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RESEARCH PAPER

A Study on Geotechnical Behavior of Municipal Solid Waste Ash Treated with Fiber and Cement

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ABSTRACT: The geotechnical properties of untreated Municipal Solid Waste (MSW) ash and the MSW ash treated with fiber and cement were investigated through a series of laboratory tests including compaction, Unconfined Compressive Strength (UCS), and Split Tensile Strength (STS) with different mixing proportions of fiber and cement. The physical characteristics of MSW ash are similar to those of silty sand, with a specific gravity of 2.26. The combination of fiber and cement is capable of improving the compaction behavior of MSW ash by increasing its strength and reducing its tendency to deform or crack under the load. It is observed from the test study that the addition of 0.5% fiber of 12 mm length with 8% cement by weight of MSW ash mix gives the optimum result in terms of UCS and STS as compared to untreated MSW ash. The increment in cohesion (c) and angle of internal friction (ϕ) is associated with the increment in cement and fiber content, respectively. An improvement factor (I_f) is defined to determine the percentage increment in the value of UCS and STS.

Keywords: Municipal Solid Waste Ash, Compaction Behavior, Unconfined Compressive Strength, Improvement Factor.

1. Introduction

Municipal Solid Waste (MSW) is produced annually in millions of metric tons. As a result, many nations place a high priority on managing waste. On the outskirts of cities and towns, MSW has been found to be dumped without any restrictions. The ecosystem, as well as the health of people and animals, are seriously harmed by this dumping. Landfills and open dumps are the most common waste disposal methods worldwide (Nanda and Berruti, 2021).

According to Control Pollution Control Board (2021), the total amount of solid waste produced in India is 160038.9 Tons Per Day (TPD), of which 152749.5 TPD is collected with a collection efficiency of 95.4%, 79956.3 TPD is processed, and 29427.2 TPD is landfilled. 50655.4 TPD, or 31.7% of the total waste produced, is still unaccounted (Central Pollution Control Board, 2021). To deal with the huge amount of waste, incineration was selected as a treatment option at the Waste-To-Energy (WTE) plant, because it reduces the volume of waste by 60-70%, depending on the incineration method used and the type of waste (Kumar et al., 2023).

Incineration of MSW indeed requires

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high temperatures ranging from approximately 850 to 1100 °C, along with an adequate air supply to ensure proper mixing of the gas stream. This high-temperature incineration process is essential for achieving complete combustion, reducing the volume of waste, and minimizing the emission of harmful pollutants (Lam et al., 2010).

Various WTE technologies for the effective management of MSW, taking into consideration aspects of technology, sustainability, and economy, have been reviewed by Kumar and Samadder (2017). Anaerobic digestion, pyrolysis, gasification, incineration, and landfill gas recovery are among the WTE technologies covered in the study. Incineration is a commonly used method to generate energy and reduce waste volume. The ideas, methods, and applicability of each technology across different MSW types are explored. MSW ash is a by-product of the incineration of waste products. MSW ash is composed of two types of ash: Fly Ash (FA) and Bottom Ash (BA). FA is said to have increased amounts of metals and salts, which collectively make up about 20% of the total weight of the ash. Thus, it might be categorized into the hazardous category (Hjelmar, 1996).

The study by Chen et al. (2023b) highlighted the progress in Municipal Solid Waste Incinerated (MSWI) FA treatment and recycling technologies, advocating for integrated approaches to manage this challenging waste stream effectively. Exploration of recycling methods to utilize FA in construction materials, such as cement and concrete, reduces the need for natural resources and provides a sustainable disposal method.

Multiple pretreatment techniques, including washing, thermal treatment, and chemical stabilization, could be used to enhance the quality and safety of MSWI FA, as explained by Chen et al. (2023c). It is observed from the results that certain pretreatment methods significantly improved the physicochemical properties and pozzolanic activity of MSWI FA. Thermal and chemical treatments were particularly effective in reducing harmful substances from the MSWI FA. According to the investigation, BA is generally classified as a non-hazardous substance (Hjelmar, 1996; Silva et al., 2019). Additionally, Combined Ash (CA), the combination of BA and FA, is frequently regarded as a non-hazardous waste element (Zekkos et al., 2013; Kumar et al., 2022).

Several studies on the usage of MSW ash as a sustainable building material, such as concrete mixes and bricks (Chen et al., 2023a), as well as an additive in soil stabilization, have been published (Zimar et al., 2022). Cement, lime, fibers, and other additives can be utilized to improve the engineering properties of soil (Yan et al., 2019; Priyadarshee et al., 2021; Sorsa and Agon, 2022). When cement is added, the achieved strength rate of stabilised material rises, but using cement as a base course also produces shrinkage and cracking phenomena, explained by Shirazi (1999).

The use of cemented soils may be limited because of the brittle failure pattern that might cause cement-stabilised soil buildings to collapse unexpectedly. When applying cement-stabilized soils at a shallow depth, brittle failure might appear more dramatically at relatively small confining stresses. In order to help cemented soils overcome their brittle nature, both natural and synthetic fibers can be added (Consoli et al., 1998; Tang et al., 2007; Ayeldeen et al., 2022; Kumar et al., 2023).

The addition of fiber to cement-stabilized soil results in friction and interaction between the soil grains and the fibers. Fiber-reinforced cement-stabilized soil is an excellent way to improve the brittle behavior of the soil because it can maintain a load even after the cement-stabilized soil fractures or de-bonds (Park, 2011).

Various research has been done on the stabilization of soil by adding cement, fiber, rice husk ash, lime, etc. (Park, 2011;

Priyadarshee et al., 2021; Sorsa and Agon, 2022). The results disclosed that the strength and durability of the soil were significantly increased by the addition of fibers and cement (Tang et al., 2007). They observed increased resistance to deformation, decreased cracking, and increased tensile strength. Furthermore, fiber reinforcement and cement stabilization provided long-term performance advantages that outweigh the original cost.

Enhancements to the treated soil or ash material include longer service life, lower maintenance costs, and increased load-bearing ability. Fiber inclusions can achieve remarkable enhancements and changes in the engineering properties of soils.

Researchers have run numerous tests on fiber-reinforced soils to determine the shear strength, compressive strength, tensile strength, and California Bearing Ratio (CBR) value (Maher and Gray, 1990; Shukla, 2017; Noaman et al., 2022). The main benefit of using randomly distributed fibers is that it prevents weak potential planes from forming parallel to the directed reinforcement (Maher and Gray, 1990). It has been discovered that adding fibers and combining them with clay and sand mixtures both raise the Unconfined Compressive Strength (UCS) value of clayey soil (Consoli et al., 1998).

The strength of fiber-reinforced cement stabilized sand is significantly influenced by the distribution and concentration of the fibers (Safdar et al., 2022). Direct shear tests on beach sand reinforced with natural and artificial fibers and metal (copper) wire were conducted by Gray and Ohashi (1983). According to test data, the shear strength of fiber-reinforced sand improves as the length of the fiber reinforcements grows. However, this impact is only observed up to a certain limit, after which additional lengthening of the fibers has no further effect. An enhanced understanding of the geotechnical characteristics of MSW ash will allow for better and more effective landfilling of the material as well as increased reuse in boundless applications of construction or circumstances in which ash is utilized in place of natural soils (Zekkos et al., 2013).

The goal of the experimental study in this research is to find out the geotechnical properties of untreated MSW ash and MSW ash treated with different proportions of fiber and cement. The improvement factor of the UCS and Split Tensile Strength (STS) values also determines the optimum percent increment with the addition of fiber and cement. A few studies are available on the stabilization of MSW ash with the addition of fiber. This experimental study appears to systematically examine how the addition of fiber and cement affects the geotechnical characteristics of MSW ash, which is a byproduct of WTE plants.

Understanding the geotechnical properties of MSW ash and how they can be modified through treatment with fiber and cement is crucial for engineering applications. Exploring parameters such as cement content, fiber content, aspect ratio of fiber, and days of curing contributes valuable insights into the enhancement of properties under these parameters.

2. Experimental Study

A comprehensive experimental study has been conducted at the Central University of Haryana, focusing on the determination of the geotechnical properties of untreated MSW ash and treated with fiber and cement. The study included a series of laboratory tests designed to evaluate different geotechnical characteristics, like particle size analysis, liquid limit, compaction properties, shear strength, UCS, STS, and other factors.

2.1. Material Used

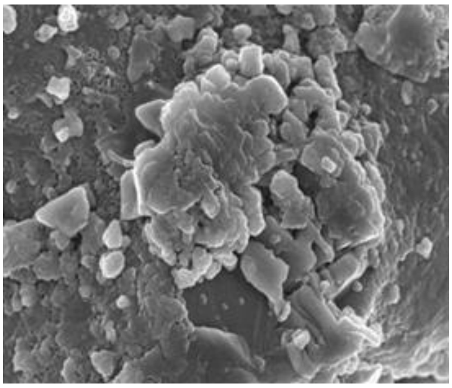
2.1.1. MSW Ash

The MSW ash used in this experimental work was collected from the WTE plant, New Delhi, shown in Figure 1a. The MSW ash is packed in polythene bags to avoid the entry of additional moisture from the atmosphere. On the basis of sieve analysis as per IS 2720 (Part 4) (Bureau of Indian Standards, 1985a), it was observed that the particle of MSW ash falls within the range of silty sand, consisting mostly medium to fine sand particles. The particle size distribution curve is presented in Figure 2.

The specific gravity of MSW ash is determined as per the IS 2720 (Part 3/Section 2) (Bureau of Indian Standards, 1980a), and it is found to be about 2.26. Liquid limit and plastic limit are determined as per IS 2720 (Part 5) (Bureau of Indian Standards, 1985b). The index properties of untreated MSW ash are summarized in Table 1. A Scanning Electron Microscope (SEM) equipped with an Energy Dispersive X-ray Analysis (EDAX) was utilized to assess the morphological characteristics of MSW ash.

The EDAX of the MSW ash sample provided the quantitative results of elemental composition presented in Table 2. The sample consists primarily of oxygen, calcium, carbon, silicon, and aluminum. ther elements, including iron, chromium, and manganese, are present in considerably smaller amounts. The SEM analysis of the untreated MSW ash sample shows a spherical shape with a few irregularly shaped particles, as shown in Figure 1b. The incineration of materials containing calcium carbonate ($CaCO_3$), such as limestone, cement, and various wastes rich in calcium, such as food remnants and paper, is one of the primary reasons for the high calcium content in MSW ash (Astrup et al., 2011). Glass, ceramics, and other kinds of polymers contain silica (SiO_2). The silica is retained in the ash when these materials are incinerated.

(a)



(b)

Fig. 1. a) MSW ash sample; and b) SEM image of MSW ash sample

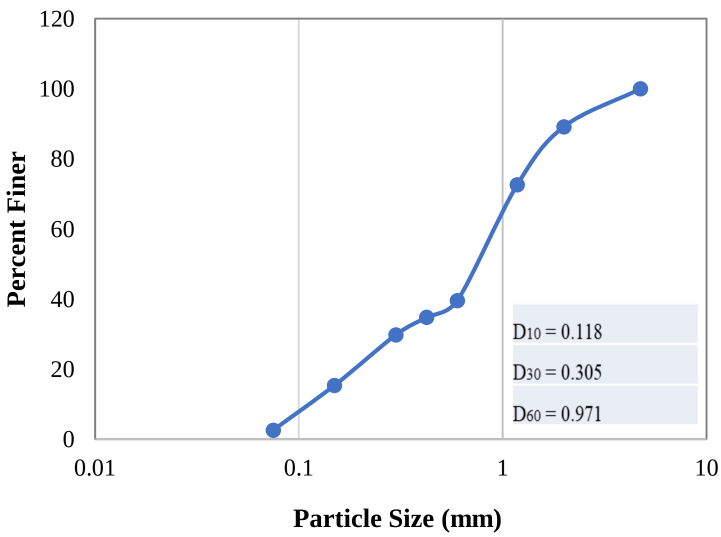


Fig. 2. Particle size distribution curve

Table 1. Index properties of MSW ash

Properties	Values
Colour	Grey
Specific gravity	2.26
Natural water content (%)	25.54
Liquid limit (%)	37
Plastic limit (%)	NA
Maximum dry density (kN/m^3)	14.82
Optimum moisture content (%)	17.14
Angle of internal friction, ϕ	36°
Cohesion (kPa)	22
Grain size distribution	
Sand fraction (%)	
Coarse sand fraction	10.8
Medium sand fraction	59.4
Fine sand fraction	27.2
Silt and clay fraction (%)	2.6
Uniformity coefficient	8.228
Coefficient of curvature	0.812

Table 2. Elemental composition of MSW ash

Element	Weight (%)
Carbon (C)	12
Oxygen (O)	28
Calcium (Ca)	26
Silicon (Si)	12
Aluminum (Al)	11
Iron (Fe)	5
Chromium (Cr)	2
Manganese (Mn)	4

Recycling and pre-sorting of MSW reduces the quantity of iron in the waste before incineration, which further reduces the Fe_2O_3 level in the ash (Patra et al., 2017). Sodium is frequently present in kitchen waste and common household products like detergents. However, during the incineration process, these products can form volatile species that are either captured in the flue gas treatment system or escape with the flue gases, resulting in lower concentrations in the ash (Quina et al., 2008). The process of the volatilization of inorganic compounds at high temperatures has been described, where the spherical morphology is attributed to the high temperature conditions in the incinerator (Thipse et al., 2002). The morphological details of particles are important for their utilization as construction materials. Ash-based composites' performance can be enhanced by controlled morphology (Hanif et al., 2017).

2.1.2. Fiber

The polypropylene fibers having lengths of 8 mm, 10 mm, and 12 mm of aspect ratios of 200, 250, and 300, respectively, were used in the present study, as shown in Figure 3. The characteristics of polypropylene fiber are summarized in Table 3.

2.1.3. Cement

Ordinary Portland Cement (OPC grade 43) is used for this study, procured from the building material shop in Mahendragarh, India. Purchased cement stored with the precaution to avoid any type of moisture.

Specific properties of the cement are determined as per IS 8112 (Bureau of Indian Standards, 2013), presented in Table 4. The details of the optimum mixes of fiber and cement with MSW ash are shown in Table 5.

2.2. Preparation and Testing of the Specimen

Before mixing the fiber and cement with MSW ash, the ash was oven-dried at 105 °C. The lumps presented in the dried sample are broken with the help of a hammer and sieved through a 4.75 mm sieve for standardization of the samples. Fiber and cement were mixed with MSW ash to prepare the specimens for the experimental study. Fiber content (0%, 0.25%, 0.5%, 0.75%, and 1%) with various lengths of 8 mm, 10 mm, and 12 mm, and cement (0%, 4%, 8%, and 12%) were added by dry weight of MSW ash mix. Standard proctor compaction, direct shear, UCS, and STS tests were performed on the test specimens.

(a (b) (c)

Fig. 3. Polypropylene fiber: a) 8 mm; b) 10 mm; c) 12 mm

Table 3. Polypropylene fiber properties

Properties	Values
Colour	White
Specific gravity, G	0.91
Cut length	8 mm, 10 mm, 12 mm
Diameter (D)	0.04 mm
Tensile strength (MPa)	600
Melting point	165 °C
Acid resistance	Excellent
Aspect ratio	200, 250, 300

Table 4. Properties of OPC (grade 43)

Properties	Value
Specific gravity, (G)	3.14
Soundness (mm)	3
Setting time	
Initial (min)	28
Final (min)	580
Consistency (%)	32

Table 5. Optimum proportion of fiber and cement with MSW ash

	Mix design	Mix ID
1	Untreated MSWI ash	UT - MSWA
	MSW ash treated with fiber	
2	Treated MSW ash (0.25% F (12 mm length)	$T\text{-}F_{0.25} + L_{12}$
3	Treated MSW ash (0.5% F (12 mm length)	$T\text{-}F_{0.5} + L_{12}$
4	Treated MSW ash (0.75% F (12 mm length)	$T\text{-}F_{0.75} + L_{12}$
5	Treated MSW ash (1% F (12 mm length)	$T\text{-}F_{1} + L_{12}$
	MSW ash treated with cement	
6	Treated MSW ash (4% cement)	$T - C_4$
7	Treated MSW ash (8% cement)	$T - C_8$
8	Treated MSW ash (12% cement)	$T - C_{12}$
	MSW ash treated with fiber and cement	
9	Treated MSW ash (0.25% F (12 mm Length) + 8% cement	$T - F_{0.25} + L_{12} + C_8$
10	Treated MSW ash (0.5% F (12 mm Length) + 8% cement	$T\text{-}F_{0.5} + L_{12} + C_8$
11	Treated MSW ash (0.75% F (12 mm length) + 8% cement	$T\text{-}F_{0.75} + L_{12} + C_8$
12	Treated MSW ash (1% F (12 mm length) + 8% cement	$T\text{-}F_{1} + L_{12} + C_8$

2.3. Compaction Test

The standard proctor test was carried out to determine the compaction characteristics, such as Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), for various mixes. The dry MSW ash with fiber, and dry MSW ash with cement separately were mixed evenly with several water contents, and a standard compaction test has been conducted as per IS 2720 (Part 7) (Bureau of Indian Standards, 1980b). The compaction test has been performed on the different prepared samples to determine their compaction characteristics. The total dry weight of MSW ash mix is obtained from Eq. (1).

$$W_T = W_A + W_{PF} + W_C \quad (1)$$

where W_T: is the total dry weight of the prepared sample, W_A: is the weight of MSW ash, W_{PF}: shows the weight of polypropylene fiber, and W_C: is the weight of cement.

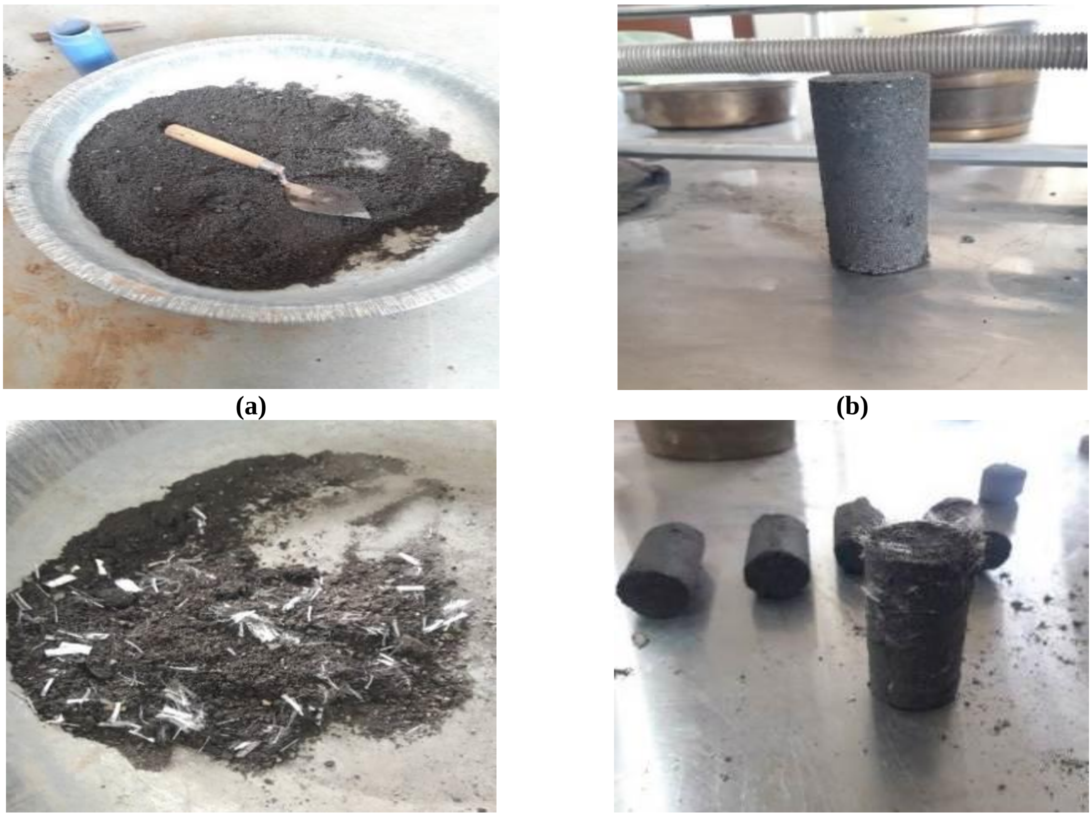
2.4. UCS Test

To determine the UCS of untreated and treated MSW ash, the sample was prepared by plain MSW ash, mixing cement, fiber, and ash, respectively. The UCS test was performed as per the codal provision of IS 2720 (Part 10) (Bureau of Indian Standards, 1991). The specimens of MSW ash, fiber, and cement were prepared with an optimum moisture content of the respective mix. The preparation of the sample for the UCS test is shown in Figure 4.

A cylindrical mould of 38 mm diameter is used to prepare the sample for the UCS test. The length of the prepared specimen is 76 mm. The OMC obtained from the compaction test for the different mixes is used to prepare the specific specimen. The prepared sample has been extracted from the mould and tested at a strain rate of 1.25 mm/min. Due to the addition of fiber and cement, the increment in UCS and STS value is also presented in terms of the Improvement factor (I_f) given by Eq. (2).

The I_f (UCS) is defined as the ratio of change in UCS value to the initial UCS value of untreated MSW ash, and I_f (STS) is defined as the ratio of change in STS value to the initial STS value of untreated MSW ash (Varaprasad et al., 2020).

$$I_f = \frac{\text{Treated MSW ash} - \text{Untreated MSW ash}}{\text{Untreated MSW ash}} \quad (2)$$



(a) (b) (c) (d)

Fig. 4. Preparation of UCS sample: a, b) untreated MSW ash sample and c, d) treated with fiber and cement MSW ash sample

2.5. STS Test

The cylindrical specimens, 38 mm in diameter and 76 mm in length, were used for the STS. The sample of untreated and treated MSW ash was prepared for STS at OMC and MDD achieved for a particular mix obtained from the standard proctor test. The STS of soil is determined according to IS 5816 (Bureau of Indian Standards, 1999).

The STS is calculated by using Eq. (3).

$$\mathrm{STS} = \frac{2P}{\pi d L} \tag{3}$$

where *P*: is the failure load, *L*: is the length of the prepared sample, and *d*: is the diameter of the prepared sample.

3. Result and Discussion

3.1. Effect of Inclusion of Fiber and Cement on Compaction Behavior of MSW Ash

It is observed that the inclusion of polypropylene fibers with cement increases the OMC of MSW ash shown in Figures 5 and 7. Increment in the OMC range from 2% to 6%, depending on the percentage of fiber and cement inclusion and the specific characteristics of the MSW ash. The reason behind the increment of OMC is absorption of water by fiber, and another is the process of heat of hydration due to the inclusion of cement (Muñoz et al., 2021; Yap et al., 2022). On the other hand, the addition of polypropylene fibers can also affect the MDD of MSW ash. The MDD of the MSW ash mixture is found to decrease as the cement percentage increases, both with and without fiber, as shown in Figures 6 and 8.

The MDD was reduced from 14.82 to 14.22 kN/m^3 when the MSW ash was treated with 0.5% fiber content of 12 mm length and 0% cement. With varying cement additions (0-12%) with 0.5% fiber content of 12 mm length, the MDD was reduced from 14.22 to 13.6 kN/m^3 as presented in Figure 6. The MDD decreases from 14.2 to 13.4 kN/m^3 when specimens with the 8% cement and various fiber content (0-1%) are introduced had varying lengths of 8, 10, and 12 mm as shown in Figure 8.

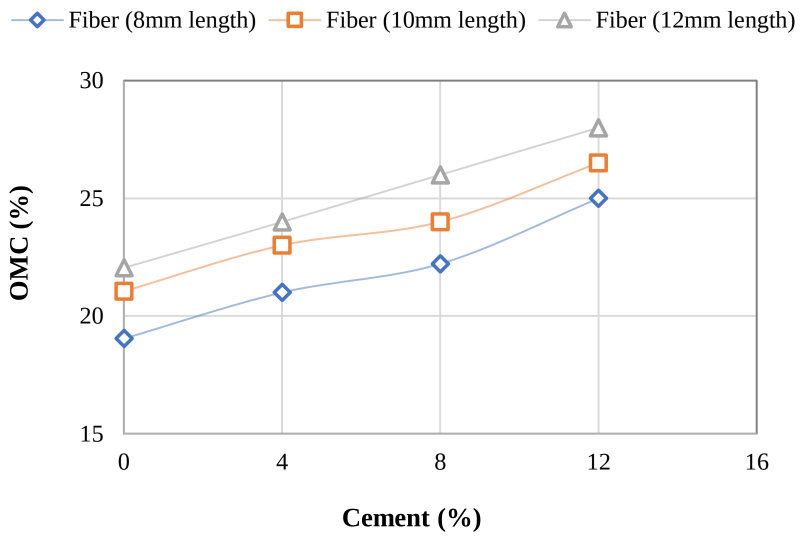


Fig. 5. Effect of cement content with 0.5% fiber on OMC of MSW ash

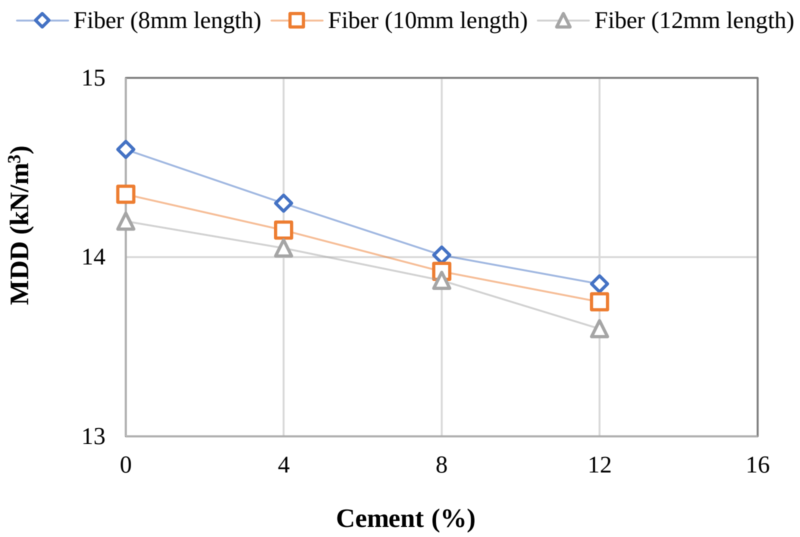


Fig. 6. Effect of cement content with 0.5% fiber on MDD of MSW ash

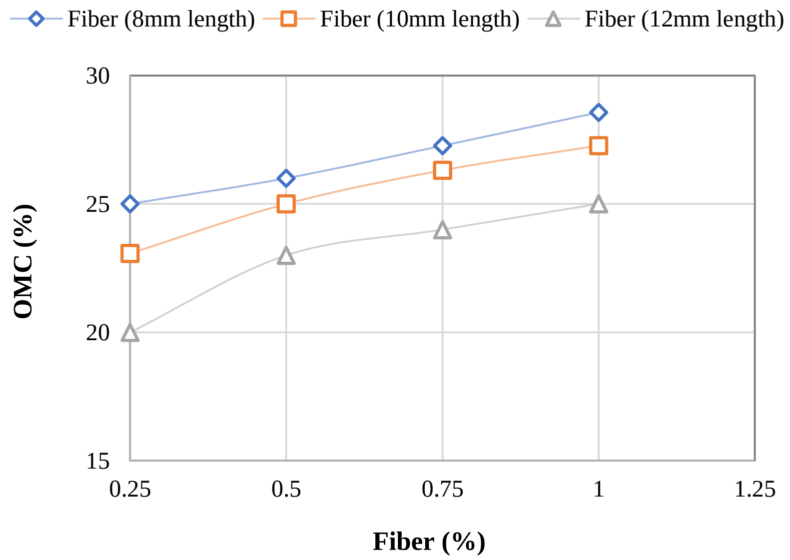


Fig. 7. Effect of fiber content with 8% cement on OMC of MSW ash

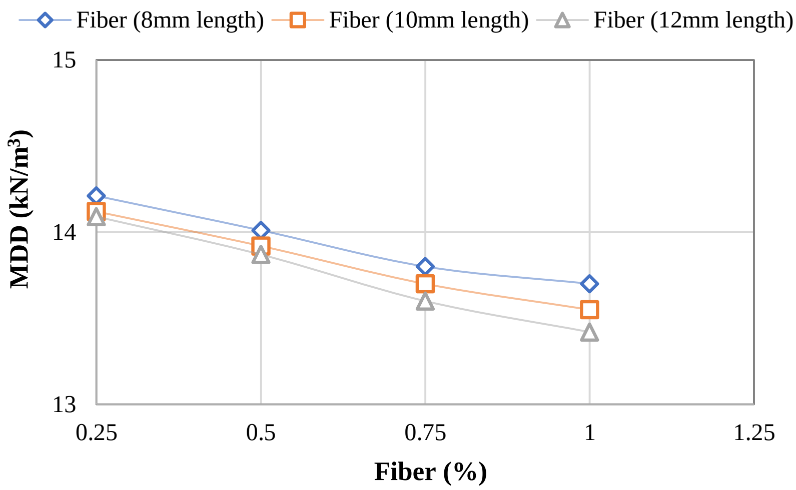


Fig. 8. Effect of fiber content with 8% cement on MDD of MSW ash

Reason behind the decrease in MDD of treated MSW ash with fiber is the inclusion of fiber makes the material lighter compared to the untreated sample, and also due to the quick reaction of ash and cement, which creates flocculation and increases the void ratio in the mix. It is also explained in previous research (Yadav et al., 2018; Zare et al., 2020). However, it is found that the effect of fiber inclusion on the MDD of MSW ash is not very significant.

3.2. Effect of Inclusion of Fiber and Cement on UCS of MSW Ash

It is observed from the result that the inclusion of cement with and without fiber reinforcement increases the UCS value of MSW ash, as shown in Figures 9 and 10, respectively, but the combination of cement and fiber appears to have a better effect, enhancing the strength of the MSW ash.

The effect of cement content and 0.5% fiber on UCS of MSW ash at 0, 7, and 28 days of curing is shown in Figures 11-13, respectively. The use of polypropylene fibers with cement can have a positive effect on the UCS of MSW ash.

Polypropylene fibers can act as reinforcement and help to improve the mechanical properties of the MSW ash. The fibers can also provide stability and prevent the formation of cracks in the material. At fiber content above the optimum, the rate of increment for the UCS value reduces as compared to the previous obtained value. The Reason behind the reduction in the rate of UCS increment is that the higher fiber content cannot develop a bond with the lesser available ash matrix.

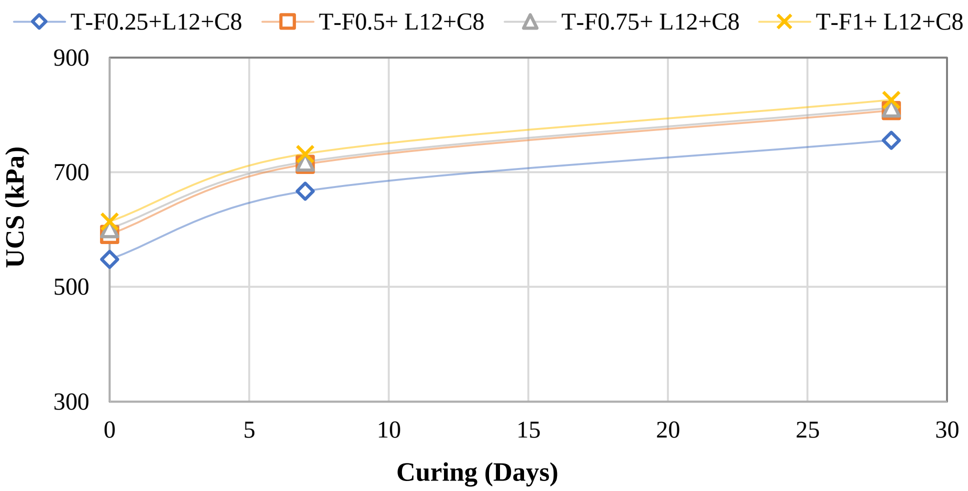


Fig. 9. Effect of curing period on UCS of MSW ash treated with fiber and cement

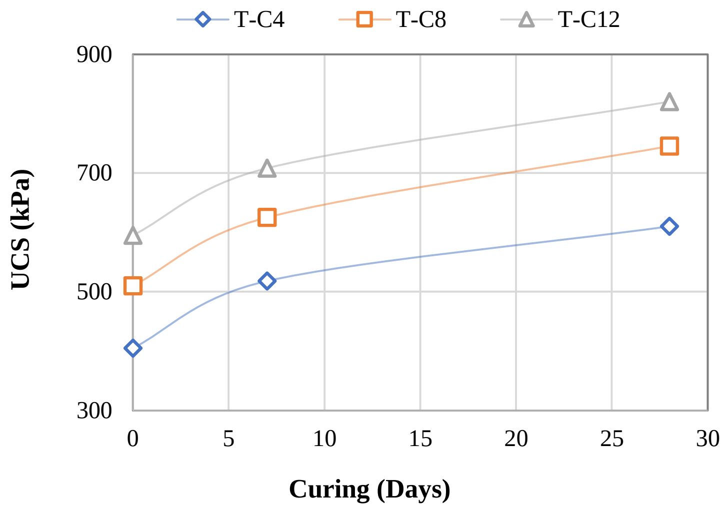


Fig. 10. Effect of curing period on UCS of MSW ash treated with different cement contents

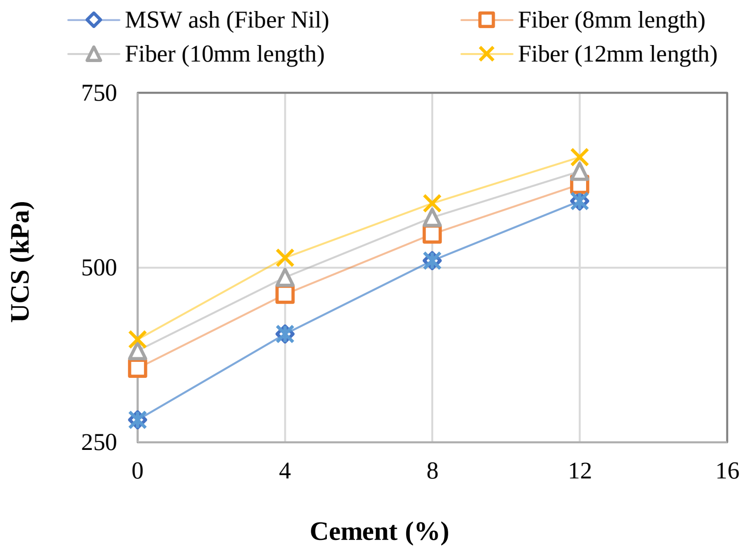


Fig. 11. Effect of cement content on UCS of MSW ash

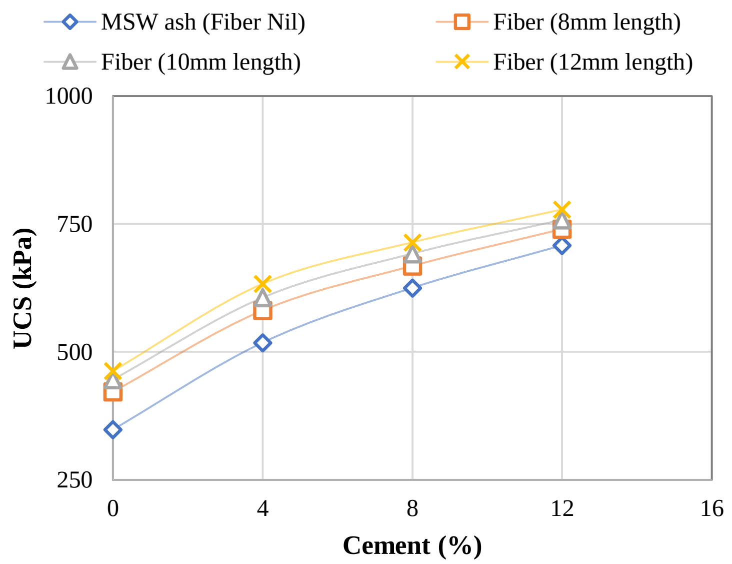


Fig. 12. Effect of cement content on UCS of MSW ash

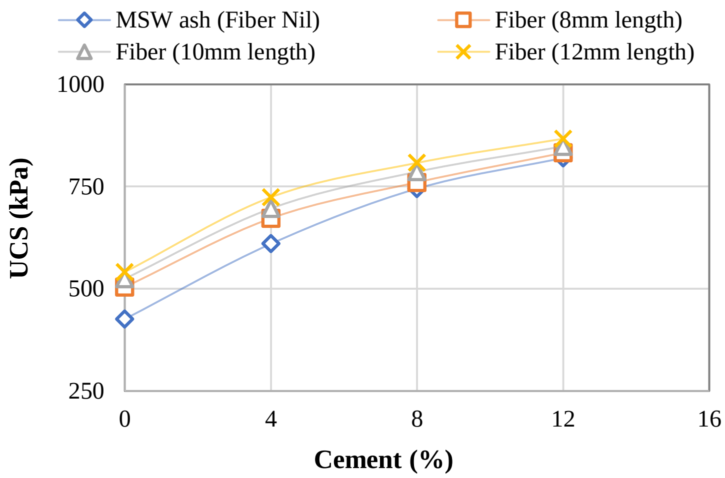


Fig. 13. Effect of cement content on UCS of MSW ash

It is found that adding 0.5% polypropylene fiber of 12 mm length with 4% cement by weight of MSW ash mix resulted in a 156% I_f of UCS at 28 days of curing compared to the untreated MSW ash sample, as shown in Figure 14. Effect of days of curing on I_f (UCS) of MSW ash at 4%, 8% and 12% cement content is shown in Figure 15. The optimum UCS is obtained by the mixing of 0.5% fiber of 12 mm length and 8% cement in MSW ash, increased I_f of MSW ash by 186% at the curing of 28 days when compared with that of unreinforced MSW ash as presented in Figure 16.

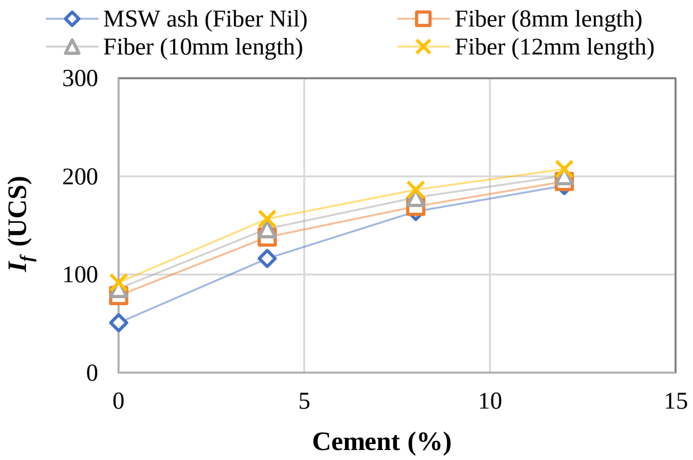


Fig. 14. Effect of cement content on I_f (UCS) of MSW ash at different fiber lengths

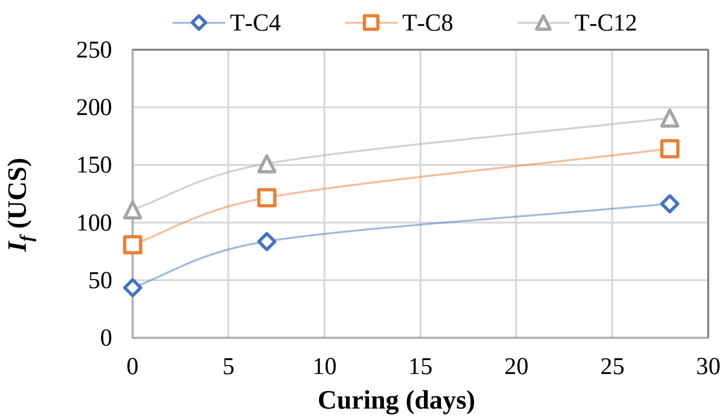


Fig. 15. Effect of curing period on I_f (UCS) of MSW ash at different cement content

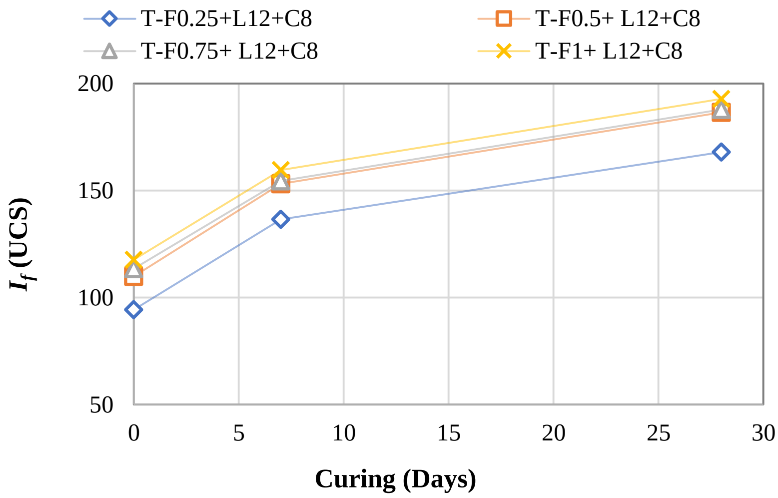


Fig. 16. Effect of curing period on I_f (UCS) of MSW ash

The optimum content of fiber obtained from the experimental result is 0.5% and the cement content is 8% as the rate of increment found maximum. Also, it is observed that the ductility of the treated ash increases with the addition of fiber as compared to untreated MSW ash. Similar result of the fiber reinforced silty sand and fiber reinforced sand have been presented (Maher and Gray, 1990; Kumar et al., 1999).

3.3. Effect of Inclusion of Fiber and Cement on STS of MSW Ash

The addition of fiber creates a bond between the ash particle and fiber when added to the MSW ash. The STS value of MSW ash treated with 0% cement and different fiber content at 0 days curing is shown in Figure 17.

The STS value of MSW ash treated with 0.5% fiber content and 0% cement at different curing days is shown in Figure 18. The STS value increases with the variation of fiber length and fiber content. The STS value increases more significantly by the inclusion of fiber and cement combined with the MSW ash. The STS value of MSW ash treated with 0.5% fiber and cement at 28 days of curing is shown in Figure 19. The optimum content of fiber and cement is found to be 0.5% of 12 mm length and 8%, respectively, as shown in Figure 20.

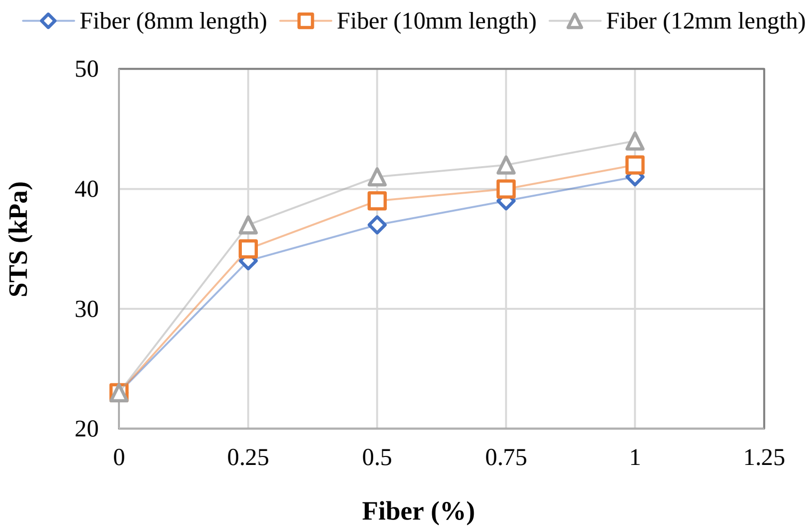


Fig. 17. Effect of curing period on I_f (UCS) of MSW ash

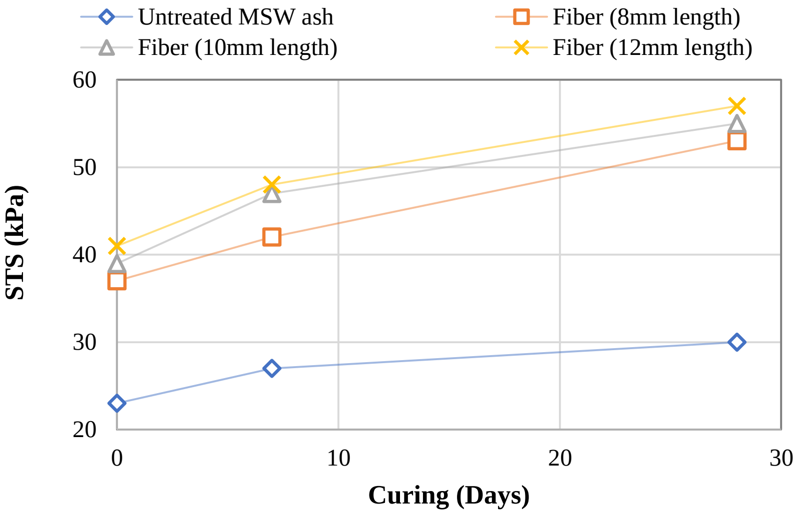


Fig. 18. Effect of curing period on STS of MSW ash

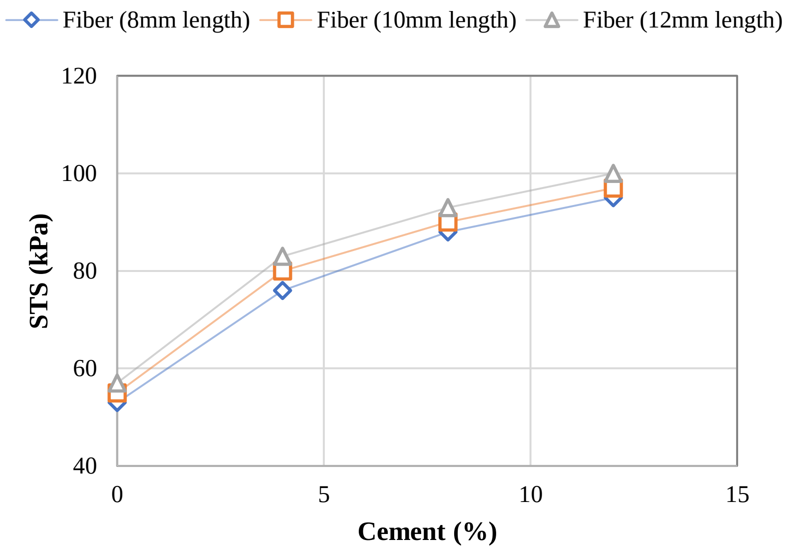


Fig. 19. Effect of cement content on STS of MSW ash

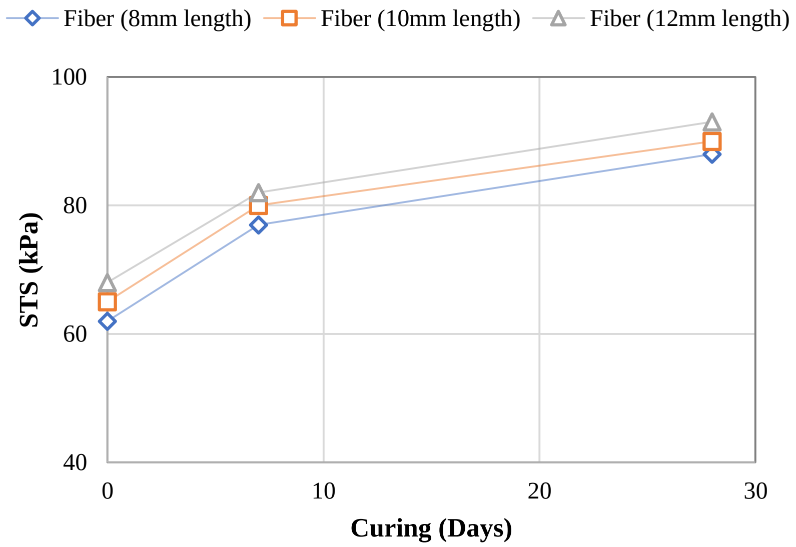


Fig. 20. Effect of curing period on STS of MSW ash

At this combination, the I_f (STS) is found 210% at 28 days of curing as presented in Figures 21 and 22. The brittle behavior of the MSW ash can be effectively improved by fiber reinforcement, which can support a load even after a cemented MSW ash debonds or fails. Similar result has been presented for the fiber-reinforced cement soil (Park, 2011). The effect of fiber content of 12 mm length with different cement percent on cohesion (c) value and on angle of internal friction (ϕ) of MSW ash is shown in Figures 23 and 24, respectively.

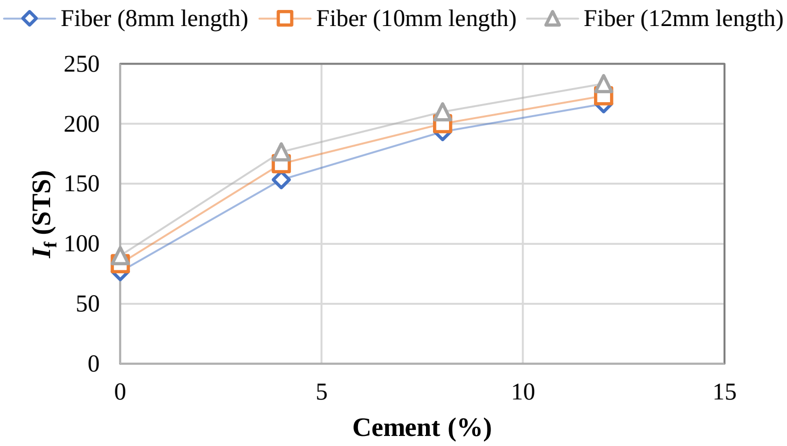


Fig. 21. Effect of cement content on I_f (STS) of MSW ash at different lengths of fiber

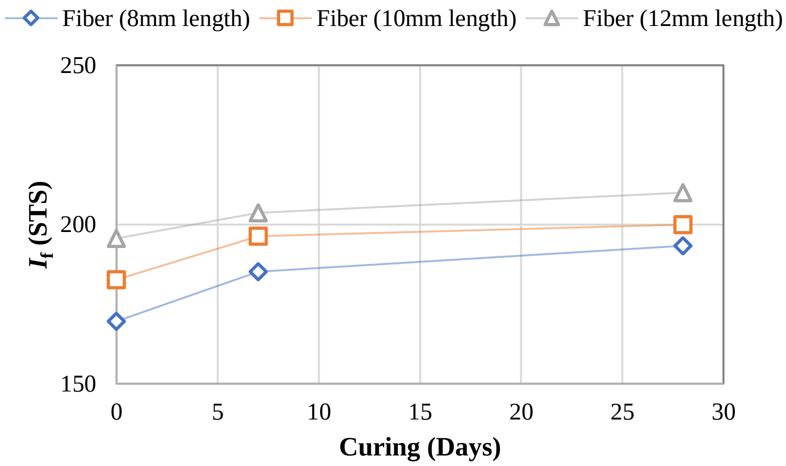


Fig. 22. Effect of curing period on I_f (STS) of MSW ash at different lengths of fiber

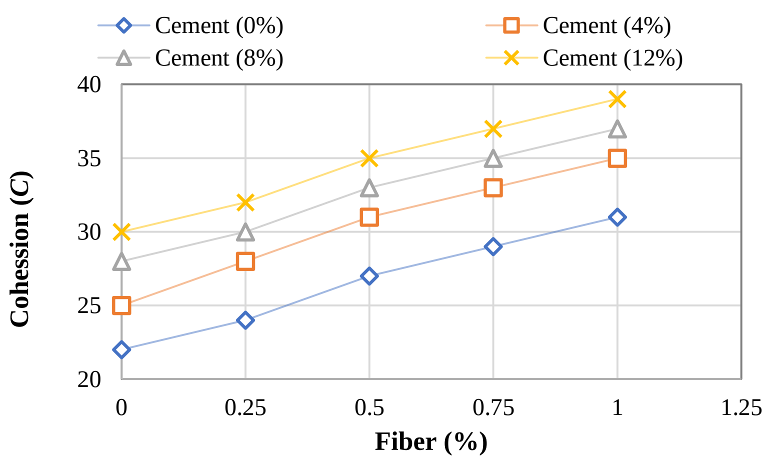


Fig. 23. Effect of fiber content on cohesion value of MSW ash

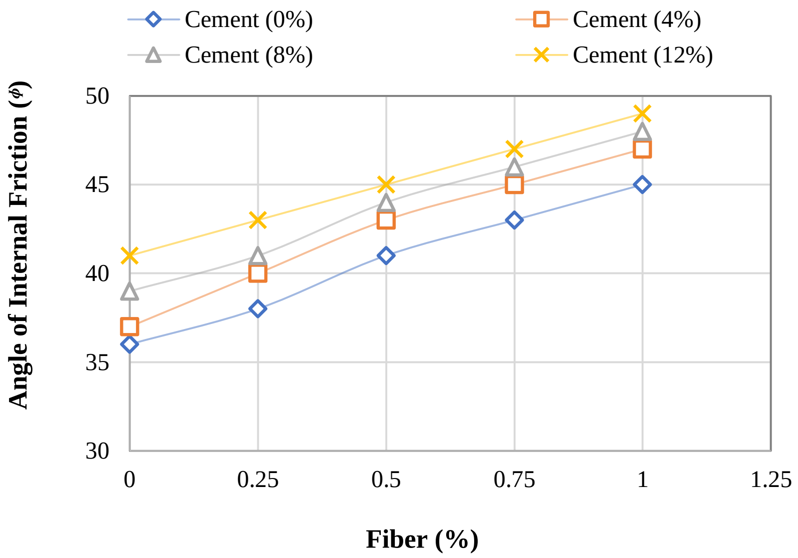


Fig. 24. Effect of fiber content on angle of internal friction of MSW ash

As the amount of fiber increases, it has been noticed that the values of *c* and ϕ also increase. The value of cohesion and internal angle of friction increases from 22 to 39 kPa and from 36˚ to 49˚, respectively, by the addition of 12% cement with 1% fiber of 12 mm length. The shear strength parameter is considerably improved by the inclusion of cement with the same fiber content. The addition of fiber content increases the cohesion value of ash-mixed clayey soil, as presented in Li et al. (2022). The addition of fiber in MSW ash reduces the brittle behavior of MSW ash.

The mechanism behind the increase in shear parameters of MSW ash is that fiber interacted with MSW ash particles and stretched during the shear, which allow to create stronger bond between the fiber and ash particles and increase the tensile strength of the fiber mix MSW ash. Similar results have been obtained in previous research carried out on different types of soil and ash (Consoli et al., 1998; Tang et al., 2007; Wei et al., 2018). The mixing of polypropylene fiber and cement in MSW ash has proven to be an effective strategy for improving UCS and STS. The enhanced mechanical properties of MSW ash make it a promising material for various geotechnical and construction applications where strength and sustainability are key considerations.

4. Conclusions

- The MDD of MSW ash decreases after the inclusion of fiber, which makes the MSW ash a lightweight material. It is because of the lower specific gravity of fiber, and also due to the quick reaction of cement and MSW ash, which creates flocculation and increases the voids in the mix.
- The UCS of MSW ash increases by adding cement and fiber. It was observed from the test results that the aspect ratio of the fiber has a significant influence on the UCS value of MSW ash. The increase in I_f (UCS) was found to be 186% with the addition of 0.5% fiber having an aspect ratio of 300 and 8% cement after 28 days of curing.
- With the addition of fiber, the STS of MSW ash increased due to the ductile behavior of fiber-reinforced MSW ash. It was found that I_f (STS) is increased by 210% by the inclusion of 0.5% fiber content with an aspect ratio of 300 and 8% cement content at 28 days curing.
- It was observed from the result that the fiber and cement increase the shear parameters of MSW ash. The mechanism behind the increment is that the addition of fiber reduces the brittleness of MSW ash. The fiber stretched during the shear, which

allows to create stronger bond between the fiber and ash particles and increase the tensile strength of the fiber mix MSW ash.

- The best possible combination of fiber and cement appeared to have a synergistic effect, greatly enhancing the UCS and STS of the MSW ash. When utilized in the recommended quantities, each component improves strength and stabilizes ash in distinct ways, resulting in optimal performance. Treated MSW ash can be used in road construction projects, especially as a base or sub-base material, a substitute material for building foundations, and to stabilize slopes to prevent erosion and landslides. The determination of UCS is essential for assessing the ability of treated MSW ash to withstand structural loads. Additionally, STS analysis provides insights into its resistance against tensile forces.

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6. Declaration

Authors declare that no AI tools were used for the preparation of this manuscript.

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