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STRENGTH CHARACTERISTICS OF CEMENT-RICE HUSK ASH STABILISED SAND-CLAY MIXTURE REINFORCED WITH POLYPROPYLENE FIBERS

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Abstract. In this paper, stress-strain behaviour of sand-clay mixture stabilised with different cement and rice husk ash percentages, and reinforced with different polypropylene fibre lengths are evaluated. Mixtures are widely used in road construction for soil stabilisation. It is observed that replacing half of the cement percentage (in high cement contents) with rice husk ash will result in a higher unconfined compressive strength. In addition, the presence of 6 mm polypropylene fibres will help to increase the unconfined compressive strength of stabilised samples, while larger fibres cause reverse behaviour. In addition, introducing a new index for assessing the effect of curing days. Curing Improvement Index it is obtained that larger fibres show higher Curing Improvement Index values. Results gained for the

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effects of curing days, and fibre lengths are further discussed and interpreted using Scanning Electron Microscopy photos. Based on the conducted Unconfined Compressive Strength, Indirect Tensile Strength, and Flexural Strength tests and using evolutionary polynomial regression modelling, some simple relations for prediction of unconfined compressive strength, indirect tensile strength, and flexural strength of cement-rice husk ash stabilised, and fibre reinforced samples are presented. High coefficients of determination of developed equations with experimental data show the accuracy of proposed relationships. Moreover, using a sensitivity analysis based on Cosine Amplitude Method, cement percentage and the length of polypropylene fibres used to reinforce the stabilised samples are respectively reported as the most and the least effective parameters on the unconfined compressive strength of specimens.

Keywords: cement, evolutionary polynomial regression, rice husk ash (RHA), polypropylene fibres, sand-clay mixture, strength.

Introduction

In the last decades, research programs were initiated with the objective of developing new materials that could be quickly and easily mixed with, or even better sprayed, on soft soils to increase their strength to carry future loads. In this way, the use of supplementary cementing materials has become an integral part of the high strength and high-performance stabilisation methods. The soil stabilisers can be natural materials, by-products or industrial wastes. Although the nature of the stabiliser and its activity in reaction with the soil is the most important parameter, the role of the energy, money and time required to gain/produce/tale these stabilisers is of great importance. Some of the commonly used supplementary cementing materials are fly ash, silica fume, ground granulated blast furnace slag and rice husk ash (RHA) (Silitonga, Levacher, & Mezazigh, 2010).

The usage of these materials as one of soil improvement techniques is believed to have some main advantages in geotechnical engineering such as increasing soil bearing capacity and shear strength, controlling or restricting deformations, accelerating consolidation process, providing lateral stability in soil slopes, increasing resistance to liquefaction phenomenon. These applications can be accomplished by modifying the soils characteristics with or without the addition of backfill material. Chemical stabilisation using cement or lime is commonly carried out in the presence of these supplementary materials to improve the performance (regarding strength and deformations) of the problematic and weak soil (Hashemi, Massart, & François, 2018; Bourokba Mrabent, Hachichi, Souli, Taibi, & Fleureau, 2017). Considering that total energy consumption in cement manufacturing is about 5 TJs per 1000 tons, and each ton of cement releases about 1 ton of carbon dioxide into the atmosphere, some recent solutions are developed to reduce cement consumption in soil improvement methods. Substantial energy and cost savings are the main results of using industrial by-products as a partial replacement for the Portland cement. Moreover, using such industrial by-products will be more in demand when they are generally in hand as the regional tale of existing factories and lands or industries. Rice husk ash as one of these common supplementary materials available worldwide is a waste material obtained from the controlled burning of rice husks at a temperature of 600 °C (Della, Kühn, & Hotza, 2002). Rice husk ash is one such substitute, which reduces the consumption of cement, thereby saving the raw material base, power and environment. In addition, the dumped rice husk is a threat to the environment causing damage to the land and the surrounding area, and the utilisation of RHA will reduce the dumping of rice husk as well as reduce the construction costs. It is an agro-waste material produced in about 100 million tons. Approximately, for each 100 kg of rice, 20 kg of rice husk is obtained. Rice husks contain organic substances and 20% of the inorganic material. Rice husk ash is obtained by the combustion of rice husk (Pande & Makarande, 2013). Husk is a by-product of the milling process of rice. During milling of paddy, about 78% of weight is received as rice, broken rice and bran. Rest 22% of the weight of paddy is rice husk. This husk is used as fuel in the rice mills to generate steam for the parboiling process. The obtained husk includes about 75% volatile organic matter and the balance 25% of the weight of this husk is converted into ash during the firing process, which is known as RHA (Kumar, Palli, & Patnaikuni, 2011). Notifying the fact that rice and all its related by-products are considerably available in Guilan province, Iran, area of study of this paper, it will be significantly efficient to apply such simply in hand and economic material in the current stabilisation and construction projects. In addition, it is noteworthy to declare that due to the high availability of RHA in this region, in the case of replacing it with other pozzolanic materials such as Ordinary Portland Cement (OPC), final costs of construction projects will be considerably saved. During the last few decades, research works have been carried out to investigate the utilization of RHA as a stabilizing material in soil improvement and construction materials (Ali, Adnan, & Choy, 1992; Anwar Hossain, 2011; Ashango & Patra, 2016; Bagheri, Ahmad, & Ismail, 2013; Basha, Hashim, Mahmud, & Muntohar, 2005; Eberemu, Tukka, & Osinubi, 2014; Ismail & Waliuddin, 1996; Jauberthie, Rendell, Tamba, & Cissé, 2003; Sabat, 2012; Sivapullaiah, Subba Rao, & Gurumurthy, 2004; Yin, Mahmud, & Shaaban, 2006). Nair, Jagadish, & Fraaij (2006) and Nair, Fraaij, Klaassen, & Kentgens (2008) carried out a structural investigation relating to the pozzolanic reactions of RHAs. Several researchers have conducted extensive works on the applications of RHA in the geotechnical engineering, especially in the improvement of characteristics of clayey soils (Cai, Shi, Ng, & Tang, 2006; Mtallib & Bankole, 2011; Muntohar & Hontoro, 2000; Tang, Shi, Gao, Chen, & Cai, 2007). Tripathi & Yadu (2013) performed experimental investigations on the bearing capacity of square footing on soft soil stabilised with RHA. Muntohar, Widianti, Hartono, & Diana (2012) investigated the effect of RHA, lime and waste plastic fibres on the engineering properties of silty soils. In addition, Tang, Shi, Gao, Chen, & Cai (2007) used the combination of cement and fibre to stabilise clayey soil and attained that the existence of polypropylene fibre in samples causes an increase in both unconfined compressive strength (UCS) and shear strength. It was concluded that the polypropylene (PP) fibres prevent the growth of cracks and subsequently prohibit the complete failure of the sample. In addition, Ghorbani & Forouzesh (2010) investigated the effects of cement and fly ash stabilisation and PP fibres reinforcement on the mechanical properties of Rasht clay. In addition, fibres are widely used to reinforcement different soils and soil-cement mixtures (Kumar & Gupta, 2016). Kumar & Gupta (2016) investigated the effect of simultaneous adding of pond ash and RHA along with cement to the clay. The unconfined compressive strength and splitting tensile strength tests on clay stabilised with pond ash, RHA and OPC reinforced with PP fibres. However, their study covers a limited range of OPC percentage (only 2% and 4% OPC were studied). Silva dos Santos, Consoli, Heineck, & Coop (2009), Consoli, Bassani, & Festugato (2010), Fatahi & Khabbaz (2012), Hamidi & Hooresfand (2013), Olgun (2013), Chen, Shen, Arulrajah, Wu, Hou, & Xu (2015), Correia, Oliveira, & Custódio (2015), Cristelo, Cunha, Dias, Gomes, Miranda, & Araújo (2015), Yi, Ma, & Fourie (2015), Oliveira, Correia, Teles, & Custódio (2016), Ayeldeen & Kitazume (2017), and Festugato, Menger, Benezra, Kipper, & Consoli (2017) used binders for soil stabilization and fibres for the reinforcement purposes, and assessed compressive and tensile behaviour of studied materials. Yilmaz (2009), Jiang, Cai, & Liu (2010), Mirzababaei, Miraftab, Mohamed, & McMahon (2012), Plé & Lê (2012), Tang, Shi, Cui, Liu, & Gu (2012), Fu, Baudet, Madhusudhan, & Coop (2018), Vakili, Ghasemi, bin Selamat, Salimi, & Farhadi (2018), and Mirzababaei, Mohamed, Arulrajah, Horpibulsuk, & Anggraini (2018) applied different fibres to reinforce soil samples and studied the effect of different fibres on their behaviour. In addition, Rios, Viana da Fonseca, & Baudet (2012) investigated the effect of porosity and cement ratio on the compression behaviour of cemented soil. The major soil of a wide area of Rasht, Guilan, Iran consists of sand-clay mixtures and the effect of RHA on the compressive and tensile strength of such soils has not yet been studied. Hence, in this paper, it is aimed to investigate the effect of cement-RHA admixture on the UCS and tensile strength of the sand-clay mixtures of the Rasht and evaluate the possibility of cement replacement by available RHA material. Moreover, in addition to investigating the effects of different cement and RHA percentages on the UCS of stabilised soil, the effect of PP fibres on the restricting soil failures are evaluated. In this study, despite research performed by Kumar & Gupta (2016), focusing on clay, RHA and OPC are directly mixed with the sample (without any other stabiliser) and the possibility of replacing OPC with RHA is investigated. Besides, efficient data analysis is carried out on the prepared experimental data sets and some new relationships for prediction of UCS, FS, and Indirect Tensile Strength (ITS) are presented. Moreover, the test results are interpreted using Scanning Electron Microscopy (SEM) photos. It is noteworthy to say that using a sensitivity analysis, the most and the least effective parameters on the UCS of both 7 days and 28 days cured samples are presented, which can significantly help practitioners.

1. Materials and methods

The major and common soil of a wide range of Rasht, Guilan, Iran is a sand-clay mixture. In recent years, due to the heavy road and civil constructions, also, regarding the quality and strength of existing soil, the need of methods to improve the strength and mechanical properties of sites soil is essential. In this regard, in this paper, focusing on the sand-clay mixture of this region, the applicability of a common soil stabilisation method, chemical stabilisation, is investigated. Hence, applying cement and RHA, as a possible replacement stabiliser for cement, which is commonly available in Guilan province; also, using PP fibres, UCS tests are conducted. Based on the tests, carried out on the studied sand-clay mixture, and containing various cement and RHA contents and different PP fibre lengths, their UCS is evaluated and compared. Moreover, to evaluate the role of curing days on the strength of stabilised samples, specimens are tested in two different curing days. Besides, since it is practically noteworthy to know about the most sensitive parameter, which controls the strength of materials, a sensitivity analysis is carried out. Finally, some new relations are presented for calculation of UCS of stabilised samples for different curing days. These new relations will significantly help design engineers to facilitate the process of selecting optimum stabilisers contents in the preliminary steps of road construction and soil stabilisation projects.

To experimentally make up the soil of a wide range of Guilan province, sand-clay mixture, 80% Rasht clay and 20% Anzali sand, consisting large area of Guilan province, collected from Anzali beach, northern Iran is mixed and composed the main skeleton of the soil studied in this paper. In addition, as the stabilisers, RHA in 2%, 3%, 5%, 7%, and 8%; also, cement in 2%, 3%, 4%, 5%, 7%, 8%, 10%, and 16% are used. Besides, soil samples are reinforced using two different PP fibre lengths (6 mm and 12 mm) all in constant fibre content of 0.2%.

According to ASTM D2487-11 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) the soil is categorised as CL and grouped as A-6 by ASTM D3282-09 Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes. In addition, Table 1 shows some physical and Atterberg limits of the studied Rasht clay based on ASTM D4318 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. According to the standard compaction test based on ASTM D698-12e2 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft^3 (600 kN-m/m^3)), Maximum Dry Density (MDD), and Optimum Moisture Content (OMC), of samples are 17 kN/m^3 and 17%, respectively.

Based on the USCS, *ASTM D2487-11*, the studied sand is SW-SC and A-2-6 based on the American Association of State Highway and Transportation Officials system, *ASTM D3282-09*. In addition, the coefficient of uniformity (C_u) and the coefficient of curvature (C_c) of the studied sand are 8.5 and 1.05, respectively. Furthermore, the studied sand holds G_s value of 2.59.

Also, based on the standard compaction test, OMC and MDD of studied sand are 16% and 18.3 kN/m^3, respectively.

Based on the standard compaction tests, 16% and 18 kN/m^3 are, respectively, OMC and MDD of the attained sand-clay mixture.

The cement used in this study is the OPC.

The most important property of RHA that controls its pozzolanic reactions is the amorphous silica content. RHA is a highly active

Table 1. Some physical and Atterberg limits of the studied Rasht clay

Parameter		Unit	Value
G_s			2.66
Liquid limit	LL	%	35.00
Plastic limit	PL	%	17.10
Plasticity Index	PI	%	17.90
Shrinkage limit	SL	%	16.00

pozzolanic material suitable for making calcium silicate hydrated gel as a product of its reaction with cement. In addition, it can be used as a suitable cement-replacing additive. Indeed, when RHA and cement are mixed in the presence of water, pH of the environment is increased, and the active silica in RHA reacts with calcium hydroxide and forms calcium silicate hydrated gels. The described reactions are shown in Eqs. (1)–(3) (Ghorbani, Hasanzadehshooiili, Karimi, Daghigh, & Medzvieckas, 2015).

$$CaO + H_2O = Ca(OH)_2; \tag{1}$$

$$Ca(OH)_2 = Ca^{2+} + 2(OH)^-; \tag{2}$$

$$Ca^{2+} + 2(OH)^- + SiO_2 = CaO{\cdot}SiO_2 + H_2O. \tag{3}$$

It is believed that these reactions will lead to an increase in the strength of stabilised samples. Chemical compositions of the used OPC and RHA are presented in Table 2.

Rice husk used in this study was obtained from Rasht, Iran. Firstly, similar to Dabai, Muhammad, Bagudo, & Musa (2009), it was naturally dried under the sunshine for three days. The dried husk was then ashed in a muffle furnace for two hours at 600 °C to obtain a finely divided ash, which is then sieved and kept ready for production of samples.

Polypropylene fibres have been broadly used for the reinforcement of cementations materials to improve the toughness and the capability of energy absorption. It is believed that they are considered effective in retarding first crack appearance and in controlling the process of crack development (Sun, Chen, Luo, & Qian, 2001). On the other hand, some studies have declared that because of their low chemical activity, there can be little or no chemical adhesion between the fibre and matrix (Linfa, Pendleton, & Jenkins, 1998). Hence, the overall effect of PP fibres in reinforcement and increasing the strength of stabilised samples is not so clear.

Hence, to investigate their effect on the strength of cement-RHA stabilised sand-clay mixtures, 6 mm and 12 mm in length PP fibres are used to reinforce the stabilised samples.

Some of the properties of the studied PP fibres provided by the manufacturer are given in Table 3.

Table 2. The chemical composition of the used OPC and RHA

Constituents	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K2O	SO_3	LOI*
Ordinary portland cement, %	22.20	5.48	3.35	63.90	1.06	0.17	0.31	2.29	1.24
Rice husk ash, %	90.60	0.49	0.73	1.51	0.88	0.22	1.80	0.43	3.34

Note: *the loss on ignition (LOI) is expressed as a weight percentage of the dry mass.

Table 3. Properties of polypropylene fibres

Properties	Unit	Value
Colour		white
Cross section	–	circular
Average diameter	μm	34
Breaking tensile strength	MPa	350
Modulus of Elasticity	MPa	3500
Specific gravity	kN/m^3	9.1
Fusion point	°C	165
Burning point	°C	590
Acid and alkali resistant	–	very good

Firstly, to attain the basic geotechnical properties of the studied soil, preliminary tests such as grain distribution and standard compaction tests are carried out. Secondly, as a widely accepted criterion, the UCS of stabilised samples is assessed to evaluate the degree of soil improvement. In addition, ITS and Flexural Strength (FS) tests are conducted to investigate the tensile behaviour of stabilised and reinforced samples. In this regard, soil samples are firstly mixed with different cement and RHA percentages and reinforced with different polypropylene fibre lengths (all in 0.2% by weight fibre content). Table 4 shows the test program along with symbols and materials percentages used to study the UCS of stabilised samples. As shown in Table 4, two series of 24 stabilised and reinforced samples are prepared. The first series is cured throughout 7 days and the second series experienced a 28-day curing period.

After preparing two series of all the samples, to achieve the required strength, and to evaluate the effect of curing days on their strength, one series of samples were cured in 7 days, and the other sample series were maintained in an isolated container and cured for 28 days.

Rice husk ash and PP fibres on the UCS of stabilised and reinforced sand-clay mixture, cement are added to the samples in different percentages (2%, 3%, 4%, 5%, 7%, 8%, 10%, and 16%) to investigate the effect of cement. In addition, RHA contents of samples are 2%, 3%, 5%, 7% and 8%. Besides, they are reinforced using 0.2% PP fibres in 6 mm and 12 mm lengths. All the prepared samples are made up using 4.9 cm in diameter and 9.8 cm in height moulds based on the *ASTM D1633-17 Standard Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory*. The samples are saturated according to the *ASTM D 1633-17* and then loaded.

Table 4. Tests program and the used symbols

Samples	Material				Symbol
	Cement, %	RHA, %	Polypropylene fibre		
			%	Length, mm	
1	4	0	0	–	C4-nP
2	4	0	0.2	6	C4-6P
3	4	0	0.2	12	C4-12P
4	2	2	0	–	C2-R2-nP
5	2	2	0.2	6	C2-R2-6P
6	2	2	0.2	12	C2-R2-12P
7	10	0	0	–	C10-nP
8	10	0	0.2	6	C10-6P
9	10	0	0.2	12	C10-12P
10	5	5	0	–	C5-R5-nP
11	5	5	0.2	6	C5-R5-6P
12	5	5	0.2	12	C5-R5-12P
13	3	7	0	–	C3-R7-nP
14	3	7	0.2	6	C3-R7-6P
15	3	7	0.2	12	C3-R7-12P
16	7	3	0	–	C7-R3-nP
17	7	3	0.2	6	C7-R3-6P
18	7	3	0.2	12	C7-R3-12P
19	16	0	0	–	C16-nP
20	16	0	0.2	6	C16-6P
21	16	0	0.2	12	C16-12P
22	8	8	0	–	C8-R8-nP
23	8	8	0.2	6	C8-R8-6P
24	8	8	0.2	12	C8-R8-12P

Regarding the similarities between UCS test of soil-cement and soil-lime samples, *ASTM D5102-09 Standard Test Method for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures* is used to conduct the UCS tests. Tests are carried out at a constant rate of 1 mm/min, and corresponding vertical loads are continuously recorded. Each test is repeated for three times and the average of all the values, values with differences less than 10%, is used for further analysis and investigations. A key problem of UCS tests is that there will be two components of the strength, one arising from the cementing and one from the suction in unsaturated samples. In this paper, after curing periods, samples were soaked in the water for 4 hours to be fully saturated, according to the *ASTM D1633-17*. Hence, the governing strengthening mechanism is cementing.

Flexural strength tests are conducted on the cement-RHA stabilised, and polypropylene fibre reinforced samples according to the *ASTM D1635/D1635M-12 Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading*. In this regard, cement in 2%, 4%, 5%, 8%, 10%, and 16%, also, RHA in 2%, 5% and 8% contents are added to the samples. Also, similar to the UCS tests, PP fibres in 0.2% content and 6 mm and 12 mm lengths are used to investigate the FS of the samples. Both 7-day and 28-day cured samples are studied, and each test is repeated for two times.

Indirect and Splitting tensile strength tests are carried out based on the *ASTM C496/C496M-17 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens* with the percentages similar to the FS test. In addition, tests are repeated for two times for all the 7-day and 28-day cured samples.

2. Results and discussion

After conducting UCS, ITS and FS tests on the samples stabilised using different percentages of OPC and RHA and reinforced with different PP fibre lengths, test results are analysed and further discussed. In this regard, results and their analyses are categorised into five different sections. Regarding the fact that UCS test is broadly used as a common index for assessing the degree of soil improvement, the focus of investigations is on the UCS tests. The first set of results describes the effect of curing days on the UCS of the samples. The second series of results are about the effect of the ratio of RHA to OPC on the UCS of stabilised samples. Indeed, the UCS of specimens is investigated in a constant OPC+RHA percentage for different RHA/OPC ratios and the possibility of replacing OPC with RHA, and the optimum RHA/OPC ratio is discussed. Third result part declares the influence of fibre reinforcement on the UCS of samples. This section contains stress-strain behaviour and UCS of samples (samples with maximum UCS and containing OPC + RHA = 16%) reinforced with different fibre lengths. Forth section presents results of ITS and FS tests on the studied samples. Finally, regarding all the data sets of performed tests, some new relationships for prediction of UCS, ITS and FS of OPC-RHA stabilised samples and reinforced with PP fibres are presented using evolutionary polynomial regression modelling. Developed relationships can be effectively applied by engineers to obtain an efficient mixture design scheme used in the preliminary step of Quality Control/Quality Assurance (QC/QA) phase of soil stabilisation projects. Besides, Cosine Amplitude Method (CAM) is applied to determine the strength of the relationship between concerning parameters and the UCS of stabilised specimens.

2.1. Effect of curing days on the unconfined compressive strength of OPC-RHA stabilised, and PP reinforced samples

All of the stabilised samples are prepared in two series. The first series of the samples were cured in 7 days, while the second series of experiments are kept in separate containers for the more extended period, 28 days curing time, to maintain their optimum moisture content. Figure 1 presents UCS of both 7 days and 28 days cured stabilised and reinforced samples.

In this paper, to investigate the effect of extra curing days (from 7 days to 28 days), a new index named Curing Improvement Index (CII) is defined. This dimensionless index is calculated using Eq. (4).

$$CII=\frac{UCS_{28\ days}-UCS_{7\ days}}{UCS_{\ 7days}}\cdot 100. \tag{4}$$

Regarding this definition, effects of extra curing days from 7 days to 28 days on the UCS of improved sand-clay mixtures are tracked. Figure 2

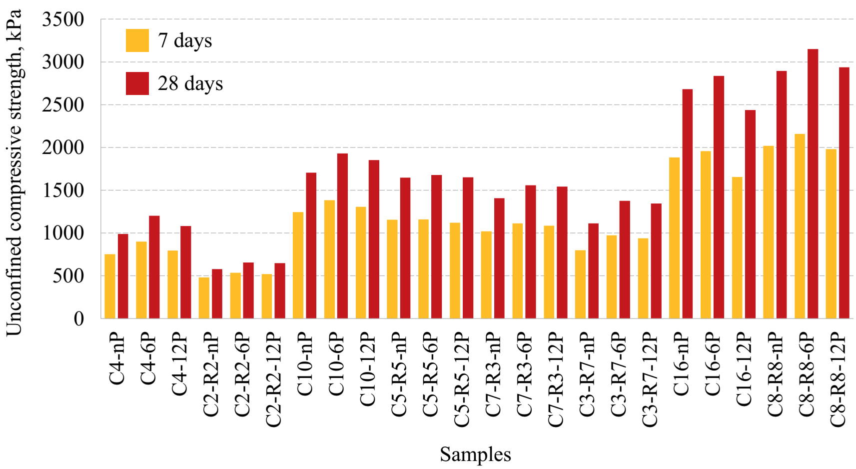


Figure 1. The unconfined compressive strength of 7 days and 28 days stabilised and reinforced sand-clay mixtures

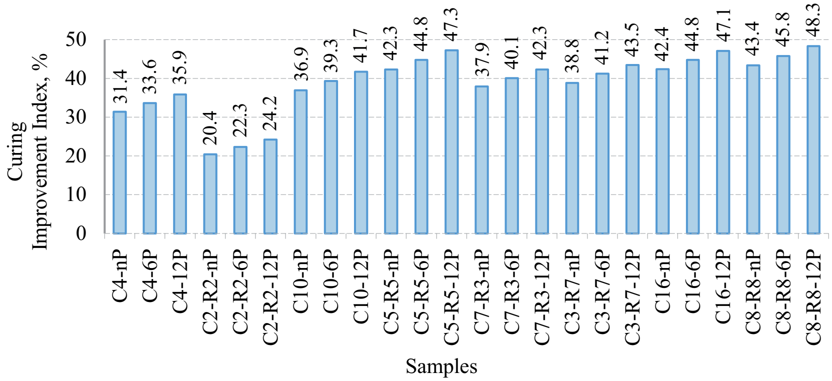


Figure 2. Curing Improvement Index of stabilised and reinforced sand-clay mixtures

presents CII values for all the stabilised and reinforced sand-clay mixtures.

The strength of all the samples is increased considering Figures 1 and 2, with increasing curing days from 7 days to 28 days. As it is shown, C8-R8-12P and C5-R5-12P samples experience the greatest CIIs. It can be seen that for a specified stabilised sample (containing the same OPC and RHA contents), the rate of increase in samples containing 12 mm fibres is higher than those samples containing no fibres or 6 mm fibres. Indeed, CII increases with presence and then increasing the length of fibres. It should be noted that it does not mean that the final strength of samples containing different fibre lengths will be the same. Indeed, CII increases with presence and then increasing the length of fibres. On the other hand, as shown in Figure 1 and will also be more explained in the following sections, samples containing larger fibre lengths experience lower UCS values. Hence, it is expected that for larger curing periods, UCS of samples with longer in fibre length can be identical to those having smaller PP fibres. Regarding the effectiveness of fibre length on the rate of strength change with time, it can be described that the time required to earn short-term compressive strength in the samples containing 6 mm fibres is lower than the corresponding time for samples with 12 mm fibres. It is because of greater occurred gaps in the 12P samples, which is due to the larger PP fibres. Hence, the 7-day strength of samples reinforced with 6 mm fibres is greater than 12P samples. On the other hand, differences between long-term strengths of 6P and 12P samples are lower than the difference among their short-term strengths. Hence, CII, which is introduced as the ratio of $\dfrac{\text{28-day strength} - \text{7-day strength}}{\text{7-day strength}}$, for 12P samples will be greater than 6P and nP samples (because they hold a lower 7-day strength). It results in a higher rate of strength change in 12P samples comparing to the 6P and nP samples.

2.2. Effect of RHA to OPC ratio on the unconfined compressive strength of OPC-RHA stabilised, and PP reinforced samples

Samples containing 10% stabiliser (OPC+RHA) are further studied to investigate the effect of the ratio of OPC to RHA in the stabilisation of the samples. In this regard, some of OPC content in 10C samples are replaced by RHA in different ways (5% cement + 5% RHA, 3% cement + 7% RHA and 7% cement + 3% RHA). This comparison is carried out for all PP fibre conditions (nP, 6P and 12P). Figures 3 and 4 show the UCS of different RHA/OPC ratios for 7 days and 28 days curing conditions.

As seen, the used OPC can be efficiently replaced by RHA, and significant UCS values can yet be achieved. It is clear, considering Figure 4, that RHA/OPC ratio of 5:5 and 0:10 result in identical UCS values and it can be concluded that in comparison to other mixing ratios, replacing half of OPC with RHA will help to gain significant UCS values. This situation is even better for 8% OPC + 8% RHA instead of 16 % OPC case. Hence, regarding all the cases, 8% OPC + 8% RHA is the best composition leading to the maximum UCS and replacing half of the desired OPC with RHA will be efficient in obtaining high UCS values.

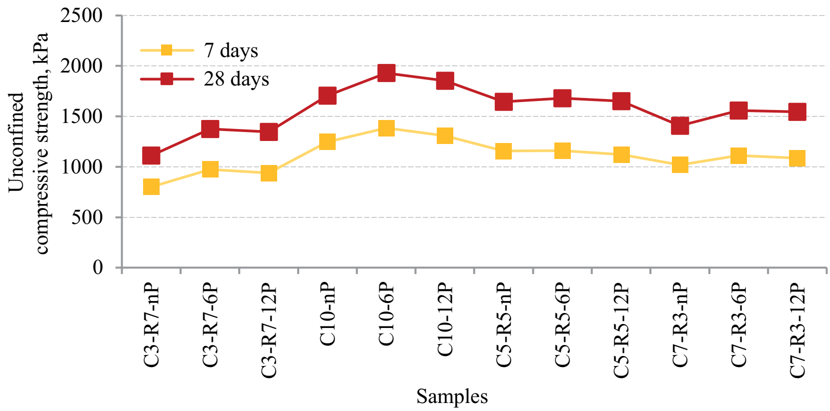


Figure 3. The unconfined compressive strength of samples containing 10% stabiliser and RHA/OPC ratios of 0:10, 3:7, 5:5 and 7:3

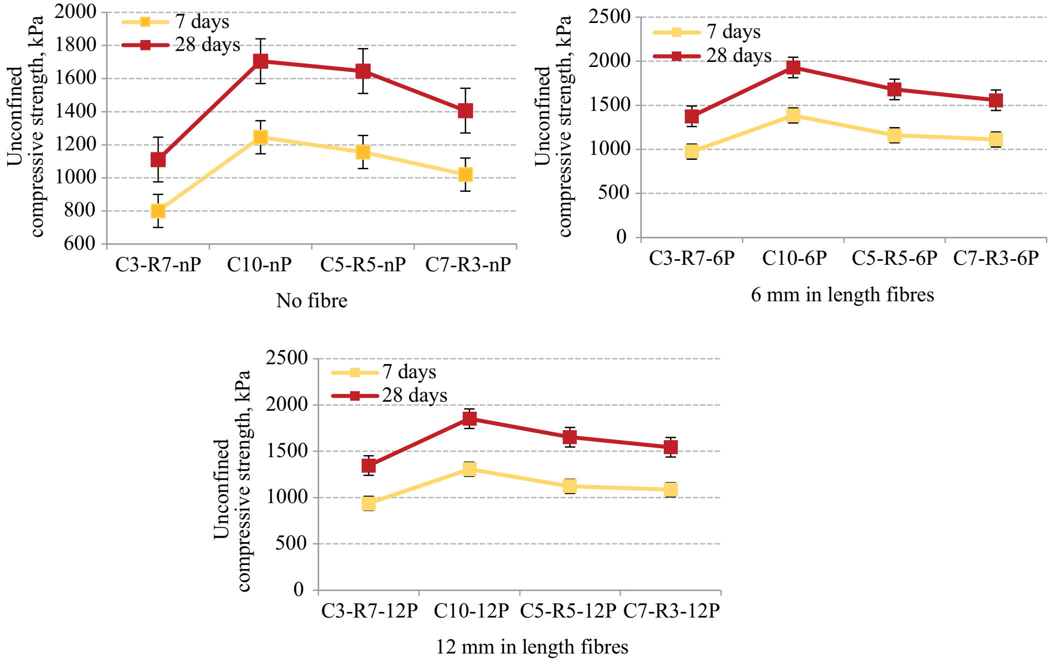


Figure 4. The unconfined compressive strength of samples containing 10% stabiliser and RHA/OPC ratios of 0:10, 3:7, 5:5 and 7:3

2.3. Effect of polypropylene fibres on the unconfined compressive strength of OPC-RHA stabilised, and polypropylene reinforced samples

To investigate the effect of fibres on the samples reinforcement and their UCS, the optimum samples showing maximum UCS are selected for further studies. They have been analysed from two points of views. Firstly, stress-strain behaviour of samples stabilised with 16% stabilisers (RHA/OPC ratios 0:16 and 8:8) is studied. Secondly, the UCS of these samples is compared for different PP fibre cases (nP, 6P, and 12P). Figure 5 shows the uniaxial stress of stabilised samples versus their corresponding axial strains for the cases of nP, 6P, and 12P.

As seen, peak strength of samples containing fibres is attained at greater strains and they can experience higher strains, while non-reinforced samples are failed at a lower axial strain saying that they show more brittle behaviours. The low modulus of the stress-strain curve up to 1% strain can be caused by experimental errors like gaps between the samples and the top cap or imperfections in trimming of the upper surface of the constructed samples. Hence, to derive the modulus of

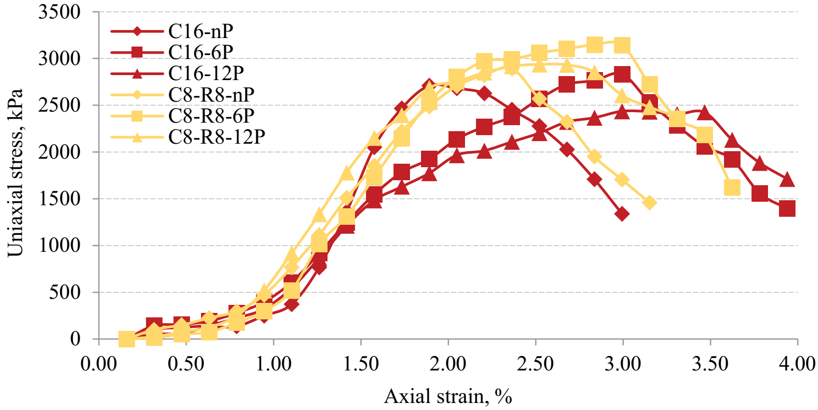


Figure 5. Uniaxial stress versus axial strain of stabilised samples and reinforced with different PP cases

stress-strain curve for different samples, it is recommended to shift the initiation of stress detection (vertical axis) to the 0.5–1% strains, where the samples are correctly sensed and loaded by the upper loading cap.

Figures 6 and 7 present the UCS of 7 days and 28 days cured sample containing 16% stabiliser (RHA/OPC ratios 0:16 and 8:8) for different PP cases (nP, 6P, and 12P).

Figures 6 and 7 show that all the samples containing 0.2% of 6 mm PP fibres exhibited an increase in their compressive strength. Although, increasing the length of PP fibres from 6 mm to 12 mm results in a decrease in the UCS of both 7 days and 28 days cured samples. This may be because 6 mm fibres are possibly better uniformly

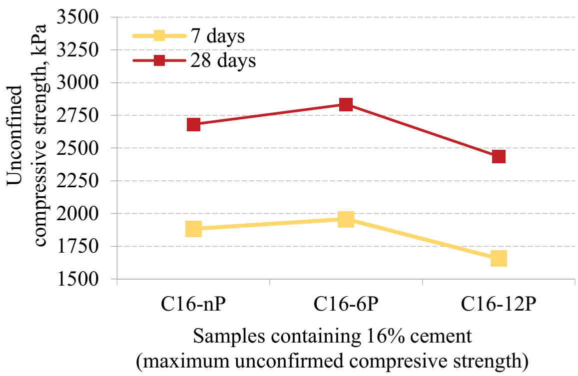


Figure 6. The unconfined compressive strength of samples stabilised using 16% OPC for different PP cases

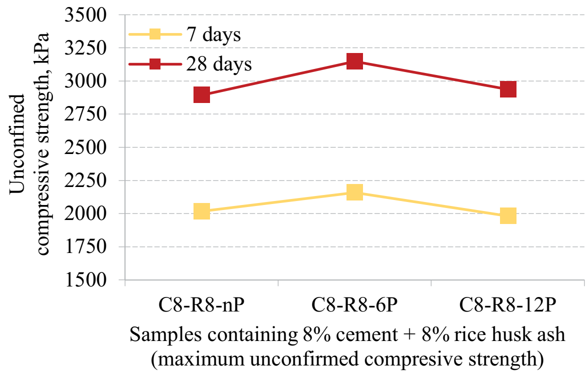


Figure 7. The unconfined compressive strength of samples stabilised using 8% OPC + 8% RHA for different PP cases

distributed along all volume of the specimen and reinforced the sample against disintegration by resisting against initiating cracking and prohibiting coalescence of micro-cracks and formation of macro-cracks. Nevertheless, in samples containing 12 mm fibres, uniformly distributing the fibres is more difficult. Hence, they may form partial clusters or protrusions, which help to create micro-defects in the OPC-RHA matrix and reduces the UCS of stabilised samples. Similar behaviours are also reported in the reinforcement of cement stabilised concrete using fibres. On the other hand, it should be noted that since the difference in the UCS of samples with and without fibres is small, it could be caused by the variability. Hence, such a conclusion should be used specifically for the used fibre lengths and quantity.

2.4. Indirect tensile strength and flexural strength of samples

Flexural strength and ITS tests are conducted to evaluate the tensile behaviour of stabilised and reinforced samples. Tables 5 and 6, respectively, present flexural strength and ITS of different studied samples. It should be noted that the presented results are averagely valued of two conducted tests for each of the stabilisers combinations.

2.5. Data analysis

Artificial intelligence techniques have large applicability in the prediction of civil engineering's complicated functions (Ahangar-Asr, Johari, & Javadi, 2012; Baziar & Ghorbani, 2005; Ghorbani &

Table 5. Flexural strength and indirect tensile strength values of both 7 days and 28 days cured samples

Sample	Polypropylene, mm	Flexural strength		Indirect tensile strength	
		7 days, kPa	28 days, kPa	7 days, kPa	28 days, kPa
C4	nP	432.47	570.75	254.97	349.12
	6P	547.21	637.43	304.99	405.01
	12P	520.73	555.06	282.43	395.21
C2-R2	nP	420.71	562.90	180.44	248.11
	6P	543.29	608.99	304.01	386.38
	12P	498.18	543.29	240.26	372.65
C10	nP	576.63	945.36	350.10	425.61
	6P	788.45	963.99	501.12	528.58
	12P	753.15	876.71	478.56	494.26
C5-R5	nP	554.08	850.24	296.16	336.37
	6P	798.26	935.55	414.82	445.22
	12P	742.36	816.89	381.48	423.65
C16	nP	664.89	996.36	427.57	453.07
	6P	853.18	1026.76	593.30	692.35
	12P	830.62	909.08	569.77	609.97
C8-R8	nP	697.25	1019.89	427.57	446.20
	6P	1019.89	1108.15	652.14	713.92
	12P	941.44	964.97	608.01	617.82

Hasanzadehshooiili, 2017, 2018; Nikoo, Torabian Moghadam, & Sadowski, 2015; Rezania, Faramarzi, & Javadi, 2011; Sadowski & Hola, 2015; Ghorbani, Hasanzadehshooiili, & Sadowski 2018). Among them, EPR, which is a new hybrid regression technique, combines the best features of conventional numerical and the genetic programming symbolic regression methods. It employs an evolutionary computing methodology to search for a model and to estimate the parameters to attain constants using least squares (Giustolisi & Savic, 2006; Ghorbani & Hasanzadehshooiili, 2018).

In this technique, the type of functions, number of terms, the range of exponents, and number of generations are used as constraints to control the output (Rezania, Faramarzi, & Javadi, 2011). When the number of evolutions increased, different participating parameters are picked up to describe the relationship between the parameters of the system. In this method, the coefficient of determination is then calculated to assess the accuracy of the output model. If the prediction of the presented model is not acceptable, or the other termination criteria (regarding a maximum number of generations and a maximum number of terms) are not satisfied, the current model goes through another evolution (Ahangar-Asr, Johari, & Javadi, 2012; Ghorbani & Hasanzadehshooiili, 2018).

To gain efficient equations for prediction of UCS, ITS and FS of 7 days and 28 days cured stabilised samples; the conducted test results are considered and used to gain the EPR models. As mentioned, three different input parameters, Cement, RHA and PP are used for predictions.

The best-obtained models for predicting UCS, ITS and FS of 7 days and 28 days cured samples are presented in Eqs (5)–(10), respectively. As shown, high coefficients of determination (R^2), for all the presented relationships (Eqs (5)–(10) prove the accuracy and high capability of the proposed models.

$$\begin{aligned} FS_{7\ -day} = & -(0.3405e^{0.5PP}) - (5.7323 \cdot 10^{-13} PP^{0.5} e^{2C}) \\ & + (9.7784 RHA^{0.5} PP^{0.5}) + (24.4403 RHA) \\ & + (31.4147 C^{0.5} PP^{0.5}) + (21.4145 C) + 335.9258, \end{aligned}$$

$$R^2 = 98.9\%; \tag{5}$$

$$\begin{aligned} FS_{28-day} = & (0.13925 e^{PP}) - (8.5732 \cdot 10^{-7} e^{2PP}) + (21.7877 e^{0.5RHA}) \\ & - (0.00010429 e^{2RHA}) - (0.22789 e^{0.5C}) + (4.4494 C^2) \\ & + 492.6418, \end{aligned}$$

$$R^2 = 99.3\%; \tag{6}$$

$$\begin{aligned} ITS_{7-day} = & -(3.4728 \cdot 10^{-9} e^{2PP}) + (0.040133 e^{RHA}) + (9.4432 RHA^{0.5} PP^{0.5}) \\ & + (89.7355 C^{0.5}) + (17.7543 C^{0.5} PP^{0.5}) + 68.1672, \end{aligned}$$

$$R^2 = 98.7\%; \tag{7}$$

$$\begin{aligned} ITS_{28-day} = & \left(3.8872 \cdot 10^{-6} \cdot e^{(2RHA+0.5PP)}\right) \\ & - \left(1.1104 \cdot 10^{-6} PP^{0.5} e^{(2RHA+0.5PP)}\right) \\ & - (2.2842 \cdot 10^{-9} C^{0.5} e^{2PP}) + (7.7926 C^{0.5} PP) + (12.6366 C) \\ & + 277.8232, \end{aligned}$$

$$R^2 = 96.3\%; \tag{8}$$

$$\begin{aligned} UCS_{7-day} = & (1.8799 \cdot 10^{-12} \cdot e^{2C}) + (40.7744 PP^{0.5}) - (0.12333 RHA^{0.5} e^{C}) \\ & + (480.5955 C^{0.5}) - (7.3645 \cdot 10^{-10} C e^{2PP}) \\ & + (0.469 C^2 RHA^2) - 215.0498, \end{aligned}$$

$$R^2 = 99.4\%; \tag{9}$$

$$\begin{aligned} UCS_{28-day} = & (0.13501 e^{0.5C}) - (0.00025837 RHA e^{2RHA}) + (643.3894 C^{0.5}) \\ & + (24.3802 C^{0.5} PP^{0.5}) + (0.2931 C RHA^{0.5} e^{RHA}) \\ & - (0.0054221 C^2 e^{0.5PP}) - 320.5798, \end{aligned}$$

$$R^2 = 99.4\%; \tag{10}$$

where FS, ITS and UCS, respectively, represent flexural strength, indirect tensile strength and unconfined compressive strength. Also, PP, RHA and C are the percentages of polypropylene, rice husk ash and cement, respectively, used in the specimens. In addition, e is the Naperian number.

Defining the most and the least effective parameters on the UCS of stabilised samples will considerably help design engineers to make a suitable stabilisation plan and will be of the high degree of importance for practitioners. Thus, using the CAM, a sensitivity analysis is conducted. This method is used to achieve the express similarity relations between the input parameter and the target function. In this method, each of the input parameters is expressed as one of the X array's elements, which is shown in Eq. (11) (Ghorbani, Hasanzadehshooiili, Ghamari, & Medzvieckas, 2014).

$$X = \{x_1, x_2, x_3, \ldots, x_i, \ldots, x_n\}, \tag{11}$$

where each of its elements is a vector with the length of m and is presented in Eq. (12)

$$x_i = \{x_{i_1}, x_{i_2}, x_{i_3}, \ldots, x_{i_m}\}. \tag{12}$$

Then, the strength of the relationship between x_i and x_j is calculated using Eq. (13) (Ghorbani, Hasanzadehshooiili, Ghamari, & Medzvieckas, 2014):

$$r_{ij} = \frac{\sum_{m=1}^{k} x_{i_m} x_{j_m}}{\sqrt{\sum_{m=1}^{k} x_{i_m}^2 \sum_{m=1}^{k} x_{j_k}^2}}. \tag{13}$$

By using this method, the most and least sensitive parameters on the UCS of stabilised and reinforced samples are attained. The calculated strength of the relationship between input parameters and UCS is shown in Table 6 for 7 days and 28 days cured samples. According to Table 6,

Table 6. The strength of the relationship between the unconfined compressive strength of 7 days of stabilised samples and concerning parameters

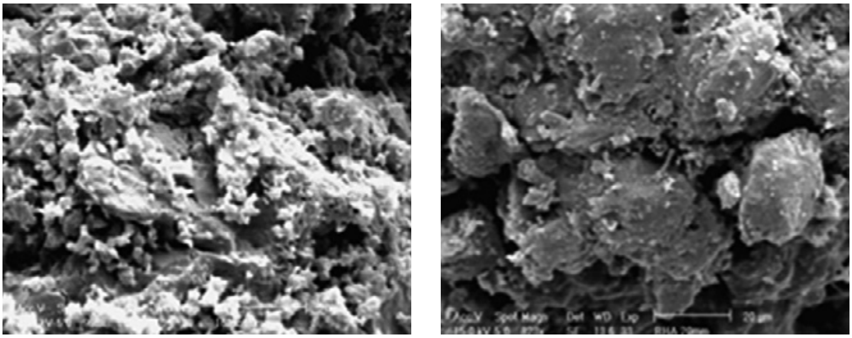
Stabiliser, %	Strength of relationship with unconfined compressive strength, %	
	7 days	**28 days**
Cement	93.99	93.93
Rice husk ash	72.37	72.68
Polypropylene	71.93	71.85

OPC content is the most influential parameter on the UCS of both 7 days and 28 days cured samples. On the other hand, the length of PP fibre has the least influence in determining UCS of both 7 days and 28 days cured specimens.

2.6. Discussion on the results using Scanning Electron Microscopy

Calcium silicate gel is the main component giving strength to the cement. The required C-S-H can be formed because of the silicates found in the soil and RHA and $Ca(OH)_2$ available in the cement. This reaction is known as the pozzolanic reaction. Since RHA contains sufficient amount of SiO_2, it can prepare the required circumstances for the pozzolanic reaction to increase the compressive strength of cement.

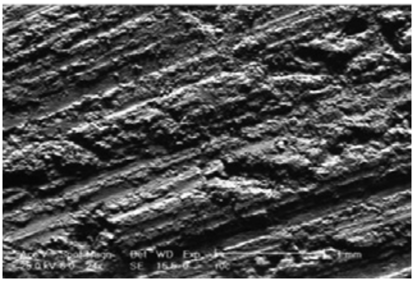
Scanning Electron Microscopy samples were obtained using cutting the samples with a laser-cutting device. It was tried to prepare the samples with a minimum disturbance on the texture of samples. In this regard, they were first dried, coated and laser-cut and then were used for scanning electron microscopy photos. As seen in Figure 8, images of electron microscopy for the samples made up of 16% cement and 8% cement + 8% RHA are presented (as the optimum samples), separately. Regarding the silicate crystals shown in both samples containing 16% cement and 8% cement + 8% RHA, it can be concluded that RHA as a suitable alternative for cement, holds the same hydration characteristics and can provide the conditions for hydration reactions.



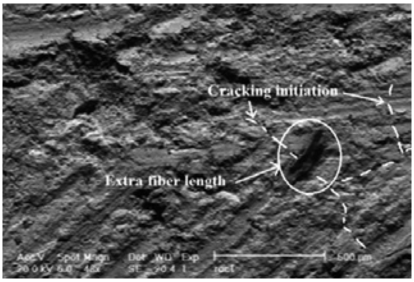
a) containing 16% cement

b) containing 8% cement + 8% rice hush ash

Figure 8. Scanning Electron Microscopy of samples



a) containing 10% cement



b) containing 10% cement + polypropylene fibre

Figure 9. Scanning Electron Microscopy of samples

As can be seen in Figure 8, comparing to the pure cement stabilised samples, samples containing 8% cement +8% RHA have a more flocculated and dense structure and hence show the higher UCS. Indeed, the addition of RHA helps to form more dense and compacted texture helping to sustain larger compressive loads. Besides, Figure 9 shows two stabilised samples. The first sample is a non-reinforced sample stabilised using 10% OPC, while the second sample is a PP fibre reinforced sample containing the same OPC content.

As it can be seen in Figure 9b, protrusion of PP fibre, as it was previously described, has made the initiation of micro-cracks and may be conducive to more defects through growing the exerted micro-cracks and making macro-cracks. The made defects can lead to a decrease in the UCS of samples. It may be the main reason that 12 mm fibre reinforced samples show lower UCS in comparison to the 6 mm fibre reinforced specimens.

Conclusions

Based on the results from Unconfined Compressive Strength Test, the following results can be concluded for the stabilised and reinforced samples:

1. Curing Improvement Index of sand-clay mixtures containing fibres and having larger fibres are higher than those not having or having the smaller ones.
2. Samples containing larger polypropylene fibres have lower unconfined compressive strength values. Moreover, 6 mm fibre reinforced and stabilised samples show greater unconfined compressive strength values.

3. Regarding the two earlier conclusions, it is possible that for larger curing, e.g. 90 days, the unconfined compressive strength of samples with longer in length fibres can be identical to those having smaller polypropylene fibres.
4. Sample containing 8% rice husk ash and 8% Ordinary Portland Cement, and reinforced with 6 mm polypropylene fibres (C8-R8-6P) is the best sample showing the largest unconfined compressive strength in both 7 days and 28 days curing periods.
5. Replacing half of the planed Ordinary Portland Cement to improve the unconfined compressive strength of the sand-clay mixtures with rice husk ash will be conducive to the identical unconfined compressive strength values. In some cases, e.g. 8:8 rice husk ash/Ordinary Portland Cement ratio, it will lead to even more results that are efficient.
6. Stress-strain behaviour of rice husk ash-Ordinary Portland Cement stabilised, and polypropylene reinforced samples shows that adding fibres to the samples results in larger axial strains before the occurrence of a failure in the stabilised specimens. Moreover, non-reinforced stabilised samples experience a more brittle behaviour.
7. The existence of small fibres will help the stabilised samples to resist against micro-cracks coalescence and formation of macro-cracks (leading to larger unconfined compressive strength values), while larger fibres lead to the formation of clusters or protrusions and micro-defects in the samples resulting in decreasing the unconfined compressive strength of the specimens. This hypothesis is also proved using Scanning Electron Microscopies.
8. Using data analysis and evolutionary polynomial regression (EPR) modelling approach, new relationships with a high coefficient of determinations are presented for prediction of unconfined compressive strength, indirect tensile strength and flexural strength of both 7 days and 28 days cured stabilised and reinforced samples.
9. Based on the sensitivity analysis, Ordinary Portland Cement content is introduced as the most effective parameter on the unconfined compressive strength of stabilised and reinforced samples. On the other hand, the length of polypropylene fibres plays the least effective role in the determination of unconfined compressive strength.

Disclosure Statement

Authors declare that there is no conflict of interests regarding this paper.

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