* **20** 12308–991
- [45] Ayothiraman R and Soumya S 2015 Model tests on the use of tyre chips as aggregate in stone columns *Proceedings of the Institution of Civil Engineers - Ground Improvement* **168** 187–93
- [46] R. Ayothiraman S S 2011 Use Of Shredded Tyre Chips As Aggregates In Stone Column: An Experimental Study *Proceedings of Indian Geotechnical Conference* 711–4
- [47] Akhitha A. A S 2017 Strength Improvement Of Stone Columns Using Tyre Chips And Aggregates *International Conference on GEOTECHNIQUES FOR INFRASTRUCTURE PROJECTS*
- [48] Saravanan S priya 2013 Study On Sintered Flyash Aggregate As Columnar Inclusions On Soft Clay *International Journal of Combined Research & Development* **1**
- [49] S. Vidhyalakshmi KE.A. Palaniappan V K S 2009 Studies on the Behaviour of Flyash Aggregate as Column Material in Soft Clay *India Geotechnical Society* 280–3
- [50] S.Ayyappan M.Sundaram K H 2010 Investigation of Engineering Behavior of Soil, Polypropylene Fibers and Fly Ash -Mixtures for Road Construction *International Journal of Environmental Science and Development* **1** 171–5

- [51] K. E. A. Palaniappan S P 2013 Improving Soft Clay Soil Using Fly Ash As Material Of Column *International Journal of Engineering Research & Technology (IJERT)* **2** 1828–32
- [52] Robert Tranter Gurmel Ghataora I J 2008 The use of recycled aggregate in vibro-stone columns- A UK Perspective *GeoCongress 2008* 630–7
- [53] Amini R 2015 *Physical Modelling Of Vibro Stone Column Using Recycled Aggregates* (University of Birmingham)
- [54] Robert T, Ian J and Gurmel G 2017 The Use of Recycled Aggregate in Vibro-Stone Columns, A UK Perspective *GeoCongress 2008*
- [55] Vikas Kumar K. Mani, Deepak Gupta A K C 2014 *Environmental Sustainability: Concepts, Principles, Evidences and Innovations* ed P (Dr. . G C Mishra (New Delhi: EXCELLENT PUBLISHING HOUSE)
- [56] Anand J. Puppala Raja Yenigalla, Ekarut Archeewa B C 2013 Settlement Mitigation Using Light Weight Fill Embankment Systems *Geo-Congress 2013* 582–92
- [57] A.J. Valsankar T A H 1987 Model Tets on Peat-Geotextile-Lightweight Aggregate System. *Geotextile and Membranes* **5** 251–60
- [58] Siamak Boudaghpour S H 2008 A Study on Light Expended Clay Aggregate (LECA) in a Geotechnical View and its Application on Greenhouse and Greenroof Cultivation *INTERNATIONAL JOURNAL OF GEOLOGY* **2** 59–63
- [59] Hoff I, Watn A and Oiseth E Light Weight Aggregate (LWA) Used in Road Pavements 1–10
- [60] Davies L, Fry C and Bull J 104 - Lightweight backfill materials in integral bridge construction 47–54