Civil Engineering Infrastructures Journal 2022, 55(2): 241-257
DOI: 10.22059/CEIJ.2021.319310.1742

RESEARCH PAPER

Effectiveness of Reusing Steel Slag Powder and Polypropylene Fiber on the Enhanced Mechanical Characteristics of Cement-Stabilized Sand

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Received: 18 Feb. 2021; Revised: 05 May 2021; Accepted: 17 May 2021

ABSTRACT: Waste generated by steel industry cases environmental and economic problems. Therefore, it becomes very important to utilize steel industrial waste material in a proper manner. One promising use for this huge amount of industrial waste is soil improvement. In this work, Unconfined Compressive Strength (UCS) tests were conducted to study the influence of steel slag on the mechanical characteristics of cement-stabilized sand. The UCS tests were conducted on the compacted specimens which prepared in the laboratory at their Optimum Moisture Content (OMC) and modified proctor Maximum Dry Density (MDD). The results indicate that use of steel slag powder as a partial replacement of chemical stabilizer such as cement in soil stabilization has advantages from economic, environmental and technical points of view. The highest value of UCS was observed in the sample containing 7.2% cement and 0.8% steel slag powder. Beyond optimum steel slag powder dosage, the UCS value decreased. The addition of polypropylene fiber into the specimens treated with cement or steel slag powder improves significantly the mechanical behavior of specimens and significantly increases the UCS and strain corresponding to the maximum compressive strength. The specimen containing 0.2% of polypropylene fiber, 6.4% of cement and 1.6% steel slag exhibits the highest UCS value when the sum of the amounts of cement and steel slag was 8%. The failure pattern of specimen indicates a transition from ductile to brittle behavior with addition of cement and steel slag. However, the addition of polypropylene fiber changes the brittle response of treated specimens to a more ductile behavior.

Keywords: Cement, Sand, Soil Stabilization, Steel Slag, Unconfined Compressive Strength.

1. Introduction

In situ soil improvement with pozzolanic additives and other agents is a method of improving the soil characteristics to solve the problem of civil construction. The effectiveness of the soil stabilization technique including physical stabilization and chemical stabilization depends on the mechanical characteristics of soil (Nicholson, 2014). Lime and cement are the oldest materials which used in

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soil stabilization. So far, extensive experimental studies have been done on the mechanical behavior soil stabilized with addition of cement or lime (Hosseini et al., 2014; Moghal et al., 2020; Deneele et al., 2016; Kwon et al., 2010; Kim et al., 2018; Yoon and Abu-Farsakh, 2009; Saeed et al., 2015; Yin et al., 2019; Bayat et al., 2013; Saadat and Bayat, 2019). The formation of cemented aggregates which is caused by chemical bonds in cement- or lime-stabilized soil would lead to improve the mechanical characteristics of the weak soil.

In the short stabilization period, the strength properties of stabilized soil could be significantly improved by filling the pore spaces and development of inter-cluster cementation bonding (Horpibulsuk et al., 2010). While the utilization of conventional stabilizers is well established in civil engineering projects, natural and synthetic fibers were also used as a reinforcement additives in cement-fiber composites to enhance the shear strength capacity and also reduce the swelling and compressibility potential (Eshaghzadeh et al., 2021; Anagnostopoulos et al., 2013; Tomar et al., 2020; Wei et al., 2018; Syed et al., 2020; Sharma, 2018; Eldesouky et al., 2016). Various synthetic fibers such as polyester fiber, polyethylene fiber, basalt fiber, and polypropylene fiber with a higher durability than the natural fibers have been used in the soil reinforcement applications (Hejazi et al., 2012). Polypropylene fiber is a synthetic fiber which is made by extrusion of a thermoplastic polymer of propylene. Polypropylene fiber is an effective additive to enhance the shear strength characteristics and ductility of cement-based materials (Olgun, 2013).

The Unconfined Compressive Strength (UCS) test is one of the major and convenient laboratory method to investigate the strength characteristics of cohesive or stabilized specimens (Eme et al., 2016). Tang et al. (2007) indicated that the UCS value, shear strength parameters, and failure strain increased when the fiber added to the cement-stabilized specimen. Sharma (2018) studied the geotechnical characteristics of dredged reservoir material which stabilized with a mixture of fiber, cement and fly ash. They showed that UCS or split tensile strength increased after stabilization and it improved further with addition of fiber.

The formulation of cement causes severe environmental pollution (Uwasu et al., 2014). The use of waste materials such as steel slag as a partial replacement for chemical stabilizer such as cement in geotechnical projects can be useful for environmental management. Many efforts have already been initiated to reduce the use of cement in soil stabilization to avoid environmental issues. Previous studies indicated that pozzolanic materials such as natural pozzolan and fly ash could be used to soil stabilization materials projects which can be useful for environmental management (Haddad et al., 2020; Salamatpoor et al., 2018; Mousavi and Wong, 2016; Vakili et al., 2013; Kumar, 2011; Stefanidou et al., 2017; Cheng et al., 2018). Most recently studies have been made to reduce the industrial wastes (Hanumantharao and Ramana, 2008; Rajput, 2018; Grenney et al., 1990). Researchers have been challenged to convert industrial wastes to construction materials. This includes soil stabilization (Gholipoor Norozi et al., 2015; Al-Bared et al., 2018; Panfilova et al., 2020; Salehi et al., 2021), concrete additives (Kim et al., 2020; Al-Bared et al., 2018), and road construction applications (Fırat et al., 2012; Jafar, 2016; Singh et al., 2018; Li et al., 2019).

Steel slag is a solid waste and one among the industrial by-products available in large quantity which is generated during the iron refining process. Steel slag has been utilized in previous studies as road and building materials (Baalamurugan et al., 2019; Dhoble and Ahmed, 2018; Yi et al., 2012; Kumar and Varma, 2020; Siddique et al., 2020). Shen et al. (2009) used steel slag and other solid wastes as effective additives for road base material. They indicated that the composite has higher early strength than the other composites having lime-fly ash or lime-soil. It has also higher the long-term shear strength than the composite contaninig cement. Wu et al. (2019) used waste steel slag as alternative material to modify expansive soil properties. Mozejko and Francisca (2020) showed that the utilization of steel slag in the compaction of clay soils as a new and cost effective approach which resulted in significant increase of UCS. Bahadori et al. (2019) studied using of natural pozzolan for stabilization of marl soil. The tests results indicated that the efficiency of stabilized marl soil increases and the expansion and ductility decreases due to increasing volcanic ash content. Bahadori et al. (2019a) investigated the effects of fly ash content and volcanic ash content on the mechanical behaviour of peat soils using UCS and CBR tests. The results showed that UCS of specimens increases due to addition of fly ash or volcanic ash. Furthermore, the CBR results showed that the filling property of the stabilizer (fly ash and volcanic ashes) can be useful as its pozzolanic activity for soil stabilization. Zare et al. (2020) investigated the effect of waste tire textile fibers on the mechanical behaviour of cement-stabilized specimens. The results showed that waste tire textile fibers can be used with and without additive cement to improve the strength and brittle response of rammed earth structures.

Lang et al. (2020) studied the influences of cement content and type, acid content, steel slag powder content and curing period time on the strength characteristics of cement stabilized specimens. The results showed that the cement content and type have important effects on the mechanical characteristics of cement-steel slag-stabilized specimens. The results indicated that the use of 5% to 10% steel slag powder could be benefit to increase the strength characteristics of cement-stabilized dredged sludge, but for stabilized specimens containing HA, the 15-20% steel slag powder was recommended. The microstructural analyses by scanning electron microscopy indicated that the addition of steel slag powder can contribute to increase of cementitious matrix products in stabilized specimens.

As maintained above, most previous studies have focused on the mechanical characteristics of cement-stabilized specimens when cement replaced by industrial waste material. In other words, the effect of addition of different amounts and types of fibers on the mechanical behaviour of specimens treated with cement and steel slag powder has not been widely studied. The objective of this study is the utilization of steel slag, polypropylene fiber and cement for soil stabilization. The UCS were conducted on specimens with various steel slag, polypropylene fiber and cement contents.

2. Experimental Program

2.1. Materials and Testing Program

So far, many researchers have proved that the UCS is a strength index which has strong positive relationship with resistance of cohesive or stabilized-soils. In this study, a series of UCS tests were performed on stabilized specimens of Varzane sand. The soil collected from the Varzaneh desert in Isfahan, Iran. The grain-size distribution curve of Varzaneh sand is presented in Figure 1. Table 1 shows the physical and geotechnical properties of Varzaneh sand. According to the Unified Soil Classification System (USCS), Varzaneh sand is classified as poorly graded sand (SP).

Table 1. Physical and geotechnical properties of soil

Characteristics	Values and descriptions
Specific gravity	2.66
Passing No. 200 sieve (%)	4
Plasticity index (%)	NP
Unified Soil Classification System (USCS)	SP
Optimum water content (%)	8
Maximum dry unit weight (kN/m^3)	17.8

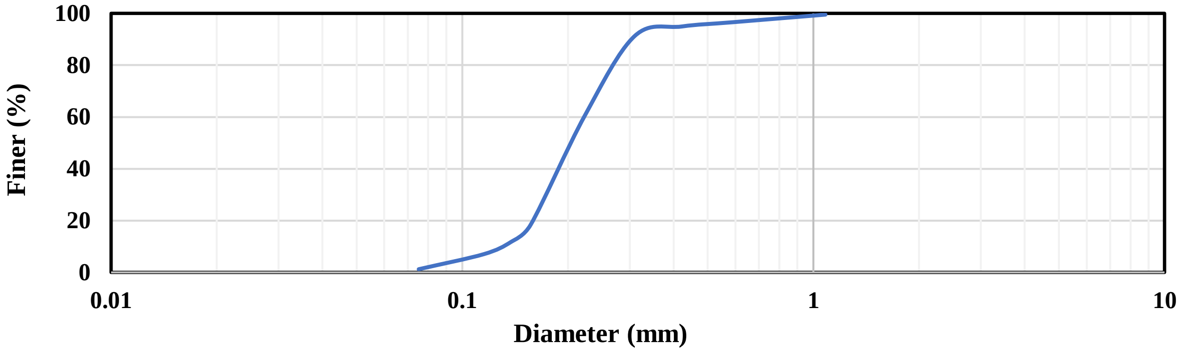


Fig. 1. Grain-size distribution curve of Varzaneh sand

Polypropylene fiber was used for reinforcing the cement-stabilized specimens. The physical and mechanical properties of the polypropylene fiber is presented in Table 2. Ordinary Portland cement was also used in the testing program for stabilization. The physical and chemical properties of cement are shown in Table 3. In this study, Electric Arc Furnace (EAF) steel slag waste produced in Mobarakeh steel company (located in Isfahan, Iran) was used. X-ray diffraction (XRD) technique was used for structural characterization and mineralogical composition of the steel slag. The chemical composition of Mobarakeh EAF steel slag is shown in Table 4. The steel slag was crushed in a laboratory then sieved. The particle size fraction finer than 149 µm was used for this work.

The mechanical behavior of treated specimens has been investigated in this work. For this purpose, an experimental program comprising UCS tests was conducted. The effects of cement content, steel slag content, and polypropylene fiber content on the mechanical behavior of specimens have been investigated. Table 5 shows a summary of the performed tests. The first and second groups of the tests were intended to evaluate the effects of addition of cement or steel slag on the mechanical behavior of reinforced specimens.

Table 2. Physical and mechanical properties of the Polypropylene fiber

Property	Values
Cut length (mm)	12
Filament diameter (µm)	13
Density (g/cm^3)	0.915
Elastic modulus (GPa)	5.51
Tensile strength (MPa)	680

Table 3. Physical and chemical properties of cement

Property/composition	Value
Specific gravity	3.14
Specific surface area (m^2/kg)	320
CaO (%)	60.4
SiO_2 (%)	15.9
Al_2O_3 (%)	9.5
SO_3 (%)	6.4
Fe_2O_3 (%)	4.1
MgO (%)	0.9
K_2O (%)	0.7
TiO_2 (%)	0.1

Table 4. Chemical composition of Mobarakeh EAF steel slag

Composition	Value (%)
FeO	29.8
CaO	31.2
SiO_2	19.2
MgO	12.2
AL_2O_3	4.1
MnO	0.6
P_2O_5	0.5

Table 5. A summary of the test details

Test Group	Cement content (%)	Steel slag content (%)	Polypropylene fiber content (%)
Group-1	0, 0.5, 1, 1.6, 1.8, 2	0, 0.2, 0.4, 1, 1.5, 2	0
Group-2	0, 2, 4, 6.4, 7.2, 8	0, 0.8, 1.6, 4, 6, 8	0
Group-3	2, 8	0	0, 0.1, 0.2, 0.5, 1
Group-4	0	2, 8	0, 0.1, 0.2, 0.5, 1
Group-5	1, 1.6, 4, 6.4	0.4, 1, 1.6, 4	0.1, 0.2

As shown from Table 5, in the first and second groups, steel slag has been partially replaced instead of cement. The third group of tests was performed to study the effect of cement and fiber contents on the UCS of specimens. The fourth group of tests was to study the effect of steel slag and fiber contents. The last group of tests was performed to investigate the effect of cement, steel slag and fiber contents on the UCS of treated specimens with varying contents of additives. It is worth noting that all specimens were subjected loading after 28 days of curing.

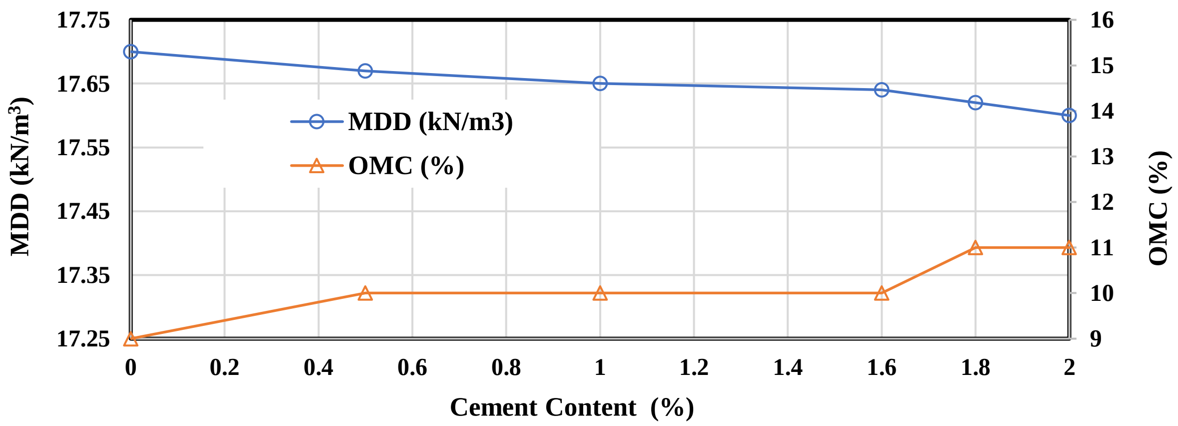
2.2. Specimen Preparation and Testing Method

In this work, the modified Proctor compaction tests were conducted to study the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of specimens containing various additives (cement, steel slag and polypropylene fiber) in accordance with ASTM D1557. UCS tests were also performed for remolded specimens prepared in the laboratory at OMC and MDD using a cylindrical mould with height and diameter of 20 cm and 10 cm, respectively. Afterwards, the materials were first dried and then the required amounts of soil, steel slag and fibers were calculated and weighted. The required amounts of additives and soil were mixed before the OMC was added. The required water content was added into the specimen to reach the OMC of each specimen based on the modified Proctor results. The specimen was compacted into the UCS mould into ten layers and then the specimen was taken out of the mould. The compacted specimen was wrapped in sealed container and cured in a curing room for 28 days with 95% humidity and 23 ± 2 °C temperature. In this work, the UCS tests were performed on the specimens after curing time of 28 days.

3. Results and Discussion

3.1. Compaction Characteristics

The results of compaction tests indicated that cement content has a more important effect than steel slag content on OMC and MDD. Steel slag content has not important influence on the OMC and MDD of specimens treated with steel slag. The results of compaction tests of specimens treated with steel slag and cement are presented in Figure 2. The results show that adding more cement slightly decreases the MDD and increases the OMC. At the addition of 8% cement, the maximum value of OMC and the minimum value of MDD were obtained. Generally, the MDD of the specimens treated with steel slag and cement is lower than that of untreated soil. However, the OMC of the treated specimens is higher than that of untreated soil. Figure 3 shows the variation of OMC and MDD of specimens treated with cement and polypropylene fiber. As shown from the results, the OMC and MDD decrease with increase of polypropylene fiber content. Increasing cement content from 2% to 8% leads to decrease MDD and increase OMC for a given polypropylene fiber content.



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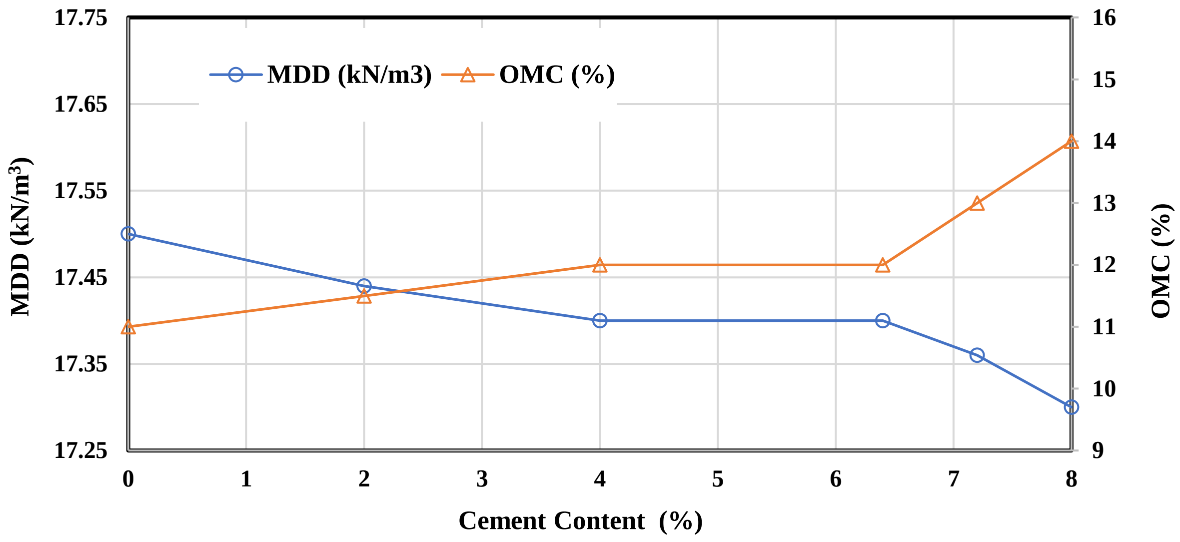

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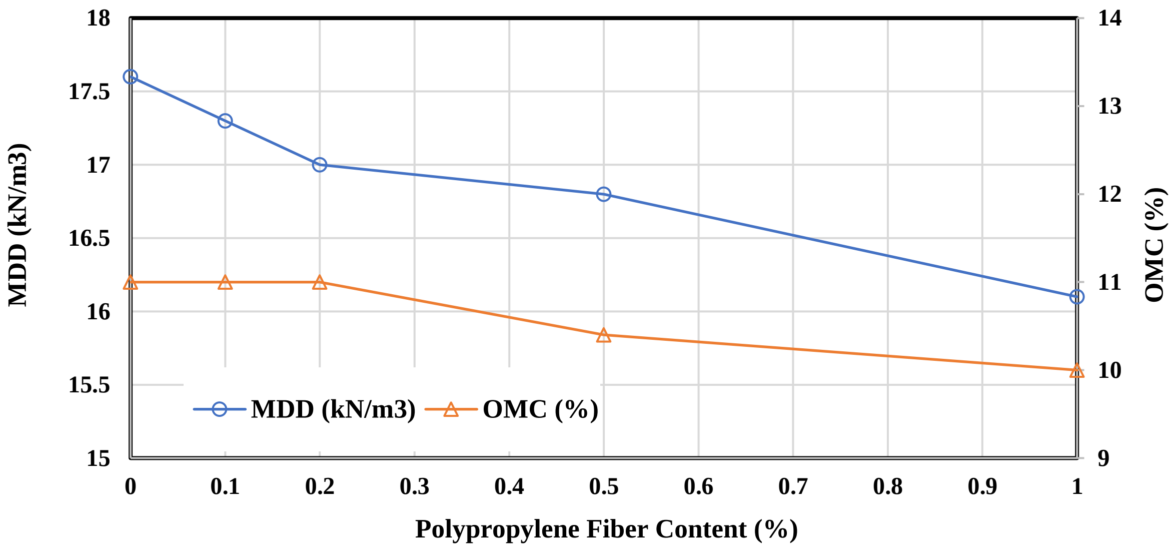
Fig. 2. Variation of OMC and MDD of specimens treated with cement and steel slag: a) Additive content of 2%; and b) Additive content of 8%



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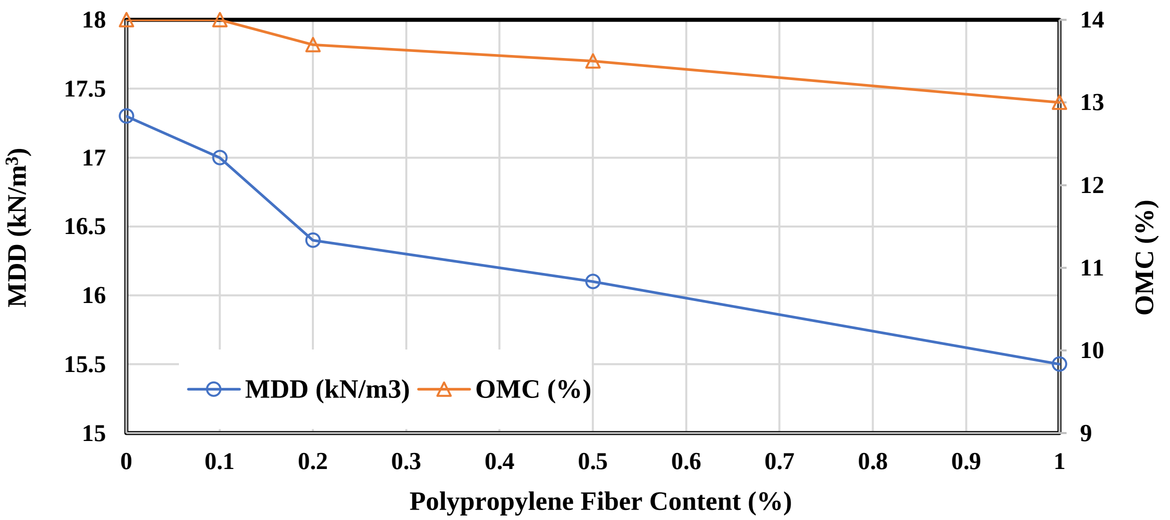

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Fig. 3. Variation of OMC and MDD of specimens treated with cement and polypropylene fiber: a) Cement content of 2%; and b) Cement content of 8%

3.2. Unconfined Compressive Tests

In this study, the controlling parameters evaluated were cement content (C), steel slag content (S), and polypropylene fiber content (P). Figures 4a and 4b show the axial stress versus axial strain curves during unconfined compressive tests for the 2% and 8% additives (steel slag and cement) content, respectively. The UCS and strain corresponding to the maximum compressive strength of specimens either increase or decrease when cement replaced by steel slag powder depending on cement and steel slag contents. The UCS values of specimens treated with steel slag and cement are presented in Figure 5. As shown from the results, compressive strength increases when cement replaced by 20% (the specimen containing S=0.4% and C=1.6%) or 10% (the specimen containing S=0.8% and C=7.2%) of steel slag for the 2% and 8% additives contents, respectively. Similar results have been reported by previous studies when cement replaced by other waste materials (Ilieş et al., 2017; Jayasinghe et al., 2016; Ahmadi Chenarboni et al., 2021; Haddad et al., 2020; Kordnaeij et al., 2019).

The axial stress versus axial strain curves of cement stabilized specimens obtained from the unconfined compression tests are presented in Figure 6. It can be seen from the results that the strain corresponding to the maximum compressive strength of the cement stabilized fiber-reinforced specimens is higher than that of the specimens treated with cement and steel slag, and increases as polypropylene fiber content increases. The cement-stabilized specimen reinforced with 1% polypropylene fiber has the highest strain corresponding to the maximum compressive strength. The UCS values of improved specimen with cement and fiber are shown in Figure 7.

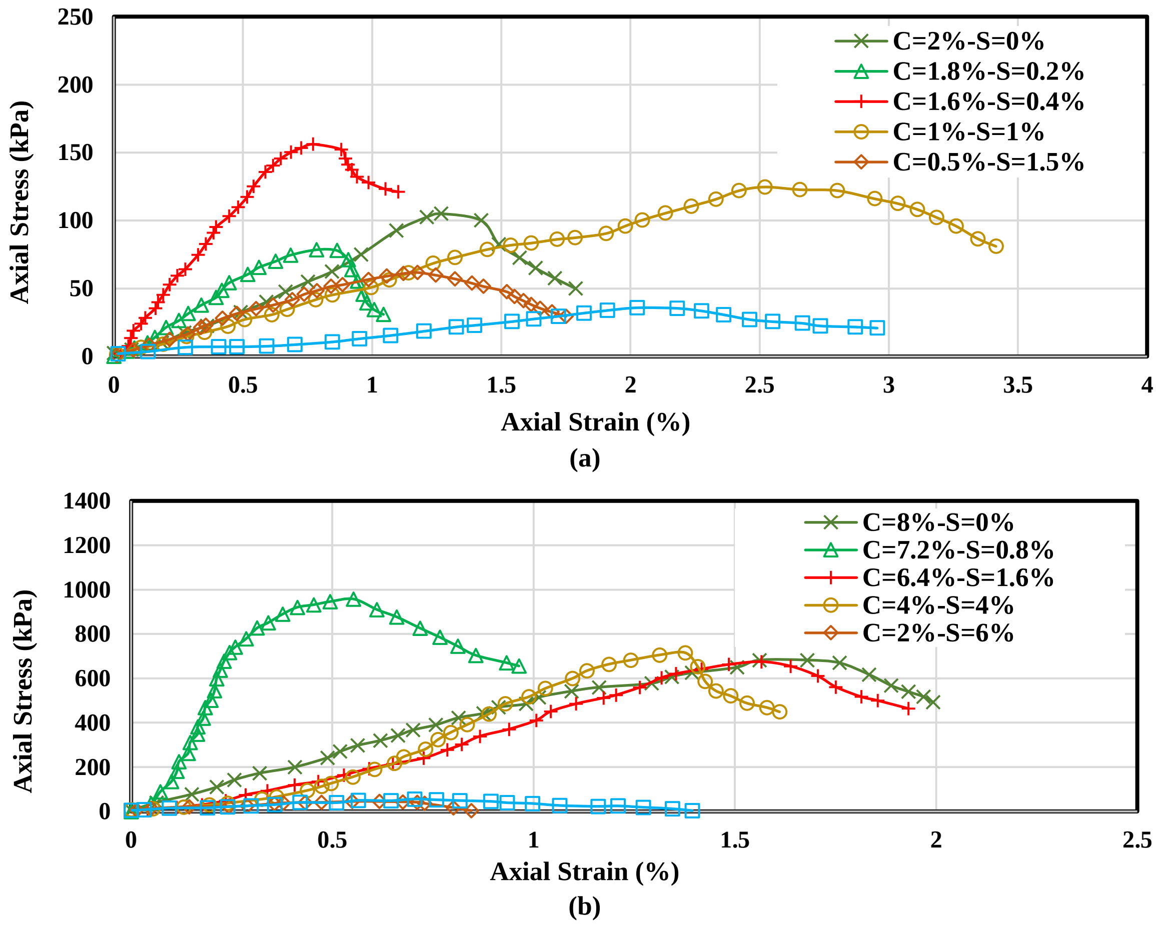
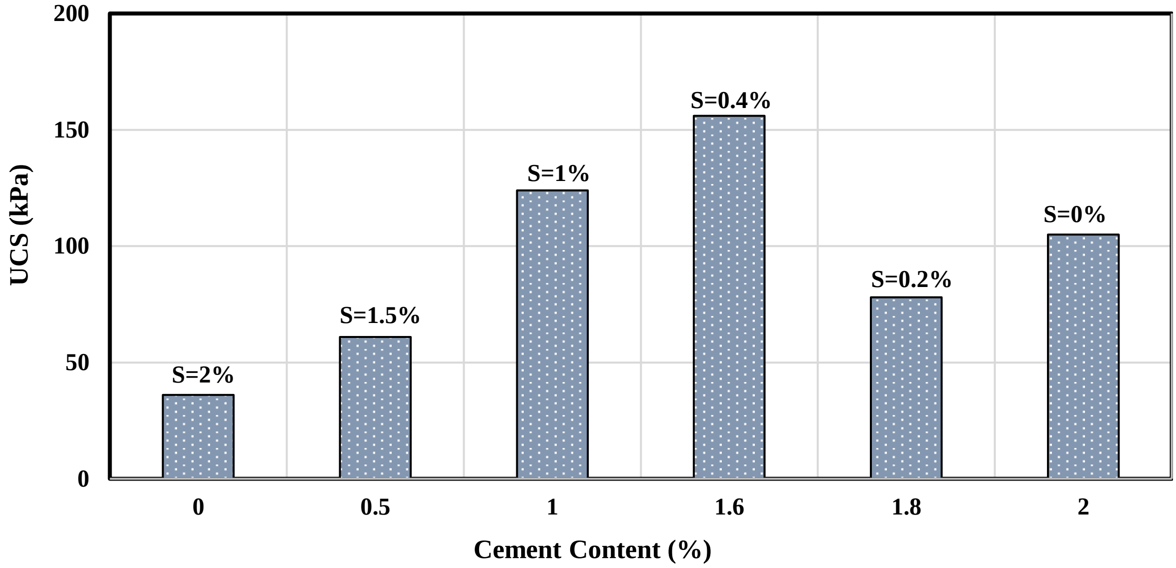


Fig. 4. Stress-strain curves of the specimens treated with cement and steel slag mixture: a) Additives content of 2%; and b) Additives content of 8%



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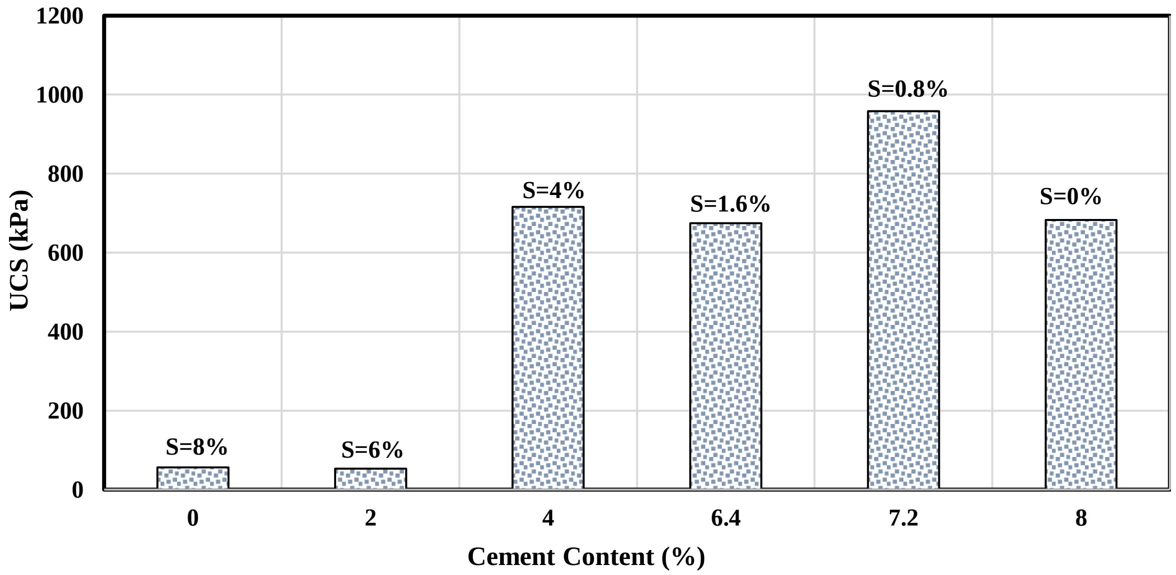

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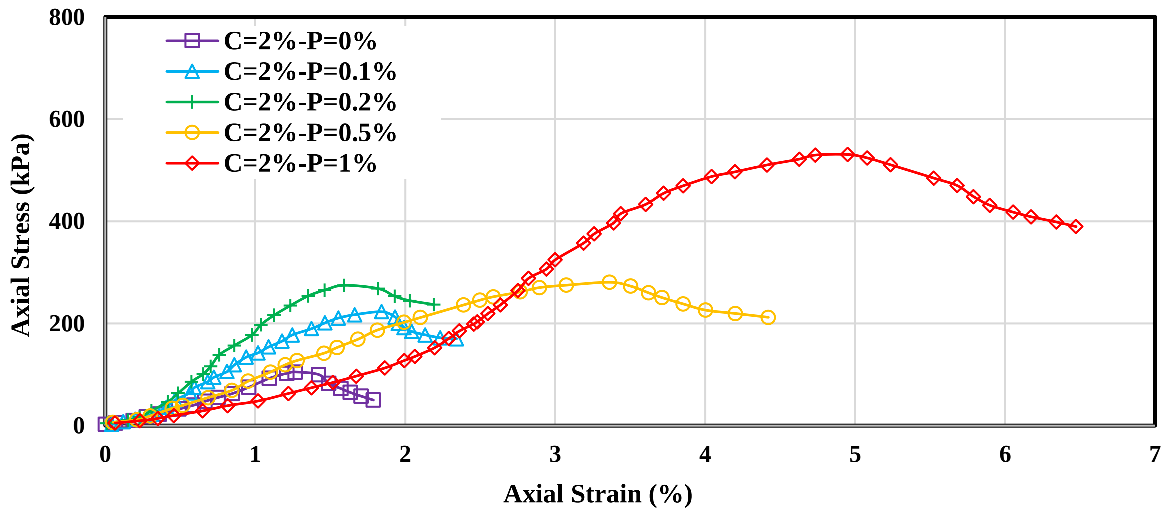
Fig. 5. UCS values of the specimens treated with cement and steel slag mixture: a) Additives content of 2%; b) Additives content of 8%



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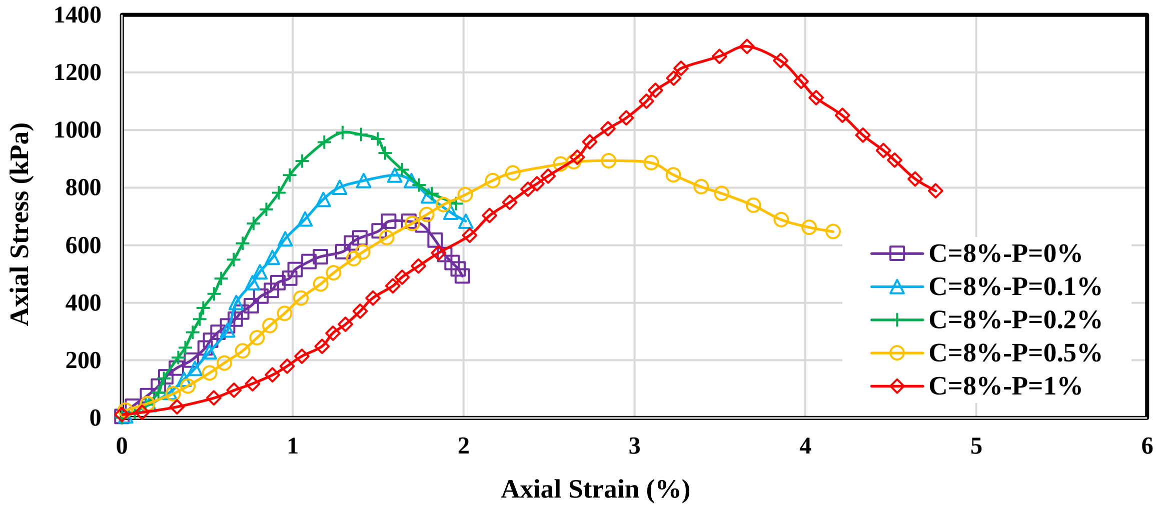


(b)

Fig. 6. Stress-strain curves of the fiber-reinforced cement-stabilized specimens: a) Cement content of 2%; b) cement content of 8%

As shown, the UCS values of cement-stabilized polypropylene fiber-reinforced specimens are greater than those of cement-stabilized specimens. The simultaneous use of cement and polypropylene fibers as an effective method to improve the mechanical behaviour of soils has been suggested by previous studies (Arabani and Haghsheno, 2020; Wang et al., 2020; Park, 2011; Khattak and Alrashidi, 2006; Kaniraj and Havanagi, 2001; Park, 2009). A comparison between Figures 5 and 7 reveals that the addition of polypropylene fiber lower than 1% is not effective compared to the case where cement is replaced with steel slag. However, the UCS values increased significantly when fiber content was further increased to 1%.

Figures 8 and 9 show the axial stress versus axial strain curves and the corresponding UCS values of treated specimens with varying contents of steel slag and polypropylene fiber, respectively. Although the addition of steel slag and fiber increased the UCS, the UCS values of all specimens treated with steel slag and fiber mixture are much smaller than those of specimens treated with cement and fiber mixture. Here too, the specimens containing 1% polypropylene fiber have the highest UCS values.

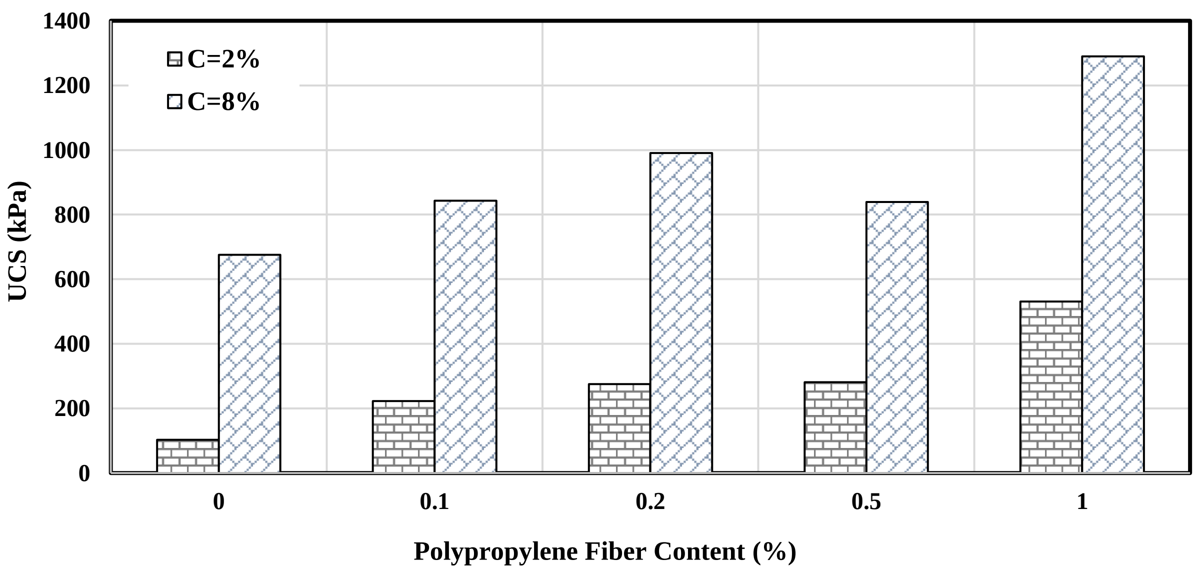
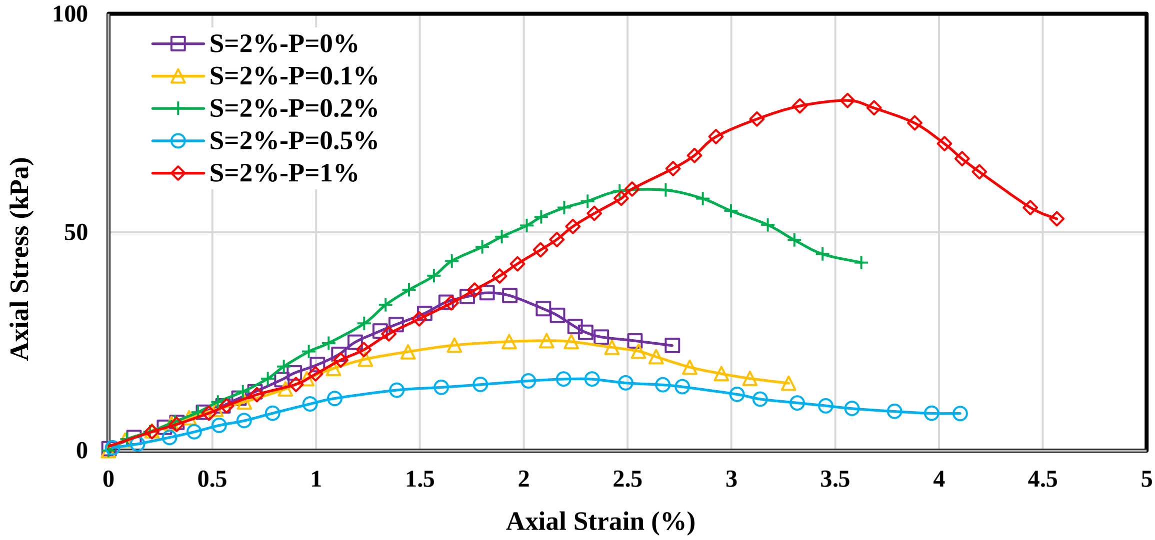


Fig. 7. UCS values of the fiber-reinforced cement-stabilized specimens



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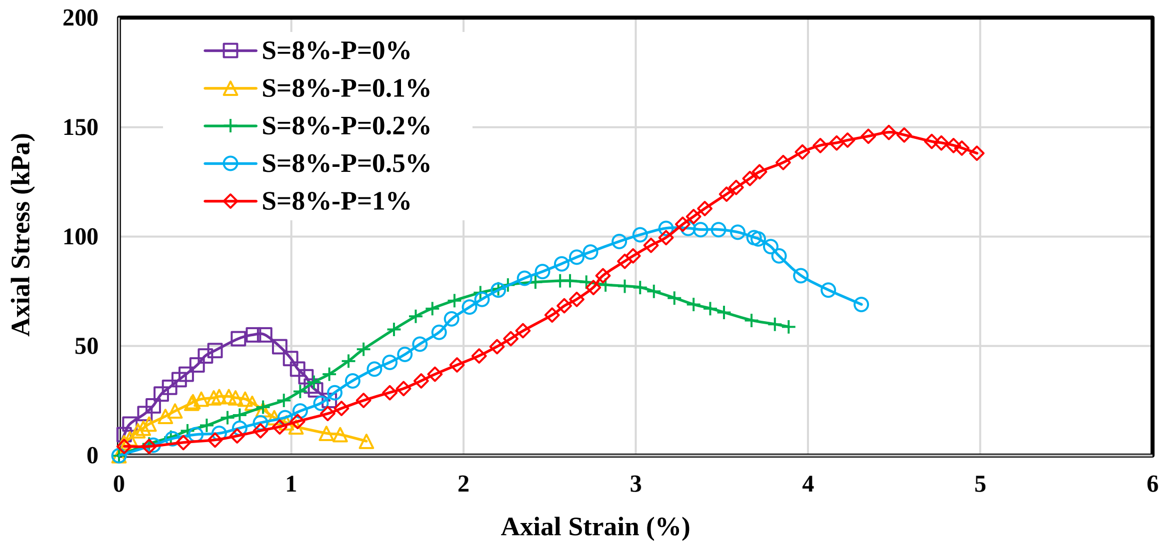

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Fig. 8. Stress-strain curves of the fiber-reinforced steel slag-stabilized specimens: a) Steel slag content of 2%; b) Steel slag content of 8%

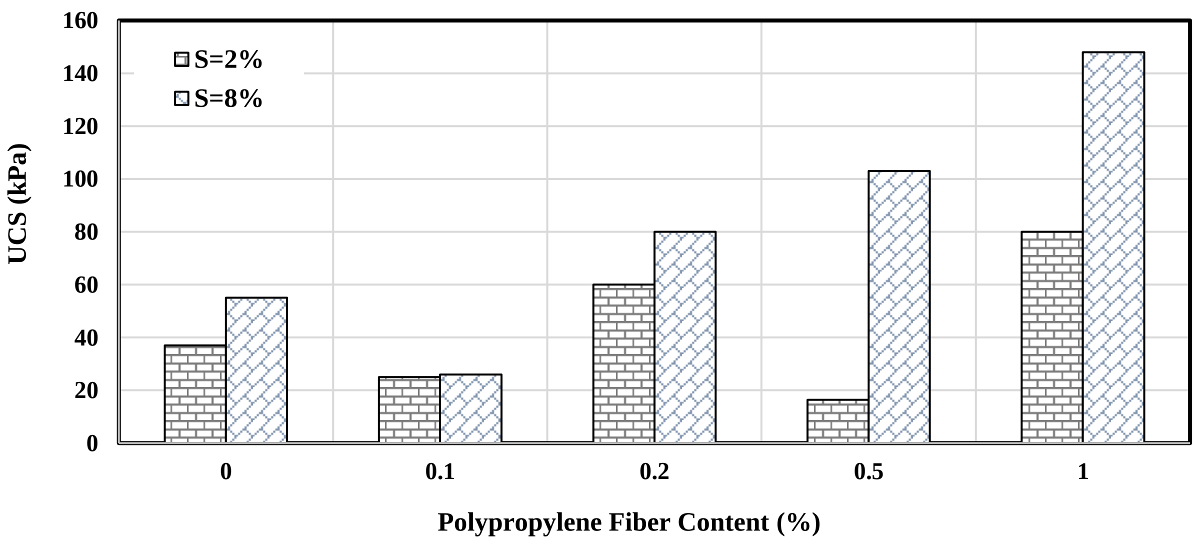
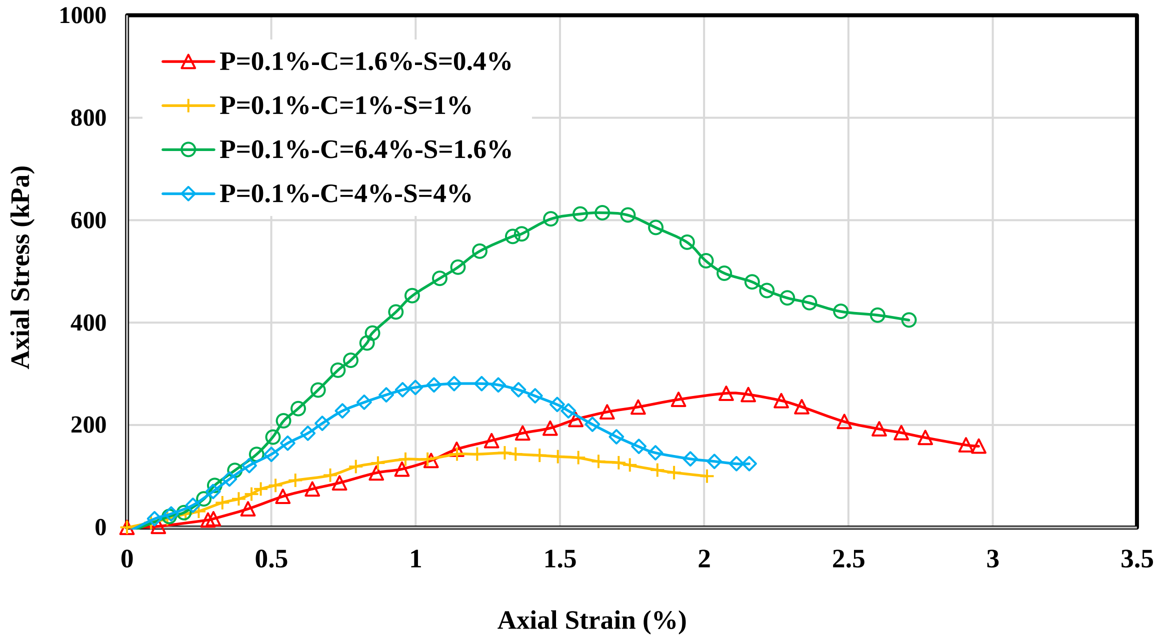


Fig. 9. UCS values of the fiber-reinforced steel slag-stabilized specimens

The axial stress versus axial strain curves of treated specimens with varying contents of steel slag, cement and polypropylene fiber contents are shown in Figure 10. The corresponding values of the UCS are also presented in Figure 11. As shown from the results, the brittleness of the specimens is reduced and ductility and UCS enhanced obviously with higher polypropylene fiber content. It can be conducted from the results that the specimen containing 0.1% of polypropylene fiber,1.6% of cement, and 0.4% steel slag exhibits the highest UCS value when the sum of the amounts of cement and steel slag was 2%. On the other hand, the specimen containing 0.2% of polypropylene fiber, 6.4% of cement, and 1.6% steel slag exhibits the highest UCS value when the sum of the amounts of cement and steel slag was 8%.



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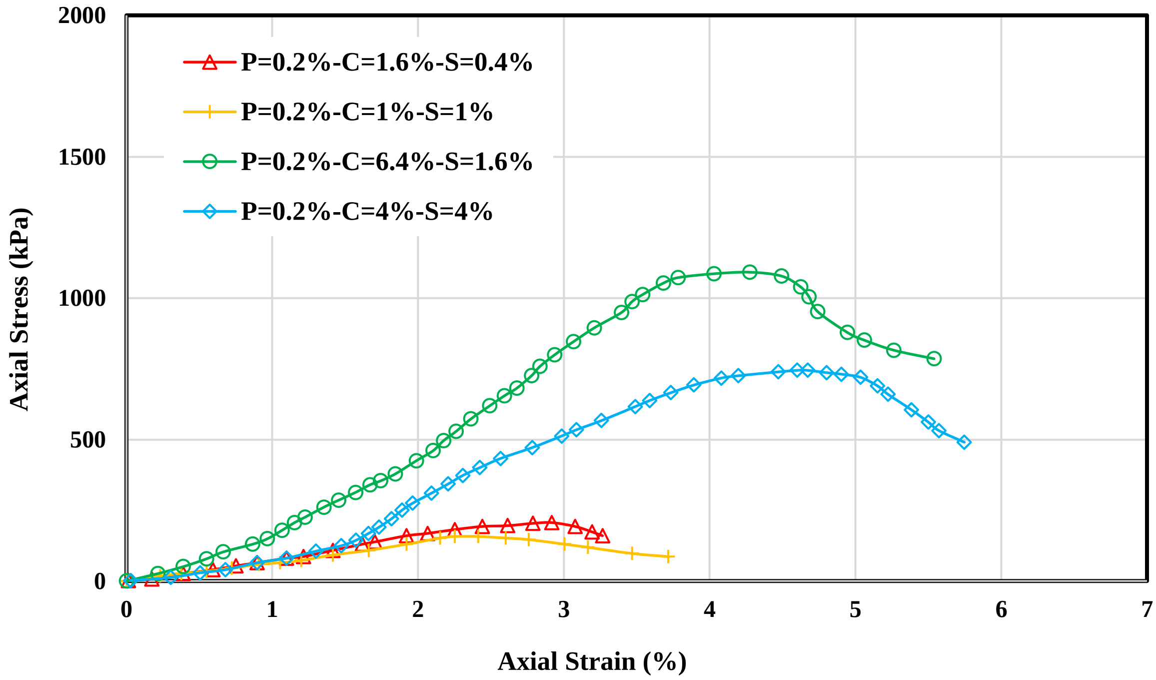

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Fig. 10. Stress-strain curves of the specimens treated with fiber, cement and steel slag mixture: a) Fiber content of 0.1%; b) Content of 0.2%

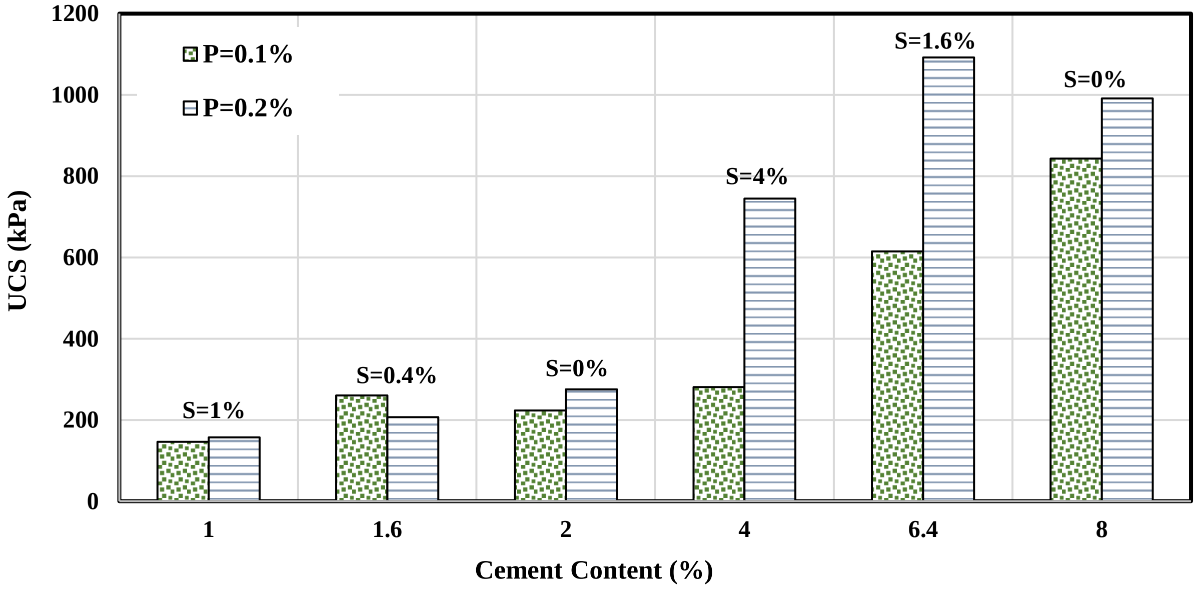


Fig. 11. UCS values of the specimens treated with fiber, cement and steel slag mixture

3.3. Failure Patterns of Specimens

The compressive failure patterns and fracture resistance of fiber-reinforced or cement-stabilized specimens under axial loading are a macro embodiment of the variation of deflection and internal particles stresses (Yang et al., 2017). Thus, it is necessary to study the failure patterns of specimens. The failure patterns of stabilized specimens with cement and steel slag powder are presented in Figure 12. The failure mechanisms of steel slag-stabilized specimens, specimens treated with fiber and cement and specimens treated with fiber, steel slag and cement are shown in Figure 13.

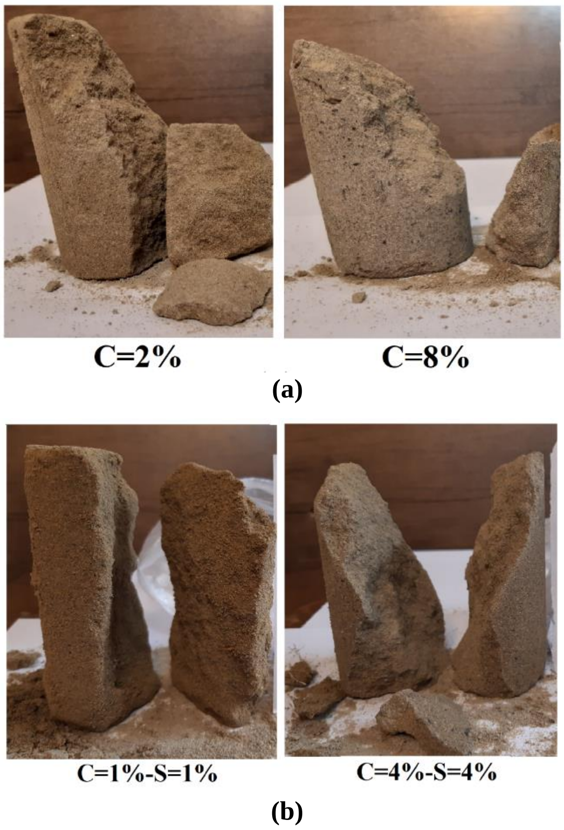
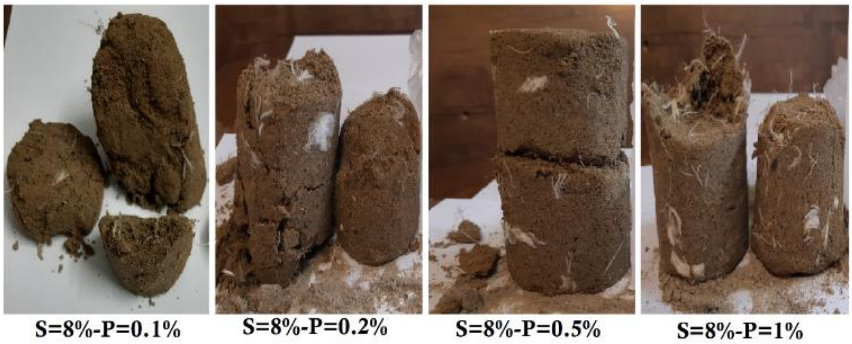


Fig. 12. Failure patterns of the: a) Specimens treated with cement; and b) specimens treated with cement and steel slag mixture

As shown in Figure 12, the longitudinal cracks have been formed in the cement-stabilized and cement-steel slag-stabilized specimens. The cracks developed rapidly through the specimen. As shown from the results, the cracks became longer and deeper from the surface. The specimens exhibited loose structure accompanied by debris and soil blocks. The results indicate a transition from ductile to brittle response due to addition of cement and steel slag. As shown in Figure 13, thin and dense cracks have been formed in the specimens containing fibers. The results show that the brittle failure characteristics of the specimens have been significantly improved by addition of fibers. Polypropylene fibers showed an apparent ‘bridging’ function and could form a stable three-dimensional network in the fiber-reinforced soil, which was able to disperse the stress and prevent the development of cracks effectively. Previous studied have been reported that the addition of fibers modified the pattern of fracture in the specimens from brittle to ductile (Yang et al., 2017; Kaniraj and Havanagi, 2001; Estabragh et al., 2012; Correia et al., 2015).

3.4. Microstructures of Specimens

In this work, the microstructures of treated specimens were studied by SEM analysis. SEM images obtained from cut-up sections of steel slag-stabilized specimen, cement-stabilized specimen, and fiber-reinforced cement-stabilized specimens. SEM images are presented in Figure 14. The SEM images were taken after curing of 28 days. As shown in Figure 14, the sand particles are coated by the cement or steel slag paste. It can be observed that the sand is composed of angular to subangular particles, while the surface of the polypropylene fibers is almost smooth. Some sand particles interlock with the polypropylene fiber surface and improve the interaction between the polypropylene fibers and sand particles. The soil particle and polypropylene fiber surfaces are enwrapped by the cement paste and the surface of the polypropylene fiber is rough with pronounced scales. The sand and polypropylene fiber are connected by the cement membrane thus to shape firmly together as a whole. It can be seen that the cement paste covered the surfaces of sand particles and increased the interlocking force between sand particles.



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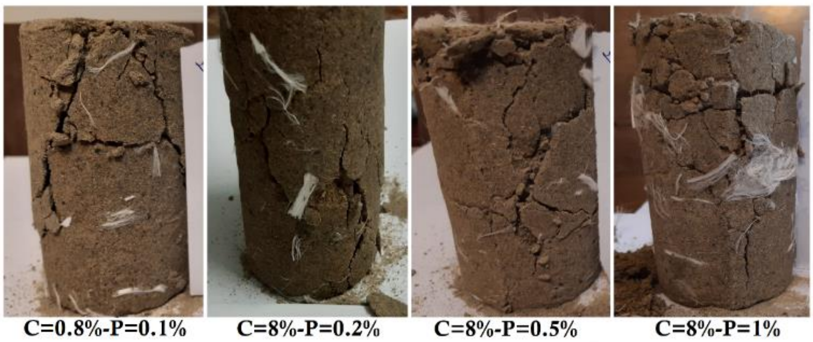
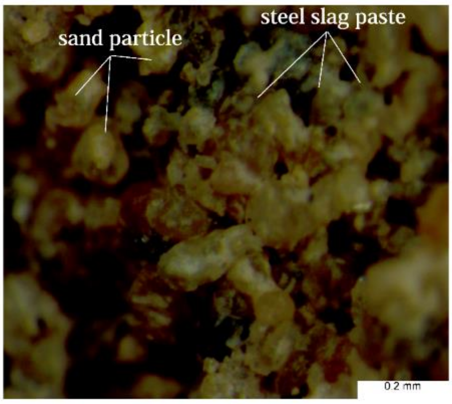


(b)

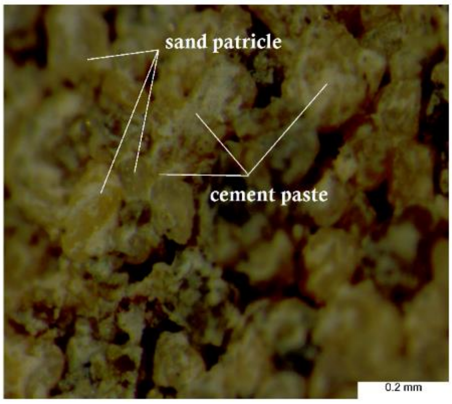
P=0.2% C=1.6% S=0.4% | P=0.2% C=1% S=1% | P=0.2% C=6.4% S=1.6% | P=0.2% C=4% S=4%

(c)

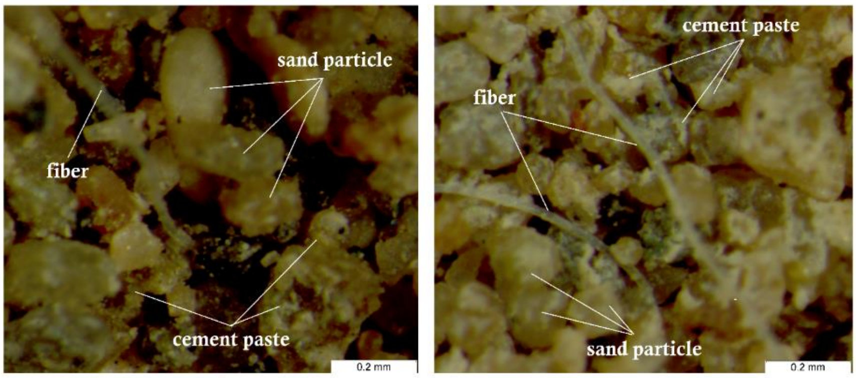
Fig. 13. Failure patterns of the: a) Specimens treated with steel slag and fiber mixture; b) Specimens treated with cement and fiber mixture; and c) Specimens treated with cement, steel slag and fiber mixture



(a) S=8%



(b) C=8%



(c) C=8%-P=1%

Fig. 14. SEM images of specimen treated with: a) Steel slag; b) Cement; and c) Cement and fiber mixture

4. Conclusions

The application of industrial wastes such as steel slag for civil projects with environmentally friendly can be useful for environmental protection. The use of steel slag powder in civil project such as soil stabilization has many economic and environmental benefits. In this paper, a series of UCS tests was done to investigate the effects of steel slag powder, cement and polypropylene fiber contents on the mechanical behavior of treated specimens. Based on the experimental results, the following conclusions were reached:

- The UCS of stabilized specimens could be improved strongly by the cement-steel slag mixture. While the total additives (cement and steel slag) content is a constant, the UCS of specimens first increases and then has a downward trend when the cement content increases. Hence, beyond optimum steel slag powder dosage, the UCS value decreased. The sample treated with 7.2% cement and 0.8% steel slag powder has a highest UCS of 958 kPa. Furthermore, the UCS values of treated specimens increase with increasing additives content from 2% to 8%.
- The addition 1% polypropylene fiber in the specimens treated with cement, steel slag powder or a mixture of them improves significantly the mechanical behavior of specimens. In other words, the addition of polypropylene fiber increases UCS and the strain corresponding to the maximum compressive strength.
- Polypropylene fiber content has significant effect on the UCS value of specimens treated with a mixture of cement, steel slag powder when additives (steel slag and cement) content increases from 2% to 8%. The specimen containing 0.2% of polypropylene fiber, 6.4% of cement, and 1.6% steel slag exhibits the highest UCS value when the sum of the amounts of cement and steel slag was 8%. Greater cement content of up 6.4% resulted in considerable drop in compressive strength.
- The longitudinal cracks have been formed in the specimens treated with cement, steel slag powder or a mixture of them. A transition from ductile to brittle behavior was observed due to addition of cement and steel slag. The specimen's brittle failure characteristics have been improved significantly due to addition of polypropylene fibers.

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