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Improvement of Earth into Concrete as an Eco-friendly Building Material – Effect of Soil Gradation and Chemical Admixtures

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Abstract: Environmental concerns and economic crises have been more critical in recent years, making it impossible to continue construction using traditional resources (cement, sand, and natural aggregates) in the same way as before. However, the use of earth is a cost-effective solution and it can enhance the sustainability of construction materials by employing soil as a building material. This study evaluated soil consistency that would be acceptable to make soil concrete and analysed the effect of chemical admixtures in achieving the maximum possible strength. Hence, the study suggested the possibility of using soil to form concrete as a replacement for cement concrete to the maximum extent with self-compacting properties. The soil was used to produce the concrete, stabilizing with cement and chemical admixtures were used to improve the strength and workability. According to the experimental investigation, it can be concluded that soil can be used as concrete with a characteristic strength of 15 MPa. The recommended native soil consistency for soil concrete should be developed by rearranging the native soil gradation to 5%–10% fines, 55%–71% sand, and 24%–40% gravel. The recommended cement amount as the stabilizer is 16% to 18% of the weight of the improved dry soil mixture. The strength and workability can be further improved by employing suitable chemical admixtures. Finally, this extensive study concluded that soil could be used to produce concrete for the construction industry through applications with minor improvements to the existing soil.

Keywords: Soil concrete, Admixture, Workability, Eco-friendly construction material

1. Introduction

Building and infrastructure demand is growing with the global population, leading to increased non-renewable material consumption and waste. The construction industry relies heavily on natural resources like sand, which has a negative impact on biodiversity and also contributes significantly to greenhouse gas emissions. This makes the industry unsustainable and in need of change [1] [2]. Thus, the adoption of environmentally friendly construction materials and technologies extensively contributes to the eco-efficiency of the construction industry, improving its sustainability [3]. In addition, the energy consumed to transport building materials is another factor that contributes to environmental performance. Therefore, the use of local resources is the preferable solution.

According to literature, the embodied energy of a building with traditional materials, such as concrete, steel, and ceramic, is twice more than that of earthen structures. For example, previous research reveals that adobe houses can reduce CO_2 emissions by approximately 100 tons per year.

Though earthen construction is considered an environment-friendly material, when it comes to burnt bricks, compressed stabilised earth blocks are more environmentally friendly than burnt bricks because burnt bricks require energy 15 times more than that required for compressed stabilised earth blocks.

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Stabilised earth blocks also contribute to minimum pollution to the environment [4-9]. It reveals that not only does the selection of material affect but also the material manufacturing technology also affects construction sustainability. Therefore, constructing with earth has many environmental benefits [10-11]. Furthermore, according to literature, earthen construction can regulate humidity and temperature, thereby improving the occupant's comfort without "energy-intensive air conditioning systems" [12-15].

In recent years, most studies in earthen construction have concentrated on mechanical, thermal, and hydrothermal properties. The economic benefits, use of non-renewable resources, waste generation, energy consumption, carbon dioxide emissions, and indoor air quality have also been investigated [16].

Although no consensus exists to utilise earth as a building material, numerous literary works claim that wattle and daub, cob, rammed earth, earth bricks (adobe), and crushed earth blocks have been used for over 13,000 years [17] [12].

Our ancestors built their homes with natural materials like earth, which was free of toxins. Modern buildings release harmful chemicals into the air, causing health problems. However, biodiversity and ecosystems are now recognized as important for improving quality of life and health [4, 18-20].

Despite these benefits, the use of earth in building construction has been limited due to lack of knowledge in the functions of material designs and a shortage of worldwide standards. Soil properties vary greatly by location and are affected by climate, topography, and seasonal changes, making earthen products non-standardized building materials. Different authors use varying standards to evaluate earthen products with varying clay-to-sand ratios and water amounts [11] [21]. Soil, used for soil-based productions, is made up of clays, silts, and sandy materials, which are combined in various proportions. Thus, the evaluation procedures for the production are subjected to a wide range of test methodologies [12].

The required mix design with soil, sand, stabiliser, water, and other materials depends on the properties of the soil [16, 21-24]. Soil cannot be used for construction due to its weak properties. However, these properties can be improved through soil stabilisation. This process aims to enhance the mechanical and physical performance of soil products by reducing its plasticity and increasing its workability. For different soil types, various authors have studied several stabilisers, including lime, cement, molasses, cow dung, sawdust, straw fiber, and sugar [22, 26-29].

The most critical issues which affect the properties of soil-based products are particle size distribution and clay content of the soil. Particle grading determines the ability of soil grains to combine into a dense structure when compacted under a given effort. This concept has been disregarded in previous research. Current earth construction guidelines propose certain soil classes with particle size distribution and clay concentration that must fall within the permissible levels. Previous studies identified that soil with 5%–30% clay content is acceptable for earth-building construction [16] [30]. Some other studies verified that the quantities of fine sand modify a natural soil to make different earth construction materials with different clay percentages. In these studies, a series of tests was conducted, and the results revealed that the mechanical properties are strongly influenced by clay content [24, 31-33]. However, the influence of grading and clay content on strength and durability remains uncertain [31].

In this context, mud concrete was developed using soil and stabilised with several stabilisers [34-36]. In the present study, soil composition and the optimum particle size distribution of soil were studied to introduce soil-based concrete. The amount of cement and the water requirement were also evaluated. The possibility of using chemical admixture to enhance the strength of soil concrete was studied further.

2. Materials and Methods

Soil is a readily available resource [22] [37] which is used as the primary raw material to produce soil-concrete in this study. The composition of native soil in Sri Lanka consists of fine particles, sand, and gravel in various proportions. The soil was mixed with water and stabilised with cement to strengthen the bond between soil particles as in cement concrete. In this approach, the gravel particles act as coarse aggregate, fine and sand particles act as fine aggregate, and cement act as a binding agent. Previous research highlighted that the cement type affects the strength and durability properties of the soil-cement products [38] [39]. Therefore, the same brand of ordinary Portland cement was used throughout the experiment to avoid the effect of cement property variations. The mix design of soil concrete was developed to achieve strength with self-compacting capacity. Therefore, identifying the optimum water requirement for self-compacting capacity was the first step. Then the optimum particle size composition and effect of chemical admixture towards the strength of soil concrete were evaluated. The compressive strength of the soil concrete was selected as the main characteristic throughout the mix design process. 150 mm cubes were used to determine the compressive strength of this soil concrete. The shape and the size of the aggregate also influence the workability, durability, strength, and shrinkage parameters [40]. Therefore, investigating the effect of gravel size is important. Hence, this study was also focused on determining the effect of the gravel size on the soil concrete.

The particle size distribution, gravel size, optimum water-cement ratio, cement content and chemical admixture requirement were identified as the main variables. Therefore, the optimum values of these variables were investigated.

2.1 Development of Soil-concrete

The development of soil concrete was done in several steps as mentioned above. First, the initial water requirement was found out. Then the best particle size distribution for soil concrete was investigated. Finally, appropriate water requirement and the possibility to add chemical admixtures to improve the compressive strength of developed soil concrete was discovered. To initiate the experiment, trial range of cement and water was decided according to the previous studies done in related soil based concrete production [34-36].

2.1.1 Initial Water Requirement

One of the primary goals of this study is to create a self-compacting soil concrete that could be set under its weight without providing any mechanical vibration or compaction effort. The flowability of the soil mix should be managed while maintaining its consistency to develop self-compacting concrete. Therefore, identifying how much water is required to make self-compacting concrete was carried out. Flow table and slump tests were performed to determine the workability and water requirement for the proper workable mix. The slump test and flow table test were performed according to the ASTM C143/C143M-20 and BS 1881-105 of 1984, respectively.

The extracted soil was mixed with varying amounts of water and 18% of cement from the total dry soil weight. The workability test was performed for three samples from each mix.

During the slump test, the soil concrete did not collapse immediately as normal concrete because of the cohesiveness of the soil mixture. Although a small slump height appeared, it may not exhibit actual workability. Therefore, a flow table test was also performed and the flow diameter was measured as shown in Figure 1.

Figure 1 - Workability Test Procedure

The proper workability of the mixture could be achieved when the maximum spread was approximately 500–600 mm in diameter. Three samples from each mix were oven-dried with a constant temperature of 105°C for 24 hrs to calculate the moisture content of the mixtures.

The results showed that, with the increment of water content, flow diameter and slump height increased. The flow diameter was within the range of 500–600 mm when the moisture content was between 16.2% and 19%, thereby achieving the optimum workability mixture. If the moisture content was less than 16.2%, self-compacting capacity cannot be achieved and segregation was observed when the moisture content was more than 19%. Therefore, the optimum water requirement from the dry mixture can be considered as between 16.2% and 19%. Figure 2 shows the variation in the workability of this mixture with water content.

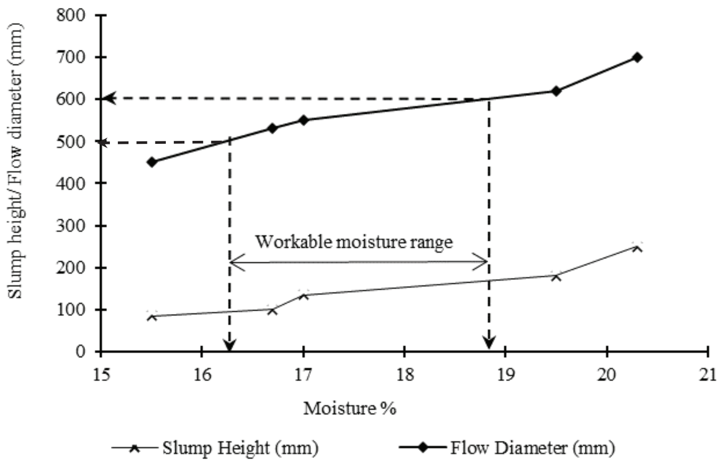

Figure 2 - Slump Height/Flow Diameter with Different Water Contents

2.1.2 Particle Size Distribution

The properties of soil construction strictly depend on the constituent of soil (i.e., gravel, sand, silt, and clay proportions of the soil) [41]. Thus, the constituents of extracted soil were determined initially. Particle sizes for the experiment series were classified as presented in Table 1 according to ASTM D 2487-11.

The excavated soil was subjected to a sedimentation test and dry sieve analysis. This study provided a basic description of the soil constituents used to produce soil concrete. The sedimentation test was first performed and according to the sedimentation test results, the selected soil consists of approximately 10% fine particles, 60% sand, and 30% gravel.

Then, dry sieve analysis test was performed to get a more accurate gradation of the extracted soil. In this study, five soil samples were selected randomly from the extracted soil. The results revealed that the extracted soil included the average values of 7% fine particles, 63% sand particles, and 30% gravel particles. The experiments were initiated using these results to determine the suitable particle size distribution for the soil concrete. The results of the sieve analysis are shown in Figure 3.

Table 1 - Soil Classification for Soil-Concrete ASTM D 2487-11

Particle type	Sieve sizes (Particle size)
Fine	Particle size less than 0.425mm
Sand	Particle size less than 4.75mm and greater than 0.425mm
Gravel	Particle size less than 20 mm and greater than 4.75 mm

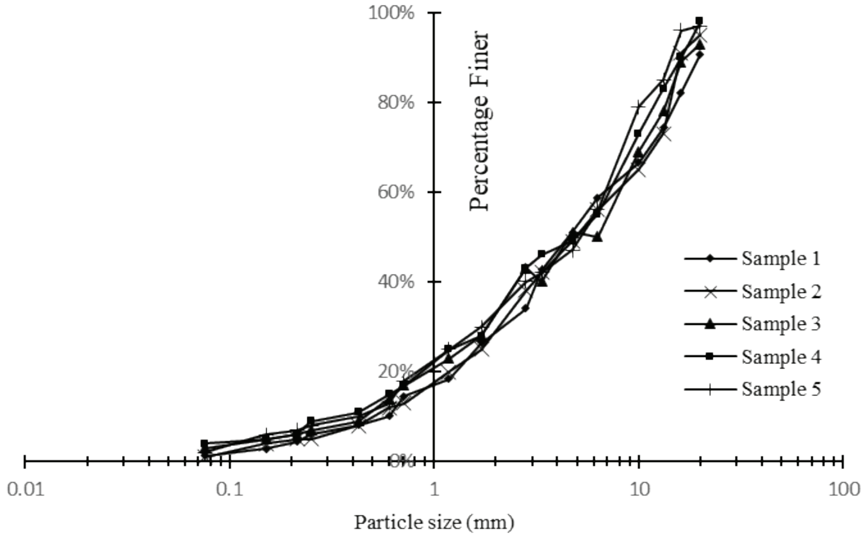

Figure 3 - Particle Size Distribution of Soil Samples

2.2 Best Particle Size Distribution for Soil Concrete

This step determines the best particle size distribution. The experiment series was carried out to determine the effect of the particle size distribution of soil to reach the maximum strength of soil concrete. First, the effect of fine content, then sand content, and finally gravel content was determined. The soil was mixed with constant cement % and constant water content. The 150 mm test cubes were cast and underwent the curing process for 28 days. Universal compressive strength test equipment with a capacity of 2000 kN was used to apply load at a constant rate of 6.8 kN/s. The standard test method according to BSEN 12390-3:2009 was adopted during the testing. The casting and the testing procedure are shown in Figure 4.

150mm cubes were cast to determine the best fine percentage while maintaining a constant level of gravel 35%, cement 18%, water content 19%, and varying fine and sand percentages, as shown in Table 2.

The strength of the soil concrete drastically declines when the fine content of soil concrete is increased, as shown in Figure 5. The maximum value of the strength of the soil concrete can be obtained by reducing the fine particle content of the mixture. Further, when the fine particle content is above 10%, compressive strength is drastically reduced. Therefore, the most suitable and practical fine percentage can be taken between 5% and 10% of the total dry soil mixture.

Table 2 - Mix Design to Analyze the Best Fine Particle Content (%)

Sample	**S1**	**S2**	**S3**	**S4**	**S5**
Fine %	5	10	15	20	25
Sand %	60	55	50	45	40

Dry soil cement mix   Steel mould   Cubical specimens   Test procedure

Figure 4 - Casting and Testing Procedure

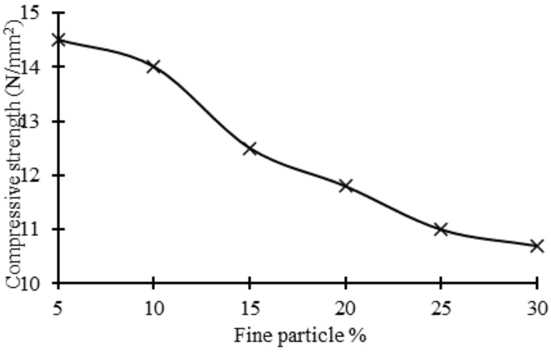

Figure 5 - Variation of Compressive Strength with the Fine Particle Content

2.2.1 Optimum Gravel Percentage

After identifying the suitable fine percentage, the best gravel percentage to achieve the best compressive strength was evaluated. During this process, fines, water, and cement percentages were maintained constant at 5%, 19% and 18%, respectively. Table 3 shows the mixed proportions prepared for this evaluation. The results revealed that the soil concrete reached its maximum strength when the gravel percentage is within the range of 24%–40%.

This gravel percentage can be maintained by arranging the finer content as 5% and the percentage of sand in the range of 71%–55%. The results are shown in Figure 6.

Table 3 - Mix Proportions to Evaluate the Optimum Gravel Percentage

Sample	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**
Sand %	85	75	65	55	45	35
Gravel %	10	20	30	40	50	60

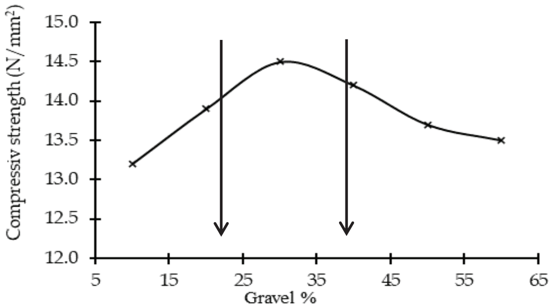

Figure 6 - Variation of Compressive Strength with Gravel Percentage

2.2.2 Optimum Gravel Size

The effect of the gravel size on the soil concrete was determined by keeping the gravel, sand, and fine percentages constant at 31%, 64%, and 5%, respectively, which are the best percentages for soil concrete according to the results obtained in the above steps. Therefore, the extracted soil was developed to these required particle size percentages by adding (or deducting) the calculated amount of gravel and sand particles to the extracted soil. Then, sieve analysis was performed to validate the particle size distribution of this developed soil, as shown in Figure 7.

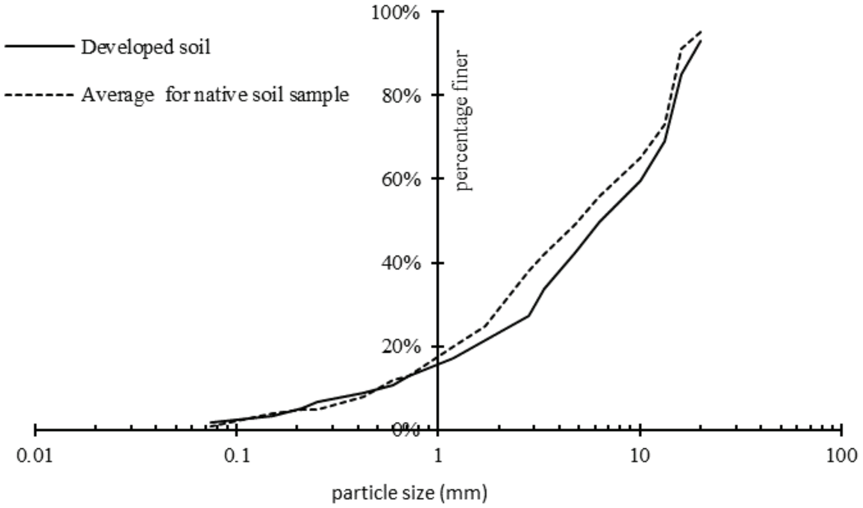

Figure 7 - Sieve Analysis Results on Developed Soil

Then, the soil concrete was mixed by varying the gravel size. The cement and water percentages were kept constant at 18% and 19%, respectively, as shown in Table 4. The variation of compressive strength as a function of gravel size is shown in Figure 8.

Table 4 - Mix Design Arrangement

Sample No.	Gravel size range (mm)
1	4.75–10
2	4.75–20
3	4.75–30
4	4.75–40
5	4.75–50

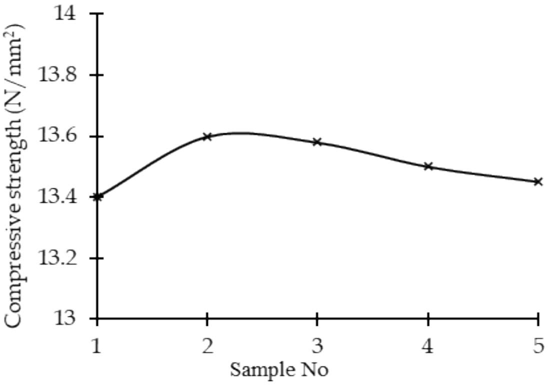

Figure 8 - Compressive Strength Variation for the Different Gravel Size Ranges

The findings revealed that the compressive strength increases initially when the gravel size increases up to a certain level. Further increasing the gravel size, the compressive strength of soil-concrete decreases. Finally, Sample Nos. 2 and 3, which contain gravel sizes ranging from 4.75 to 30 mm, yielded the highest levels of strength for the soil concrete.

The optimum constituent of soil was concluded for the strength requirement. Then, the strength variation with water content was observed.

2.2.3 Strength Variation with Moisture Content

150 mm cubes were cast with the modified soil to investigate the compressive strength variation with water content. The modified soil to fines 5%, sand 65% and gravel 30% was mixed with five different water contents, and the cement content was maintained at a constant of 18%. The mix proportions are shown in Table 5.

Table 5 - Mix Proportion Arrangement to Determine the Strength Variation with Moisture Content

Sample No.	Water amount (ml)	Equivalent water %
S1	3000	14.8
S2	3500	16.0
S3	3750	16.7
S4	4250	18.2
S5	4500	19.8

The results indicated that the increase in the water content causes a linear decrease in the compressive strength with a gradient of −16.00, as shown in Figure 9. Therefore, this study revealed that the reduction of the amount of water in the soil-concrete is essential. However, a large amount of water is required in soil-concrete manufacturing to maintain the hydration process of cement and maintain proper workability with the cohesiveness of soil. Therefore, the reduction of water content is significant to maintain the workability and improve strength further. For that, the next step was to investigate the possibility of using chemical admixtures to maintain workability and improve strength under low water content.

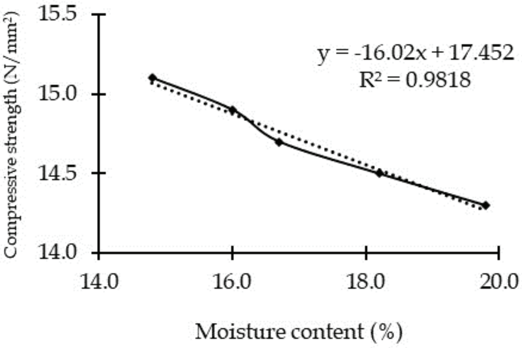

Figure 9 - Compressive Strength Variation with Water Content

2.3 Behaviour of Soil Concrete with Chemical Admixtures

The properties of soil concrete with admixtures were studied in this section. The principal approach was to examine the compatibility of admixture in soil concrete and determine the optimum combination of cement and admixture to enhance the properties.

Four types of superplasticisers available in the current market were selected among several types of chemical admixtures. The properties of the selected admixtures and the recommended dosage of manufacturers for cement concrete production are mentioned in Table 6. The flow table test and compressive strength test were conducted to identify the effect of chemical admixture on soil concrete. The series of experiments were designed for mixes, as shown in Table 7. The admixture dosage was selected according to the manufacturers' instructions. The flow table diameter variation for soil-concrete mixes with the type AD1 to different dosages is shown in Figure 10 for the represented samples. All types of admixtures behave in the same way as shown in Figure 10, but at a different level.

The results indicated that the addition of 750–1250 ml/100 kg of cement effectively reduces the water requirement of soil concrete to maintain optimum workability. Flow diameters show a linear variation with a constant gradient. The variation of workability and the amount of water reduction of soil concrete with the admixture types were calculated. Table 8 shows the reduction in water amount due to the admixture dosages/types by maintaining the workability.

Table 6 - Properties of the Selected Admixtures and Recommended Dosage for Cement Concrete Production

Admixture Code	Commercial Name	Manufacturers' details			
		Appearance	Recommended Dosage	Expected property	Standard
AD1	Rheobuild 561	Dark brown liquid	0.7–1.2 L per 100 kg cement	Easily flowing and free from segregation; has the same water/cement (w/c) ratio as that of a no-slump concrete without additive	ASTM C494 Type B, D & G, BS5075 Part 3 for high-range water-reducing admixture
AD2	MasterEase 3703	Light brown liquid	0.2–3.0 L per 100 kg cement	Improves the quality of surface finishes, decreases shrinkage and cracking, enhances durability	ASTM C494 Type F&G
AD3	Brocrete S888	Amber-colored clear liquid	0.6%–1.5% of cement		
AD4	Brocrete S838	Amber colored clear liquid	0.5%–1.1% of cement		

Table 7 - Design Mix Proportions

Admixture Type	Dosage	Water	No. of Flow table test	Specimen code	Total no of test
ADi	Dj	Wk	Xa	(AD)iDjWkXa	
i = 1,2,3 & 4	j = 1,2,3	k=1,2,3,4& 5	a= 1,2 & 3	Eg.$(AD)_3D_1W_2X_1$	225

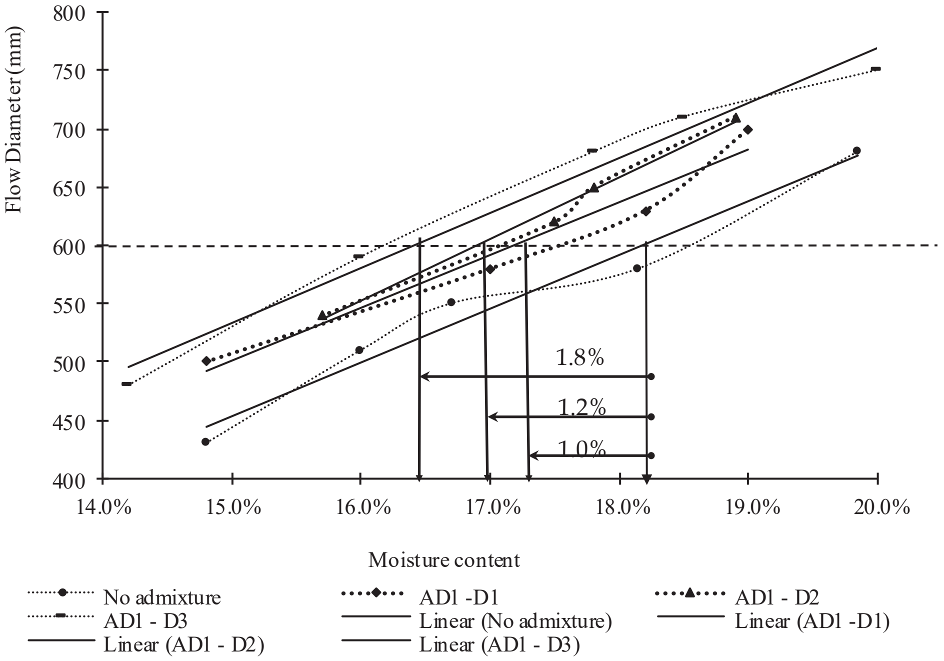

Figure 10 - Workability Variation with Moisture Percentage for Soil-Concrete with Admixtures

Table 8 - Reduction in Water Amount due to the Admixture Dosages/Types

Admixture type	Dosage (ml/100 kg of cement)	Reduction in water (%)
AD1	750	1.0
	1000	1.2
	1250	1.8
AD2	250	1.1
	500	1.4
	750	2.0
AD3	350	1.5
	500	1.8
	750	2.1
AD4	750	1.0
	1000	1.4
	1250	1.8

The workability variation of the soil-concrete mixtures with different admixtures shows the same linear variation as the soil-concrete without admixtures in different levels. This observation revealed that soil concrete workability can be improved by adding different chemical admixtures with varying dosages. Therefore, the use of chemical admixtures helps to enhance workability at a different level. However, the dosage must be decided by doing a trial mixture.

The data presented above lead to the conclusion that an admixture can be added to minimize the required water content. Further, it can lead to an increase in the compressive strength. Then, cubes were cast to investigate the increase in compressive strength of soil-concrete with admixtures,

Based on the equation ($y = -16.02x + 17.452$), the expected compressive strength at different water content can be calculated. The experimental results indicated that the strength increment is somewhat higher than the expected value because of the reduction of water amount. The results are tabulated in Table 9.

Figure 11 shows the calculated compressive strength and experimental compressive strength with the admixture dosage. Therefore, the addition of admixtures can improve the workability of soil concrete and compressive strength.

Then, the effect of admixtures towards the compressive strength and the compressive strength variation with the age of soil-concrete with different cement percentages were investigated. The cubes were cast with a constant moisture percentage (18%) and constant admixture dosage (12 ml/kg cement) by varying the cement percentage from 14% to 20%.

The compressive strength variation is graphically presented in Figure 12. The results indicate that the admixture causes the increment of compressive strength. This compressive strength increment pattern follows the strength increment pattern of the soil concrete without admixtures. Based on the results, 18% of cement content is proposed as the best cement content considering the strength increment and the cost-effectiveness. The compressive strength variations within 90 days were investigated for selected cement percentages. The rapid increment of the compressive strength for the different cement contents for up to 10 days and a slight decrement of this variation was observed hereafter for up to 90 days, as shown in Figure 13.

Table 9 - Predicted and Observed Compressive Strength of Soil-Concrete with Selected Admixtures

Sample Code	Samples with admixture (AD1)(ml)	Expected compressive strength (N/mm^2)	Observed average compressive strength (N/mm^2)	Strength increment (N/mm^2)
A0	No admixture		14.34	
A1	3.00	14.20	15.1	0.9
A2	5.00	14.40	15.5	1.1
A3	7.00	14.60	15.9	1.3
A4	10.00	14.63	16.1	1.52
A5	12.00	14.73	16.3	1.60

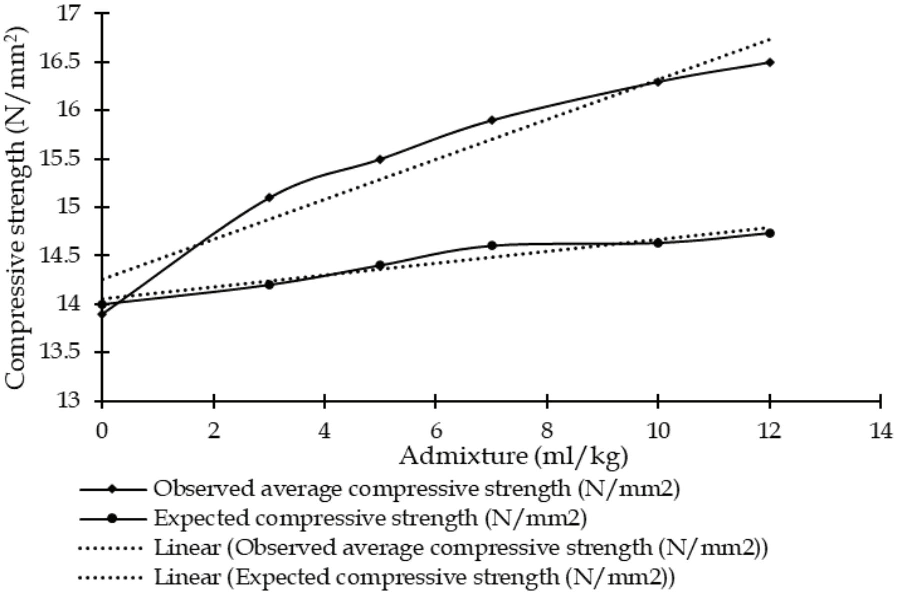

Figure 11 - Variation of Compressive Strength with the Admixture Dosage

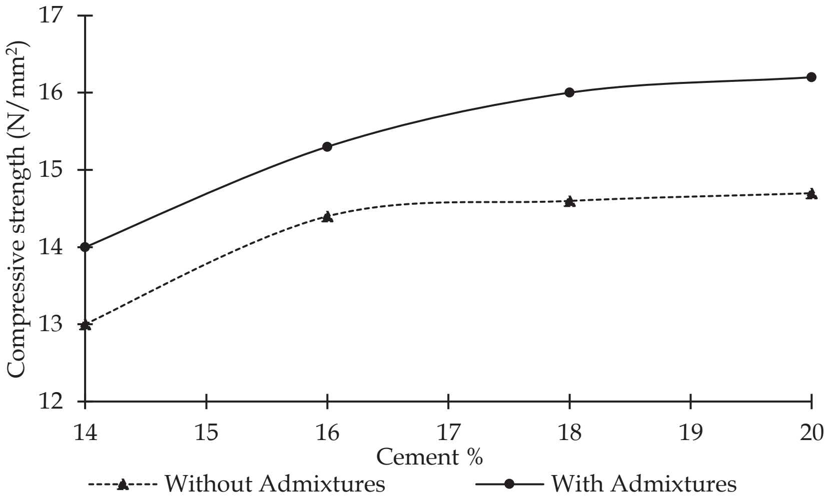

Figure 12 - Compressive Strength Variation with Cement Percentage

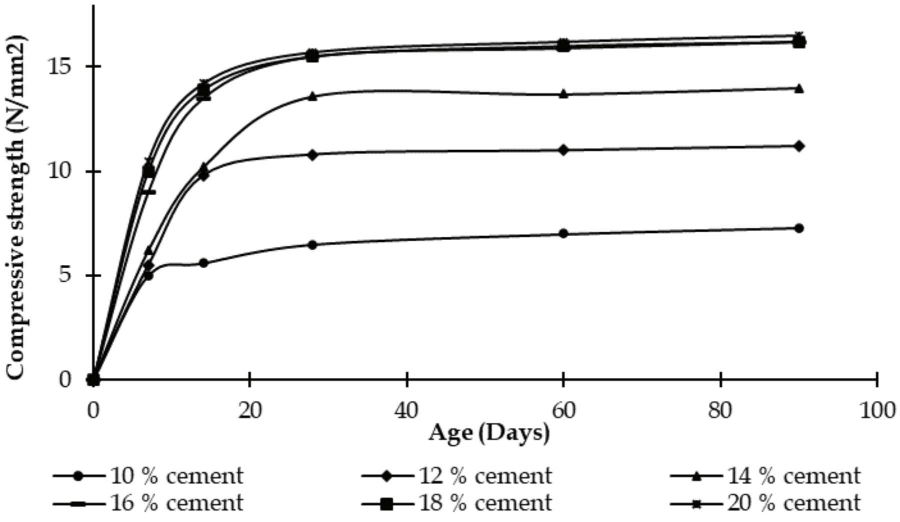

Figure 13 - Strength Variation within 90 Days

3. Conclusion

In this study, detailed investigations were conducted to identify the possibility of improving the soil as concrete. The soil was developed by stabilising with cement and mixing with water to produce soil concrete. The consistency of the soil needs to be identified to achieve high-strength soil concrete.

During the soil-concrete design process, the soil-concrete was prepared by varying the consistency of soil, cement content, and water requirement to enhance the compressive strength. According to the results obtained, it can be recommended to modify the native soil to have 5%–10% fines, 55%–71% sand, and 24%–40% gravel. The most suitable gravel size was found to be in the range of 4.75 -25 mm, and the most appropriate cement content was identified as 16%–18%, following the weight of dry soil. Moreover, 16% cement content is identified as the optimum value for the soil concrete. No further increment of compressive strength was observed with the increment of cement. The water content should be maintained at 18%–20%, following the weight of dry soil. Compressive strength can be enhanced by reducing the water content, however, workability can be reduced. Therefore, chemical admixtures were used to maintain the workability while reducing water content. Further, results proved that the compressive strength can also be improved by using chemical admixtures. The soil concrete produced according to the concluded mix design, concrete with characteristic strength of 15 MPa can be produced.

Finally, the authors concluded from this extensive study that the soil can be used to produce concrete where the strength requirement is less than grade 15 such as screed concrete for foundations, as floor concrete (tile bed), etc. This novel investigation can be considered an innovative concept for sustainability.

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