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Factors affecting properties of MSWI bottom ash employing cement and fiber for geotechnical applications

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Abstract

The present study is based on municipal solid waste incineration (MSWI) bottom ash stabilization when amended with cement and fiber. To simulate the effect of inclusion of cement and fibers on the behavior of MSWI bottom ash, numerous experiments were performed. The CBR test was considered as a basic parameter during the study. For CBR, a comparison was made among different test specimens under soaked and unsoaked conditions, with and without cement and fibers. The maximum dry unit weight of the bottom ash reduces, and moisture content rises due to the inclusion of cement and fiber. The results revealed that the relatively better combination was found to be highest gain of CBR value in case of 8% cement and 1% fiber. The study results also demonstrated that addition of fiber used to stabilize MSWI bottom ash reduces the stiffness as well as changes the behavior from brittle to ductile. Due to the free availability, such material can be used in compacted fills, embankments and road construction in very liberal manner. A multiple linear regression analysis of test results was carried out in order to develop a mathematical relationship to understand the intensity of different factors, i.e., MSWI bottom ash, cement content, fiber content, fiber length and curing period. The simulated model agreed reasonably with the experimental results.

Keywords MSWI bottom ash · Cement · Fibers · Stabilization · CBR

1 Introduction

Nowadays, due to bulk increase in municipal solid waste incineration (MSWI) ash, its disposal in an environmental friendly manner is becoming a burden as well as the global concern. The resulting bottom ash extracted from incineration of municipal solid waste as a by-product is generally inorganic in nature and consists of oxides of aluminum, calcium, iron, silicon and other components. The resultant compounds are produced directly by the chemical interaction of various components during incineration, and rest of the part can be manufactured through the interaction of various compounds existing

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into the burning environment. Thus, in order to reuse such waste components and to remediate their disposal issue, the geotechnical application is being an important aspect. Before taking the MSWI bottom ash for such application, it is necessary to stabilize it. In modern construction practice, lime was used as a stabilizing agent, in the year 1924 (Mc Caustland 1925). As the roads were required to be expanded in width to cope up with the increased volume of vehicular traffic in the year 1930, the stabilization of soils began to rise. The present scenario shows that numerous modes of stabilization have been developed and the concept is still continuing not only on soil but it has extended up to fly ash, pond ash and MSWI ash also. The concept has passed through some other novel approaches, i.e., interaction of these materials with fiber. The various researchers have recommended that fiber-reinforced soils are accessible composite material and can be advantageous over past structural behavior (Cavey et al. 1995; Muntohar 2000; Consoli et al. 2002; Kaniraj and Gayathri 2003; Ghiassian et al. 2004). The researchers have made an effort to appraise the effect of different parameters on the behavior of different properties of the composite of the peak strength, i.e., shear, compressive, tensile strength, etc., and reported that these parameters increased with increasing fiber content. Based upon certain parametric test, the study conducted by the other researchers made a comparison among the different materials, i.e., sandy soil, silty and clayey soil, by considering California bearing ratio (CBR) as a baseline (Hoover et al. 1982). In their results, soil–fiber composites were established to be more effective for rectifying the CBR values of sandy soil than that of silty or clayey soil. The application of fly ash as a sub-base material is also in trend and has shown its potential as an alternative if it is reinforced with polypropylene fibers (Kumar and Singh 2008). When soil is introduced with fly ash, then an augmented CBR value has been identified. In the literature, it has been evidenced that inclusion of 10% of fly ash in specimens may result increase in CBR value of about 4 times compared to the initial condition (Karthik et al. 2014). On the same juncture, by the inclusion of fly ash about 18% increases of 8 times in CBR value are experienced compared to the initial stage. It has been proved that randomly oriented discrete fibers improve the CBR value of soil as discussed earlier. In this context, ample of literature is available that concerns with the improvement in engineering properties due to inclusion of fibers (Ramlakhan et al. 2013; Sabat and Bose 2013; Umar et al. 2013). Some of the researchers used nylon fibers and jute fibers as a reinforced media in black cotton soil (Ramlakhan et al. 2013). During their study, a comparison was made among both the specimens. The study results revealed that CBR value can be amplified by 50% than that of unreinforced soil. In same study, jute fiber was experienced to be having 96% CBR value. A maximum of 2% fiber content was recommended for increasing the CBR value, and beyond this limit, the value diminished under soaked condition (Sabat and Bose 2013; Umar et al. 2013). Many investigators used fibers under varying test conditions and recommended that the finished product can be used as a pavement material in road construction (Raymond 2002; Tang et al. 2007). Nowadays, the approach has shifted to MSWI bottom ash and is still in progress, as evident from previous studies (Singh and Kumar 2017a, b). The application of MSWI bottom ash in combination with cement reduces the environmental risks and contributes in improved mechanical property (Show et al. 2003). For stabilization, the purpose is to reduce the solubility and toxicity of containments (Lam et al. 2010). It reduces the settlements of the landfill and consequently expedites its rehabilitation. Due to free availability, such material can be used in compacted fills, embankments and road construction in very liberal manner. The use of MSWI ash was reported as a substitute to aggregate in sub-base material for roads and embankments applications (Forteza et al. 2004). It is observed that the effect of fiber addition on the geotechnical aspect of MSWI bottom ash has not been investigated in much detail as their influence in case of soil and fly ash. Furthermore, according to author's knowledge, the limited researchers have worked on regression analysis of CBR using studied in the material. Thus, on the basis of these gaps, it was felt that the field is still in infancy and needs further investigation on geotechnical applications of MSWI bottom ash. In addition to this, an attempt has also been made in which CBR value was set to be a role of different parameters including cement content, fiber content, fiber length, curing period and MSWI ash content. Also, a comparison was made between unreinforced and fiber-reinforced specimens. During experimentation, the cement content was taken as 2–8% and the polypropylene fiber used in the study was of varying lengths of 6–18 mm and in the range of 0.5–1%, respectively. For CBR test, the specimens were kept for different soaked conditions of 4 and 28 days.

2 Materials and methodology

2.1 MSWI ash

The incineration ash used in the present study was procured from the Municipal Solid Waste Incineration Plant, Chandigarh (Fig. 1). The chemical composition of MSWI ash for different parameters was obtained by conducting standard tests using procedures outlined as per IS 1727-1967, and particle size distribution was analyzed as per ASTM D6913-04. The compositions of MSWI ash were identified as SiO_2: 55.36%, Al_2O_3: 9.2%, CaO: 19.39%, Fe_2O_3: 4.93%, MgO: 0.41%, Pb: 0.07% and Zn: 0.02%. On the basis of wet sieve analysis, around 74.5% of the particles were found in the range of 1.18 mm to 75 µm (poorly graded sand) and the majority of ash consists of medium to fine sand particles (Fig. 2). The specific gravity of MSWI ash is obtained to be 2.05.

Fig. 1 Photograph view of municipal solid waste incineration ash used during experimentation

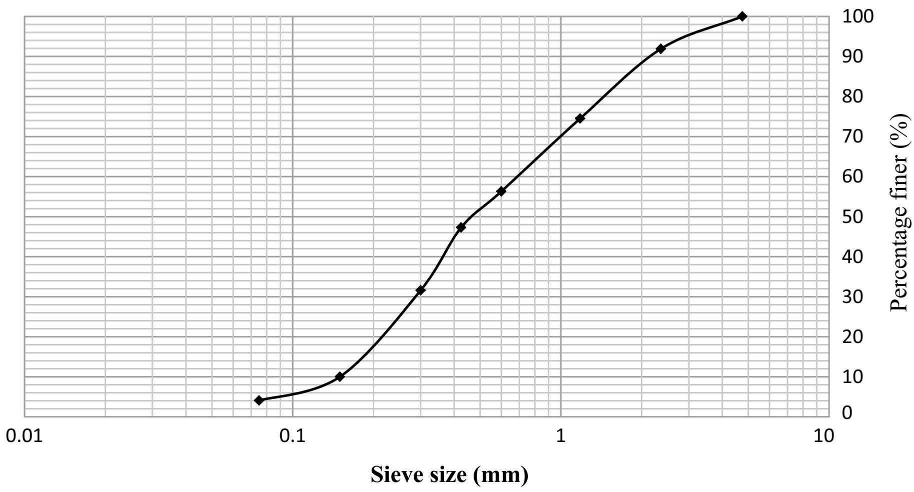


Fig. 2 Particle size distribution curve of MSWI ash

2.2 Fiber characteristics

The polypropylene fiber used during experimentation was completely resistant to sea water. In addition to this, it was experienced to be having higher tensile strength and very limited effect of abrasion and less prone to wear and tear. The physical characteristics of fibers are as follows: specific gravity, 0.9–0.91; diameter, 0.02 mm; water absorption, 0.3%; tensile strength, 600; cut length, 6, 12 and 18 mm (Fig. 3).

2.3 Heavy compaction test

The heavy compaction tests were performed as per ASTMD (1557-78) to determine the maximum dry unit weight (γ_{dmax}) and the moisture content (W_{opt}) of the MSWI ash. The tests were carried out on the MSWI ash, with cement and fiber or as an individual mixed with various moisture contents and discussed in detail in Singh and Kumar (2017b).

2.4 Preparation of mix specimens

Before taking the MSWI ash for experimentation, it was firstly dried into hot air oven, so that precisions can be maintained regarding its water content. The equation for total dry weight W of a MSWI ash–cement–fiber mixture is

$$W = W_A + W_C + W_F \tag{1}$$

where W_A, W_C and W_F are dry weights of MSWI bottom ash, cement and fiber, respectively. Therefore, Eq. (1) can be written as

$$W = (P_A + P_C + P_F) \times (W_{ACF}) \tag{2}$$

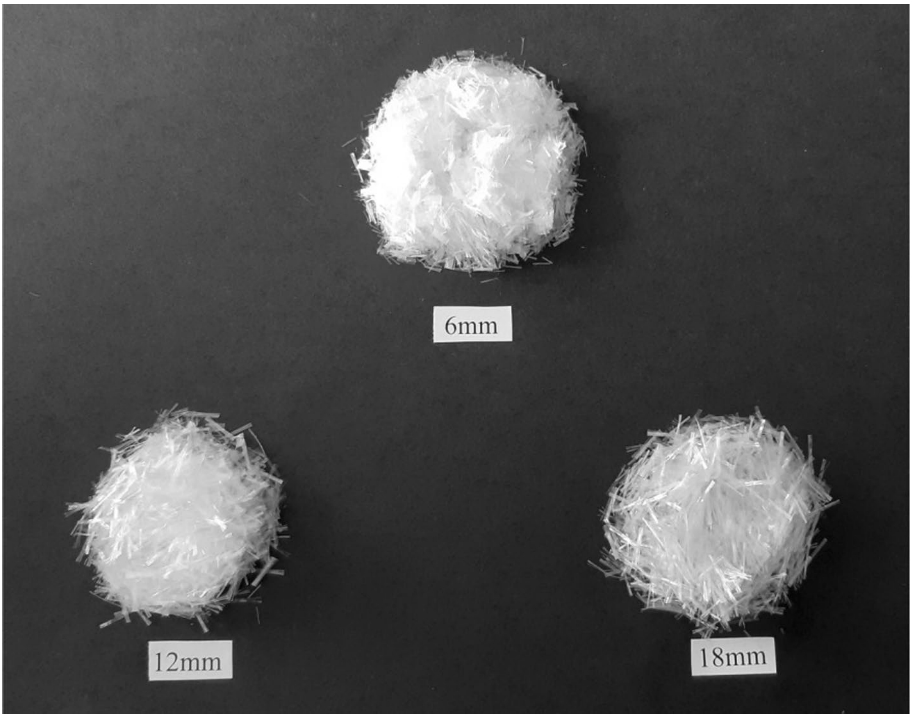


Fig. 3 Polypropylene fibers used during experimentation

where P_A = proportion of MSWI ash = W_A/W_{ACF}, P_C = proportion of cement = W_C/W_{ACF} and P_F = proportion of fiber = W_F/W_{ACF}, W_{ACF} = cumulative weight of ash, cement and fiber. The different values of P_A are 100, 98, 96, 94 and 92. P_C: 0, 0.02, 0.04, 0.06 and 0.08 and P_F: 0, 0.005, 0.0075 and 0.01. All the compacted specimens were prepared at their respective heavy compaction of dry unit weight and OMC.

During preparation of specimens, the required amount of MSWI ash was measured in dry state. When the cement and fiber was not introduced to MSWI ash then in that case only water was mixed in required amount, depending upon its OMC. For preparing the next specimen, the MSWI ash was amended with cement alone for stabilization on individual basis. Thereafter, the required amount of water was applied to the mixture up to final OMC. For applying the requisite reinforcement for study view point, the MSWI ash was incorporated with both cement and fiber for its stabilization. For this, the moist MSWI ash and cement mixture was firstly prepared as explained in stabilization with cement only and then the required amount of fiber was mixed with moist mixture. The mixing process was carried out manually till a homogenous condition was achieved.

2.5 CBR tests

One hundred and twenty-three sets of experiments were performed for both the conditions, i.e., soaked and unsoaked, in the presence and absence of fiber (Table 1). For this, a standard CBR mold having diameter of 152 mm and 170 mm height with a provision of detachable collar was used. The specimens were prepared in accordance with ASTM D1883-05

Table 1 Detail of California bearing ratio (CBR) tests

S. no.	MSWI ash (%)	Cement (%)	Fiber content (%)	Curing period (days)	Fiber length (mm)
1.	98	2	0	0, 4, 28	–
	97.5		0.5	0, 4, 28	6, 12, 18
	97.25		0.75	0, 4, 28	6, 12, 18
	97.0		1.0	0, 4, 28	6, 12, 18
2.	96	4	0	0, 4, 28	–
	95.5		0.5	0, 4, 28	6, 12, 18
	95.25		0.75	0, 4, 28	6, 12, 18
	95.0		1.0	0, 4, 28	6, 12, 18
	94	6	0	0, 4, 28	–
3.	93.5		0.5	0, 4, 28	6, 12, 18
	93.25		0.75	0, 4, 28	6, 12, 18
	93.0		1.0	0, 4, 28	6, 12, 18
4.	92	8	0	0, 4, 28	–
	91.5		0.5	0, 4, 28	6, 12, 18
	91.25		0.75	0, 4, 28	6, 12, 18
	91.0		1.0	0, 4, 14	6, 12, 18

at OMC using standard proctor test to mimic the wet and soft conditions typically observed in the field. During specimen preparation, the compaction was applied to the specimens in five different layers at OMC and then these were kept in water for 4 and 28 days to mimic the soaked conditions and to find the respective CBR values at this stage.

3 Results and discussion

The (CBR) results were obtained from 123 experimental tests at 0, 4 and 28 days of curing period (soaked and unsoaked conditions) in the presence and absence of cement along with fiber, see Table 2.

3.1 Effect of cement and fiber

3.1.1 OMC and dry unit weight

The characteristics of bottom ash depend on the moisture content (W_{opt}) and maximum dry unit weight (γ_{dmax}) at which the bottom ash was compacted. It was observed that with the increase of cement and fiber, the (γ_{dmax}) of bottom ash–cement–fiber mixture was decreased from 16.8 to 16 kN/m^3 while the (W_{opt}) increased from 11 to 20.3%. This may be attributed due to the reaction among cement, bottom ash and fine fraction of ash as pozzolanic materials in which they form cluster like coarse aggregates. This cluster occupied large space and further increased the volume and consequently decreased the maximum dry unit weight. While, due to absorption of water by polypropylene fiber the OMC value increased (Singh and Kumar 2017b).

Table 2 Results of California bearing ratio (CBR) tests

Cement content	% Fiber	CBR value (6-mm fiber)			CBR value (12-mm fiber)			CBR value (18-mm fiber)		
		0 Days	4 Days	28 Days	0 Days	4 Days	28 Days	0 Days	4 Days	28 Days
100% MSWI ash	0	15	19	21						
2%	0	17	23	25						
	0.5	18	25	28	19	26	31	20	29	33
	0.75	19	25	29	20	29	33	21	32	36
	1.0	20	26	31	21	33	37	22	35	41
4%	0	22	32	42						
	0.5	23	36	48	26	38	53	27	42	55
	0.75	24	38	50	27	42	55	28	45	58
	1.0	25	40	53	27	45	57	29	49	62
6%	0	30	40	58						
	0.5	31	55	70	31	60	74	32	63	77
	0.75	31	58	76	32	63	78	33	67	82
	1.0	32	62	80	33	66	83	34	70	85
8%	0	34	50	65						
	0.5	34	66	78	35	70	84	36	73	89
	0.75	35	71	81	36	77	87	37	80	93
	1.0	36	75	87	36	80	92	38	82	96

3.1.2 Effect of cement content

The CBR tests were performed on various mixes in which the percentage of cement in bottom ash was varied from 0 to 8%. After curing period of 0, 4 and 28 days, the CBR values revealed an increasing trend for stabilized mixes of MSWI bottom ash with the inclusion of cement. The CBR values of unsoaked and soaked samples of MSWI ash were found to be 15 and 19%, respectively. As per IRC-SP 20 [Indian Road Congress (IRC) 2002: 2012], the sub-base material should have minimum soaked CBR of 15% in case of rural roads. From the CBR results, the soaked CBR value of MSWI ash increased with the addition of cement. So the resulted material so obtained can be effectively used in sub-base course by replacing natural materials. With the inclusion of cement content 2–8%, the augmentation in CBR value was varied from 13.5 to 126%, 53 to 233% and 66 to 333% for 0, 4 and 28 days, respectively (Fig. 4). The inclusion of cement, ash particles with interlocking characteristics and remodeling in the cohesive nature of the cement could be reason behind this augmentation (Sharma and Hymavathi 2016).

3.1.3 Effect of fiber length

The influence of fiber length 6–18 mm (1% fiber) on the CBR of MSWI ash mixed with 2–8% cement content for 28 days of curing is presented in Fig. 5. It was revealed that with the increase in fiber length there was continuous enhancement in the CBR value of MSWI ash with cement mix. The results also revealed that 18 mm length of fibers provided relatively better CBR value and quantified as 96 after 28 days. Due to addition of cement content from 2 to 8% and fiber 1%, the gain in CBR value was varied from 106 to 480% for cut length of fiber 6 mm and 173 to 540% for cut length of fiber 18 mm, after 28 days of curing period, respectively.

3.1.4 Effect of fiber content

The influence of fiber content when varied from 0.5 to 1% on CBR value of MSWI ash mixed with various percentage of cement content 2–8% at curing age of 4 and 28 days for 6, 12 and 18 mm length of fibers, respectively. It was revealed that as the fiber content increased, there was continuous raise in the CBR value of mix specimens. The

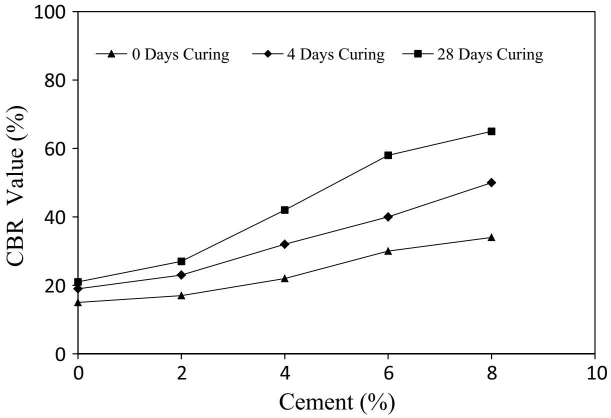


Fig. 4 Variation of CBR value with cement for different combinations of MSWI ash and cement

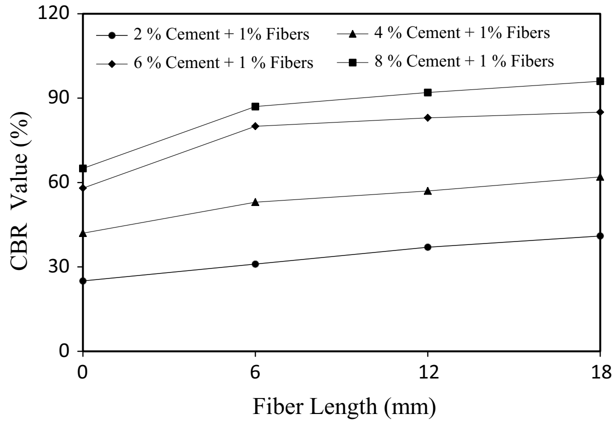


Fig. 5 Variation of CBR value with cement for different cut lengths of fibers in MSWI ash after curing period of 28 days (1% fiber content)

inclusion of cement, ash particles with interlocking characteristics and remodeling in the cohesive nature of the cement and fiber could be reason behind this augmentation (Sharma and Hymavathi 2016). On increasing cement content from 2 to 8% in MSWI ash, for 6 mm cut length fiber, the improvement in unsoaked CBR value was found to be 20–127%, 26–133% and 33–140% for 0.5, 0.75 and 1% fiber content, respectively. Furthermore, the development in soaked CBR value for 18 mm cut length of fiber was found to be 93–386%, 113–433% and 133–447% after 4 days (Fig. 6) and 120–493%, 140–520% and 173–540% after 28 days (Fig. 7) of 0.5, 0.75 and 1% fiber content, respectively. The maximum CBR value was observed to be varying from 173 to 540% against the addition of 1% fibers into the stabilized bottom ash. Figure 8 shows the effect of fiber content 0.5–1% (18 mm) on the stress–strain nature of bottom ash when mixed with 8% cement content for curing periods of 28 days. From Fig. 8, the results revealed that as the fiber content is increased, there is a considerable increase in the peak strength. Moreover, the inclusion of fiber in MSWI ash not only improved the peak strength but also maintained peak strength up to larger strains, thereby changing the brittle behavior to ductile in nature.

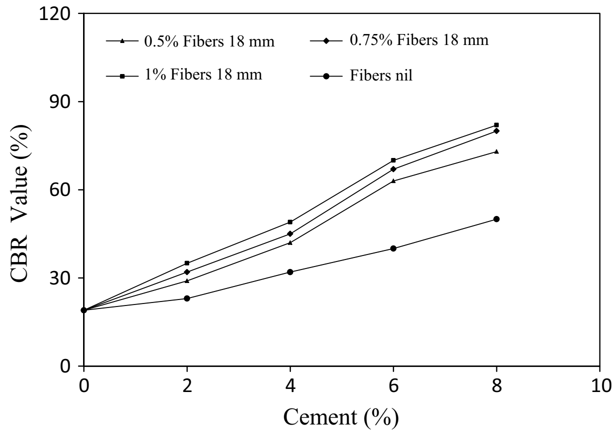
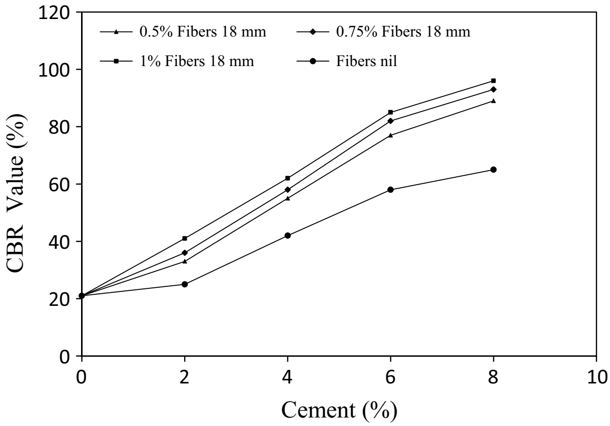


Fig. 6 Variation of CBR value with cement for different combinations of MSWI ash and fiber content 0.5–1% after curing period of 4 days (18-mm fibers)

Fig. 7 Variation of CBR value with cement for different combinations of MSWI ash and fiber content 0.5–1% after curing period of 28 days (18-mm fibers)



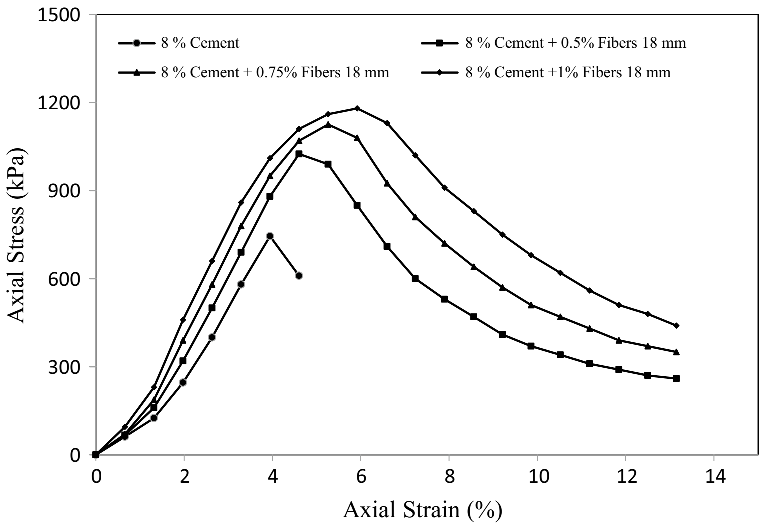


Fig. 8 Stress strain curves for different combinations of MSWI ash, cement and fibers after 28-day curing

3.1.5 Effect of curing period

The inclusion of cement content from 2 to 8% and fiber content of 1% for 6 mm cut length showed an improvement in CBR value from 73 to 400% and 106 to 480% after 4 and 28 days, respectively. Similarly, with the addition of cement content from 2 to 8% and 1% fiber content, the CBR value has been improved from 120 to 433% (12 mm cut length of fibers) and 133 to 447% (18 mm cut length of fibers) after curing period of 4 days and 146 to 513% (12 mm cut length of fibers) and 173 to 540% (18 mm cut length of fibers) after 28-day curing period (Fig. 9). Load penetration curves were obtained by varying cement content from 2 to 8% and fiber content from 0.5 to 1% for cut length of 18 mm (Fig. 10) for 28-day curing period.

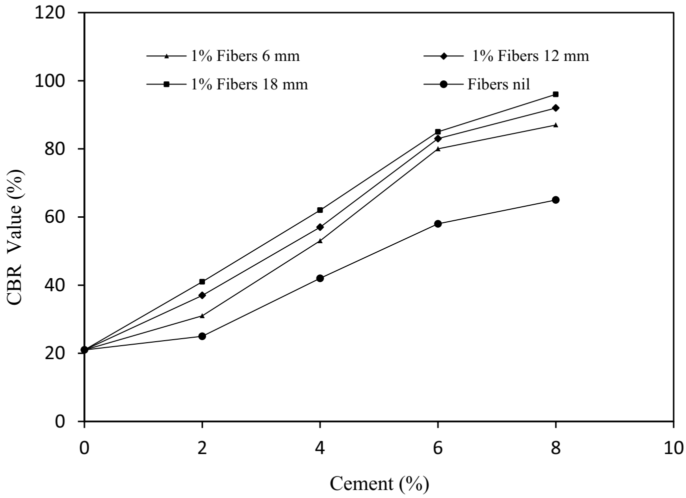
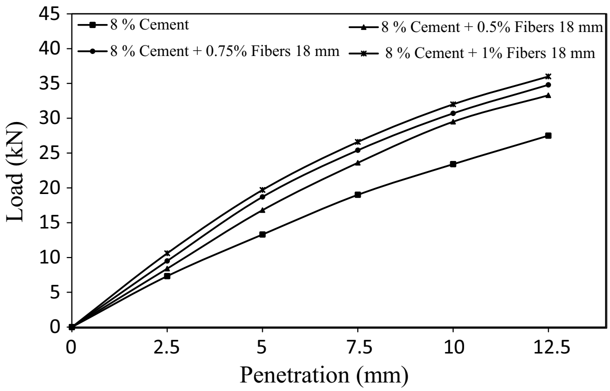


Fig. 9 Variation of CBR value with cement for different cut lengths of fibers in MSWI ash after curing period of 28 days (1% fiber content)

Fig. 10 Load versus penetration curves for different combinations of MSWI ash with 8% cement and fiber content 0.5–1% after 28-day curing period (18-mm fibers)



3.2 Multiple linear regression analysis and statistical results of CBR

The trend of CBR values for different combinations of MSWI ash, cement and at 1% fibers after 28 days under soaked conditions is shown in (Fig. 11). It was observed that on increasing cement and fiber content in MSWI bottom ash, the CBR value of mix specimen also increased. Under soaked condition, as represented in (Fig. 11), when MSWI ash was introduced with cement only, then the maximum CBR value was achieved as 65%, while in case of fiber-reinforced MSWI ash, it was exhibited as 96%. Under unsoaked condition, when MSWI ash introduced with cement only, then the maximum CBR value was depicted as 34%, while in case of fiber-reinforced MSWI ash, it was found to be 38%. Thus, it is revealed that the fiber-reinforced bottom ash is more advantageous than that of unreinforced bottom ash under soaked condition.

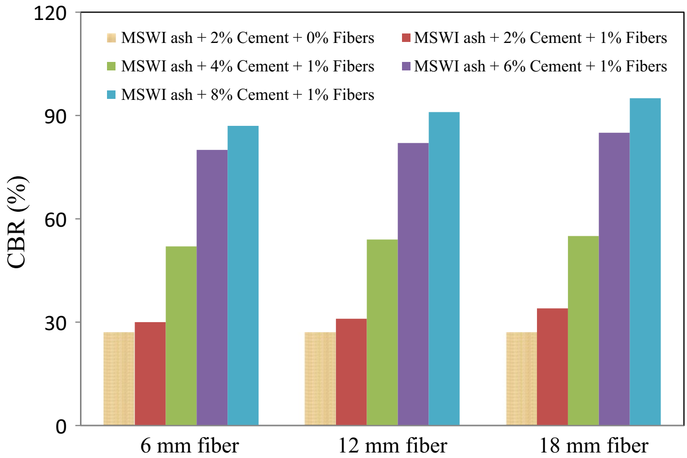


Fig. 11 CBR trend in different combinations of MSWI ash, cement and at 1% fiber under soaked conditions

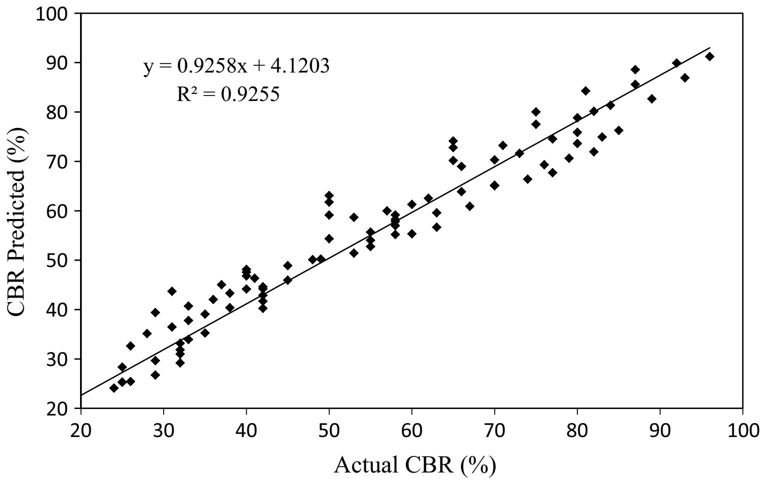


Fig. 12 Predicted and observed CBR values enumerated from regression analysis under soaked conditions

The estimated and predicted CBR values under soaked and unsoaked conditions are depicted in Figs. 12 and 13, respectively. The predicted equation obtained from regression analysis is:

$$\mathrm{CBRp}_{\text{Soaked condition}} = (1513.44) - (15.16 \times \mathrm{MSWI}) - (7.68 \times C) + (1.88 \times F) + (0.22 \times \mathrm{FL}) + (0.46 \times \mathrm{CP})\ \left(R^2 = 0.93\right) \quad (3)$$

$$\mathrm{CBRp}_{\text{Unsoaked condition}} = (-6480.54) + (64.93 \times \mathrm{MSWI}) + (67.41 \times C) + (68.7 \times F) + (0.1 \times \mathrm{FL}) + (0.43 \times \mathrm{CP})\ \left(R^2 = 0.92\right) \quad (4)$$

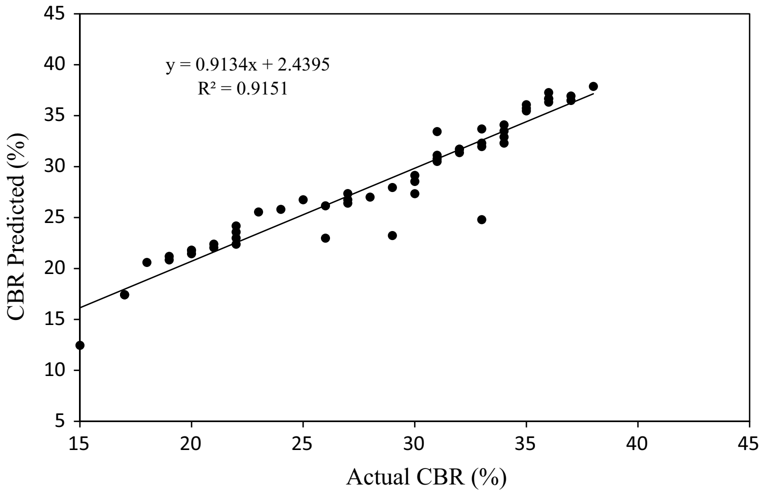


Fig. 13 Predicted and observed CBR values enumerated from regression analysis under unsoaked condition

where MSWI ash, *C*, *F*, FL and CP are MSWI ash content in %, cement in %, fiber in %, fiber length and curing period in days, respectively. The coefficient of determination (R^2) was observed as 0.93 and 0.92 for Eqs. (3) and (4), respectively. During statistical analysis, it was observed that all considered parameters significantly affected the CBR value under soaked and unsoaked conditions at $P < 0.05$ level of significance.

4 Conclusions

The application of the bottom ash yielded from MSW incinerators is found in the pavement and highway constructions. The following prominent conclusions were deduced from the present investigations.

4.1 Recommendations

The finished product could be a good alternative over the conventional material and has the potential to overcome the environmental issues. It is proposed that mix specimens of MSWI ash and cement along with fiber in optimum proportion can also be effectively used as sub-base and base materials for the roads construction, back filling and improvement in soil bearing capacity of the structure.

- The CBR value of unsoaked and soaked samples of MSWI bottom ash was found to be 15 and 19%, respectively. As per IRC-SP 20 (IRC 2002), the sub-base material should have minimum soaked CBR of 15% in case of rural roads. From the CBR results, the soaked CBR value of MSWI ash increases with the addition of cement. Subsequently, due to increase in cement content from 2 to 8%, there was an improvement in CBR values as 71.65 and 141.67% for MSWI ash under unsoaked and 4-day soaked conditions, respectively.

- Due to the inclusion of cement content from 2 to 8% along with 1% fiber in the overall mix, there was an improvement in CBR values from 33 to 140% in unsoaked condition, whereas an improvement of 133–447% and 173.34–540% was observed in soaked CBR values after 4- and 28-day soaking, respectively. This may be attributed to the fact that the inclusion of fiber in the mix improves its load deformation behavior by interacting with the soil particles mechanically through surface friction and also by interlocking.
- Multiple linear regression analysis performed during the study investigates that the coefficient of determination, i.e., R^2 value, is 0.93 and 0.92 for soaked and unsoaked conditions, respectively, which reveals that the experimental results are in good agreement with the predicted values.

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