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Research article

Feasibility in the development of engineered stone using incinerated municipal solid waste

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ABSTRACT

Owing to the exponential growth of industrialization and urbanization, an increased scarcity and spiraling cost of the landfill sites resulted in environmental burden in disposing of waste. These waste residues needs to be warranted either safe disposal or recycling. One such waste is the incinerated municipal solid waste (MSW) ashes accounted in producing about 6% per year in India. In the present study, MSW ashes were utilized in the development of polymer based engineered stone. A bio-based cashew derived hardener blended with epoxy resin was used as a polymeric binder at varied weight percentages viz., 10%, 15%, 20%, 25% and 30% respectively. Structural, physio-mechanical and durability aspects ascertained a feasibility of the developed engineered stone. Two-stage optimization techniques i.e. cement-based for waste residues and polymer-based for composite employed. Engineered stone developed using particulates of normalized ratio 78:22 (fly-ash: bottom ash) and polymer binder at a dosage greater than 20 wt% resulted in better properties such as flexural strength in the range of 21.5–32 MPa and considered as a high quality stone as per ASTM standards. Similarly, a least water absorption (< 0.3%), porosity (0.001%) and relative wear and tear loss (< 0.8%) was observed. Polymer blended composite immobilize the leachate of heavy metals. The present research outlines the constraints in the waste disposal and provides a suitable solution for effective utilization of incinerated ashes in the construction sector.

1. Introduction

Energy recovery specifically electricity from municipal solid waste (MSW) through incineration process has obtained a massive attention in the world wide [1–3], however, the secondary waste generated during the recovery process has pursed a strategic plans in the management under effective utilization of the waste rather landfill [4–6]. In Asian countries, about 1.5 Lakh tonne of MSW generated per day and only about 20% are processed and remaining are landfilled [7]. Among the various countries, United State stands first in generating a huge MSW with low recycling rates [8]. Other major countries such as Japan, France, Sweden, Norway, Germany and India [9] possesses the incinerated plant to recover the energy. Typical secondary waste generated after incinerating MSW are fly-ash and bottom ash [10]. Hence, the above secondary waste has to be warranted by effective utilization in the field of construction sector. Moreover, the above waste are utilized as a supplementary material in concrete and mortar which resulting in better properties [11].

Artificial stone (Engineered stone) is one of the construction material diligently uses waste materials for the development. An arise of engineered stone over ornamental (natural) stone is owe to the reduced consumption of natural resources. As reported in literature [12], to develop a 330 m^2 of particle board/slab, approximately 30 m^3 of natural stone has to be extracted, out of which 20 m^3 of stone remains as waste in the quarry. Moreover, compared to the artificial stone, in ornamental stones, the wastages are high, products are in irregular shapes, faulty and non-standard. Apart from this, some losses are inevitable with respect to deposit characteristics, stone quality and the cutting process in the natural stone [13]. In the case of cost comparison, the volume consumption and unit price (square feet) of the engineered stone are higher than that of natural stone, however, utilization of waste as a byproduct in the development of artificial stone paves an avenue for

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Table 1
Chemical composition of raw materials.

Oxides	Al_2O_3	SiO_2	Na_2O	MgO	K_2O	CaO	Fe_2O_3	SO_3
Cement	4.50	18.85	0.16	0.89	0.39	66.5	4.96	2.4
Fly-ash	3.07	4.65	9.82	2.01	4.58	43.91	2.96	9.72
Bottom ash	47.96	28.56	1.48	0.49	0.62	16.8	1.26	3.06

better application with cost effectiveness [14]. Engineered stone comprised of waste material as particulates bonded over cement-based or polymer based binder. At most cases, polymer based resins are preferred for the better properties. Certain constrains in the utilization of the polymer binders viz., binder ratio, composition, type of resin, processing temperature, curing, etc., which influences the properties of the engineered stone [15,16]. Hence, a careful consideration in selection of the polymeric binder is required.

From the previous studies, it is ascertained that epoxy resin with amine-based hardeners are used as a binder, moreover, these are synthetic hardeners. Alternative to the above, bio-based hardeners could also be used in the aspects of natural resources and eco-friendly environment. One such bio-based amine derived from cashew nut shell possess about 5–6% cardanol, 18–20% cardol and 70–75% anacardic acid [17,18]. This amine possess hydrophobicity with visco-elastic behavior due to its long aliphatic side chain.

In this regard, the present research deals with the effective utilization of MSW ashes in the development of engineered stone using bio-based amines.

1.1. *Significance of the study*

Secondary waste from municipal solid waste incineration has been used widely in the construction sectors as supplementary material with wide spread applications in cementitious composite [19–22] of mortar, lightweight aggregates, artificial aggregates, filler material, etc. Although, its replacement level were limited since higher percentage of replacement would lead to leach out of heavy metals [23]. Cement-based binders fails to immobilize the heavy metals from leaching, in contrast, polymer binder firms the materials by controlling the movement of ions/heavy metals. Considering this limitation, the present study extended the application to polymer composites significantly focusing on maximum usage of waste residues. In addition, the study emphasizes on bio-based polymers in the development of engineered stone using waste residues.

2. Materials and methods

2.1. *Materials used*

Incinerated municipal solid waste ashes such as fly-ash and bottom ash were obtained from Local Market, Mettur, Tamilnadu, India. Fly-ash captured from control devices of flue gases using bag filters, scrubbers or electrostatic precipitation, whereas, bottom ash collected from incineration furnace. Fly-ash enriched in sulphate, calcium compounds, heavy metals and chloride, whereas, bottom ash consist lower concentration of heavy metals and soluble salts than that of fly-ash. Ordinary Portland cement of grade 53 obtained from Ultratech cements, Coimbatore, Tamilnadu, India has been used in the study which possessing specific gravity of 3.15 and standard consistency of 25. A particle size distribution of cement determined by sieve analysis typically lies in the range of 1–50 μm. The chemical composition of the raw materials characterized through XRF (X-ray fluorescence) analysis and the details are presented in Table 1. A polymeric resin Diglycidyl bisphenol ether (DGEBA) and cashew derived bio-based hardener was obtained from Roto polymers, Chennai, India.

Table 2
Compressive strength of mortar.

Cement (%)	Fly-ash (%)	Bottom ash (%)	Average stress (MPa)
10	50	40	9.56
10	60	30	10.21
10	70	20	10.68
10	80	10	8.72
10	40	50	7.15
10	30	60	7.05
10	20	70	5.84
10	10	80	4.72

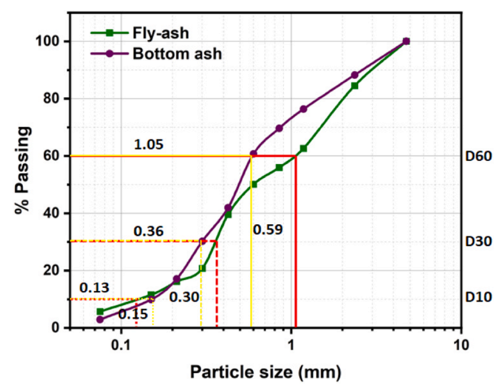

Fig. 1. Particle size distribution of incinerated MSW.

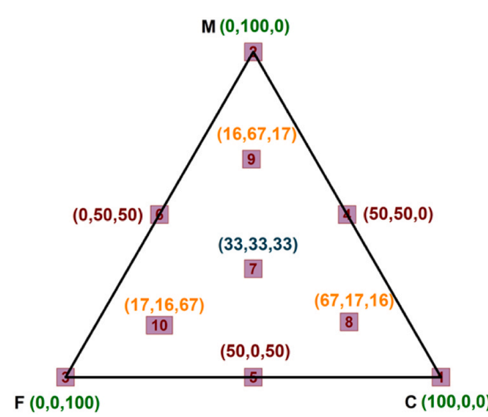

Fig. 2. Granulometric classification – A simple lattice method.

2.2. *Mix ratio – optimization of incinerated ashes*

Fly-ash and bottom ash are used as a filler material in the development of artificial stone. The ratios of the above waste are to be maintained thereby varying the percentage of the binder to achieve the desired properties of the stone. In this regard, a cement mortar cubes are cast at varying ratios of fly-ash and bottom ash to determine the optimized mix through compressive strength. The test results of the mortar (Table 2) infers that fly-ash and bottom ash at a ratio of 70:20 shows the highest compressive strength of 10.68 MPa. Therefore, the particulates such as fly-ash and bottom ash blended at a normalized ratio of 78:22 in

Table 3
Density of MSW ashes.

Mixture	Weight ratios of MSW			Density (g/cm^3)
	Coarse	Medium	Fine	
1	1	0	0	1.32
2	0	1	0	1.25
3	0	0	1	1.18
4	1/2	1/2	0	1.23
5	1/2	0	1/2	1.19
6	0	1/2	1/2	1.11
7	1/3	1/3	1/3	1.37
8	2/3	1/6	1/6	1.39
9	1/6	2/3	1/6	1.34
10	1/6	1/6	2/3	1.21

the development of the stone.

2.3. Sample preparation/formulation of filler materials

A particle size of the incinerated ashes were analyzed through sieve analysis (Fig. 1) and the particles passing under 850 μm were considered for the production, whereas, the coarser particles (> 850 μm) was further crushed in a jaw crusher and reutilized to attain a zero wastage. According to the Brazilian standards, high packaging dense material possess better properties with reduced pore volume [24]. Hence, a granulometric classification was made using simple lattice method – a ternary diagram as shown in Fig. 2. A classified particles ((i) coarse: 1.18–0.45 mm, (ii) medium: 0.45–0.075 mm and (iii) fine: > 0.075 mm) were filled in a known volumetric medium and compacted at a pressure of 10 kg/m^2 and repeated at 3 consecutive vibration. Table 3 illustrates the packaging density of the incinerated ashes and Mix 8 found to be the highest density and considered for the production of stone.

2.4. Preparation of artificial stone

The raw materials such as fly-ash and bottom ash are oven dried at 105°C to remove the moisture content. Followed by the above, the incinerated ashes such as fly-ash and bottom ash are filled in a pan mixer at a ratio of 78:22. Though, the optimized mix of fly-ash and bottom ash formulated in cement-based is 70:20, however, in engineered stone, cement is excluded and only the filler materials is used. Hence, an obtained mix ratio of solid waste (70:20) normalized to 78:22. Eqs. 1 and 2 represents the normalization of fly-ash and bottom ash respectively. The mixture dry mixed at a speed of 120 rpm/min for 1 min. Then, the polymeric binder are added to the mixture at varied percentages and mixed at a same speed for 2 min. After thorough mixing, the matrix is transferred to the vibrating medium for 1 min to remove the air voids. The air-entrapped matrix is placed in a mould of size 300 × 300 × 12 mm and cold pressed at a pressure of 150 kg/cm^2. The developed stone was cut into various sizes to analyze the physio-mechanical properties viz., density (50 ×50 mm), flexural (160 ×40 mm), abrasive wear (100Ø mm) and water absorption (50 ×50 mm). A fractured sample about 10 g taken after mechanical analysis and oven-dried at 105°C to remove atmospheric moisture and then used for structural (FTIR) and microstructural (SEM, XRF) analysis. An average of three samples considered for the validation of results.

$$\text{Fly} - \text{ash} = \frac{70}{70+20} \times 100 = 77.78 = 78 \quad (\text{approximately}) \tag{1}$$

$$\text{Bottom ash} = \frac{20}{70+20} \times 100 = 22.22 = 22 \quad (\text{approximately}) \tag{2}$$

2.5. Characterization techniques

The engineered stone have been characterized by the following techniques. Fourier Transform Infrared (FTIR) spectral analyses were carried out by attenuated total reflection (ATR) method using the Shimadzu IR-Affinity−1S instrument (Japan). The elemental composition of the incinerated municipal solid waste was measured by the X-ray Fluorescence micro-analyzer, Horiba XGT−5200 (Japan). Field emission scanning electron microscopy (FE-SEM) images of the fractured stone was captured by Carl Zeiss (USA), Sigma with Gemini column with a resolution of 1.5 nm.

The density of the stone was determined according to ASTM/NBR 15845 by measuring the mass-to-volume ratio. Similarly, water absorption (ASTM D570 [25]), and porosity (calculated using Eq. 3) of the stone was measured.

$$\text{Porosity} = \frac{V_p}{V_b} \tag{3}$$

Where, $V_p = \frac{W_{Saturated} - W_{Dry}}{Density\ of\ water}$.

V_b – Volume of sample.

According to ASTM C348–18 [26], the flexural strength of the stone was characterized for a specimen size of 160 × 40 mm and tested in INSTRON 8801, a servo-hydraulic universal testing machine (United Kingdom). Using an H22 wheel, a specimen of size 100 mm in diameter by 12 mm thick, the Taber abrasion test was performed at 500 cycles. Presence of heavy metals in the MSW ashes and its composite was determined by ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy) method by diluting 2 mm sieved sample in acetic acid of pH 4.5 and maintained the liquid to solid ratio of 20:1. The agitation carried out in rotary tumbler at a speed of 30 rpm for 20 h. An obtained suspension filtered through 0.45 μm filter membrane and then acidified in nitric acid to pH less than 2. A validation carried out for triplicate. The

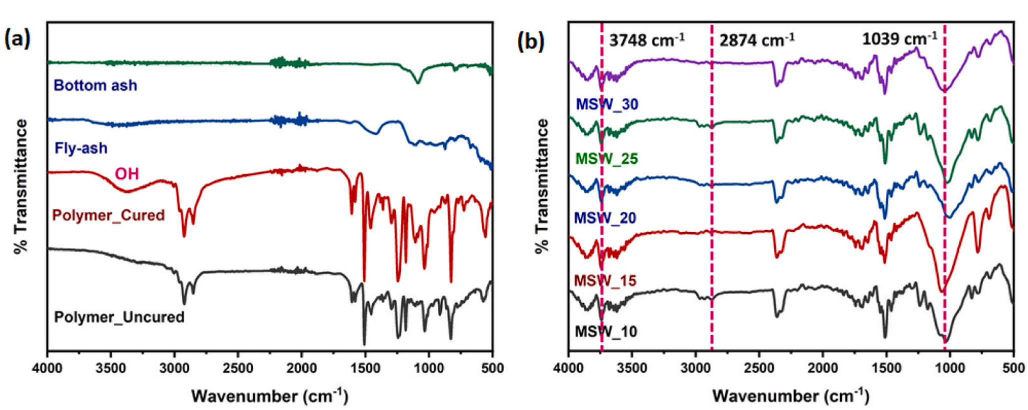

Fig. 3. FTIR analysis (a) Polymer and MSW ash (b) Composites.

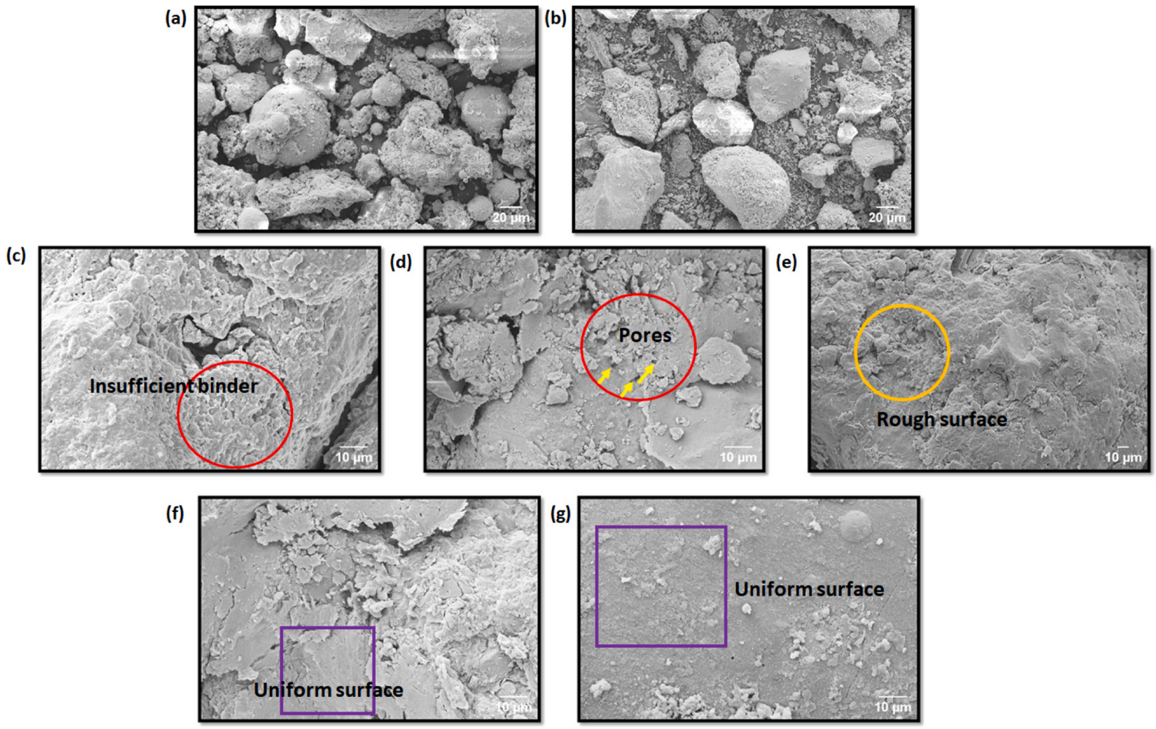

Fig. 4. (a) Fly-ash (b) Bottom ash (c-g) MSW_10, MSW_15, MSW_20, MSW_25, MSW_30.

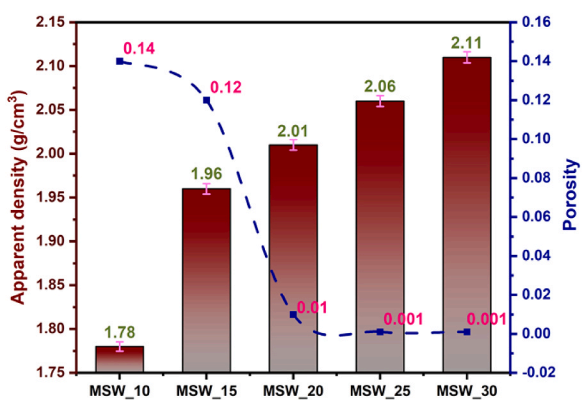

Fig. 5. Apparent density and porosity of an engineered stone.

elements meet the standard EPA Method 6010D.

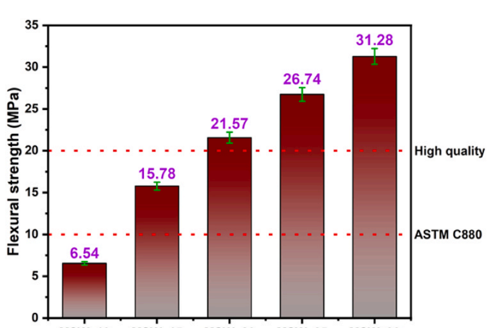

Fig. 6. Flexural strength of an engineered stone.

3. Results and discussion

3.1. Structural and micro-structural analysis

The structural formulation of polymer (uncured/cured), raw material and composites were ascertained through FTIR analysis (Fig. 3). Appearance of bandwidth at 917 cm^{-1} (epoxy ring) and 3287 cm^{-1} (N-H stretch) in polymer uncured was disappeared in polymer cured and MSW composites with a new bandwidth formation at 3748 cm^{-1} due to the epoxide ring opening with OH stretching [27]. A bandwidth at wavenumber 2912 cm^{-1} and 2874 cm^{-1} indicates the aliphatic stretching vibration of polymer composites. A strong bandwidth at 1039 cm^{-1} appeared in incinerated ashes and MSW composites refers to the asymmetric stretching of Si-O-Si bond [28].

The microstructural analysis of the incinerated ashes and MSW composites were studied through SEM micrographs of fractured sample after mechanical analysis as shown in Fig. 4. The morphology of the incinerated fly-ash was observed to be sub-spherical and spherical glassy particles with porous and rough surface texture due to the condensation of heavy metals and volatile salts [29]. Meanwhile, an incinerated bottom ash is irregular, fibrous, angular dense particles with less porous structure [30] than that of fly-ash. At lower concentration of polymeric binder (MSW_10), the resin becomes insufficient to encapsulate the filler materials; for MSW_15 and MSW_20, a micro pores and rough surface observed respectively. While increasing the binder concentration (MSW_25 and MSW_30), a binder dispersion enhanced and encapsulate the fillers uniformly resulting in compact and dense structure with reduced porosity, in addition, the same evidenced from the values of apparent porosity (Fig. 4f-g).

3.2. Physio-mechanical properties

The physical properties viz., apparent density and porosity of the MSW composites were presented in Fig. 5. From the observation, the density of the composites increased with increasing binder concentration (10–30 wt%) and attained the maximum density of 1.98 g/cm^3 for MSW_30. The density of the developed MSW engineered stone was

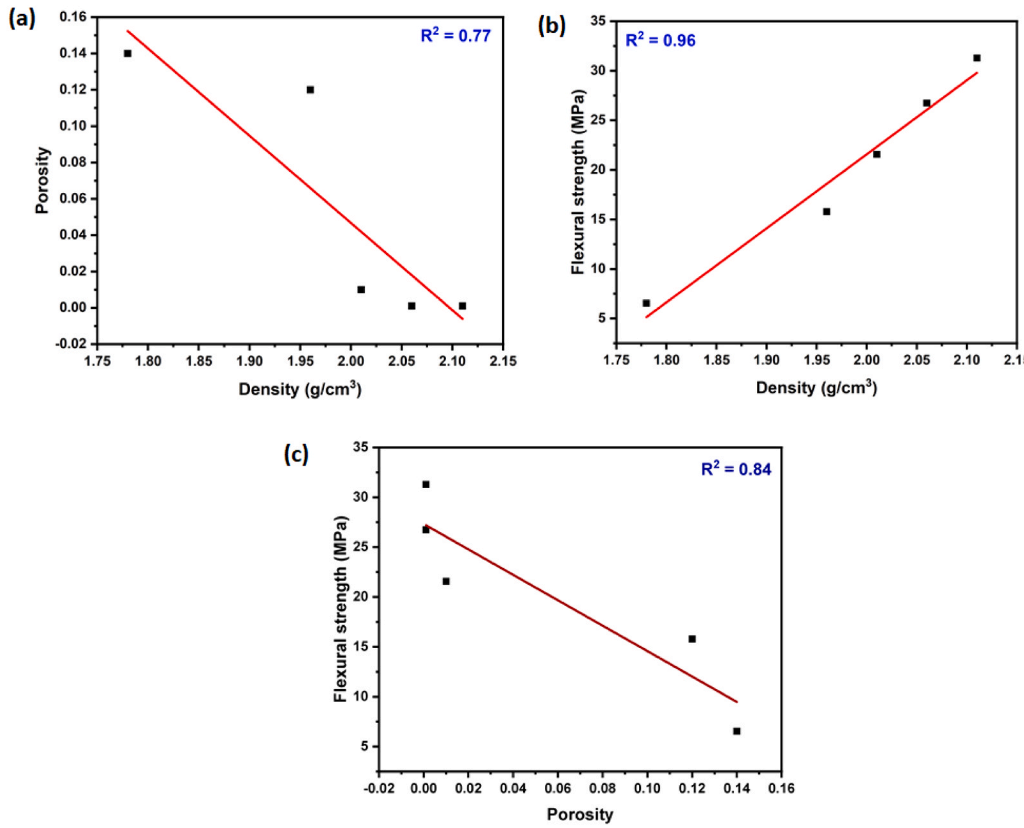

Fig. 7. Correlation among density, porosity and flexural strength.

found to be lower than that of market available stones (2.4–2.5 g/cm^3) [12,31] and stones made of varied waste such as PET/gravel/glass fines (2.3–2.15 g/cm^3) [16,24,32–35]. This reduced density is attributed to the composition of the stone consisting low density fillers such as fly-ash (1.12 g/cm^3) and bottom ash (1.25 g/cm^3) and polymeric resin of 1.18 g/cm^3. With this reduced density, the logistical cost could also reduce as it relies on the material density [36]. Porosity of the composite was ascertained through occurrence of cracks and flaws of a material. The developed composite showed the maximum apparent porosity of 0.14% for MSW_10. Meanwhile, increasing the binder percentage by 5 wt%, the porosity reduced significantly to the least of 0.001. This phenomenon is attributed to the fineness of the filler and particle consistency with the polymeric binder. In addition to the above, the vacuum pressure, compaction, heating and cooling rate, could also influence the porosity of the composite [14].

A flexural strength of the developed stone was ascertained through 3-point bending test as presented in Fig. 6. At lower dosage of polymeric binder (10 wt%), the MSW_10 composite exhibited minimal flexural strength of 6.54 MPa. When increasing the binder percentage beyond 10 wt%, the flexural strength gradually improved to 31.28 MPa for MSW_30. As per the standard ASTM C880, the minimum flexural strength of the engineered stone should be 10 MPa which achieved at MSW_15 (15.78 MPa) composite. In addition, for high quality stones (strength greater than 20 MPa), the composite satisfied the requirement at 20 wt% of polymeric binder and beyond 20 wt%, an enhanced strength was achieved which is equivalent to the engineered stone made of granite (31–32 MPa) and marble dust (10.76–25.70 MPa) [12,16,35,37].

A relationship among the density, porosity and flexural strength of the developed composite determined by correlation through regression method as shown in Fig. 7. Porosity showed a linear correlation with density and flexural strength of value R^2= 0.77 and R^2= 0.84 respectively. While, density with flexural strength showed strong positive correlation of value R^2= 0.96.

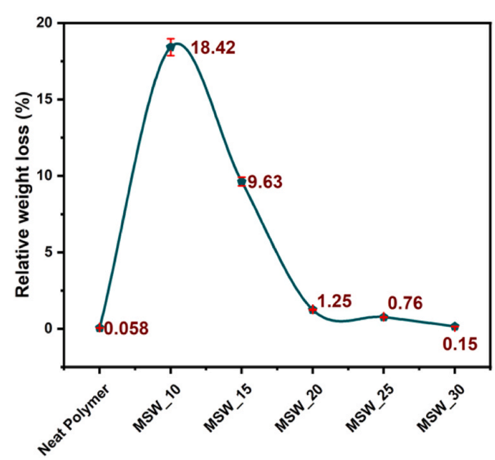

Fig. 8. Wear and tear loss of polymer and MSW composite.

The relative weight loss of a material was ascertained through wear and tear by subjecting the sample to the loading rate of 0.25 kg for 500 cycles (Fig. 8). A maximum weight loss of 18.42 g and 9.63 g was noticed for MSW_10 and MSW_15 composite respectively. Meanwhile, increasing the binder percentage beyond 20 wt%, the abrasive wear gradually reduced to 1.25 g, 0.76 g and 0.15 g for MSW_20, MSW_25 and MSW_30 respectively. On other hand, a neat polymeric binder possesses a least weight loss of 0.058 g due to its long aliphatic side chain which attributes resilient nature [38]. Based on the above, the developed composite could be recommended for heavy traffic (resin ≥ 20 wt%), medium traffic (resin – 15 wt%) and for indoor applications (resin – 10 wt%).

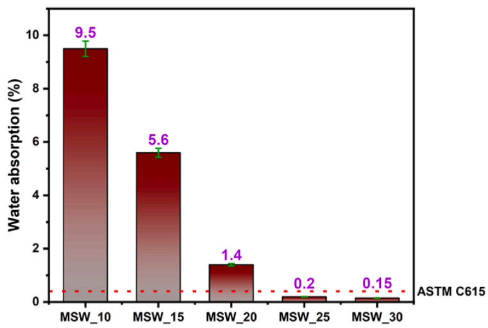

Fig. 9. Water absorption of an engineered stone.

3.3. Long-term performance

Water absorption of the developed composite ascertained after 24 h of immersion (Fig. 9) was found to be high for MSW_10 and MSW_15 of values 9.5% and 5.6% respectively. For MSW_20, the water absorption slightly reduced to 1.4%, whereas, at 25 and 30 wt% of polymeric binder, the composite exhibited a least water absorption of 0.2% and 0.15% respectively. According to ASTM C615, the developed engineered stone classified as Class A1, when the water absorption of the stone less than/equal to 0.4% shall recommended for indoor/outdoor environment and pedestrian floors from low to high traffic areas [39]. Similarly, for coating applications, water absorption should be $\leq$ 0.2% as per NBR 15845 standards.

Presence of heavy metals in an incinerated MSW and its composite was ascertained through leachate analysis as presented in Table 4. From the observation, incinerated ashes possessing higher concentration of lead (> 1.2 mg/L) and arsenic (> 1 mg/L) followed by chromium (> 0.6 mg/L) and barium (> 0.1 mg/L). Least concentration of copper, nickel and cadmium was observed. In the case of composites, leach out of heavy metals was minimized due to the presence of polymeric binder. More precisely, as increasing the percentage of the binder, release of heavy metals is significantly reduced. Since, the polymeric binder binds the particles and limits the leach out of the heavy metals. This phenomenon is supported by the SEM micrographs where the polymer resin encapsulates the filler material thus reducing the particle voids and thus forms a uniform and denser microstructure. Further, FTIR spectrum also supports the complete curing of polymer resin by forming stable polymeric network which retains the fillers within the polymer matrix.

4. Conclusion

The present research facilitates the effective utilization of incinerated MSW ashes in the development of engineered stone using bio-based polymeric resin. Engineered stone developed using particulates such as fly-ash and bottom ash at a normalized ratio of 78:22 and blended over DGEBA and cashew derived bio-based hardener at varied percentage ranging 10–30 wt% respectively. The properties and performance of the developed stone ascertained through various aspects such as physio-mechanical, structural and durability aspects. The findings inferred that as percentage of resin increases, the functional characteristics of the engineered stone also increased. However, the desired characteristics of the stone as per standards and quality achieved at a mix MSW_25. At 25 wt% of polymeric binder, flexural strength of 26.74 MPa, wear loss of 0.76 g and water absorption of 0.2% was observed. A positive correlation observed among density, porosity and flexural strength of the engineered stone. Moreover, the microstructural studies correlates with the performance of the composite by evidencing micro-pores, rough surface and filler consistency with the binder dosage. Toxic leaching of heavy metals from the developed composite were minimized and as well as within the permissible limit owe to the resin bonded. Hence, utilization of municipal solid waste residues as a supplementary material in polymer based composite would valorize the waste and replace conventional fillers by providing technical feasibility and supports solid waste management.

5. Practical applications and future scope of the study

The developed engineered stone using incinerated municipal solid waste residues such as fly-ash and bottom ash at higher mix ratio enables maximum utilization of waste which significantly reduce the disposal rate, with a dual benefit of solid waste management and supplementary material for construction sectors. The developed stone under laboratory analysis found to be light-weight and possesses desirable strength than that of market available stones of density 2.4–2.5 g/cm^3 and strength of conventional mineral fillers used in the development of engineered stone made of granite (31–32 MPa) and marble dust (10.76–25.70 MPa). In order to explicit the market quality, a large-scale implementation of the product and its potential techno-economic assessment such as material cost and life-cycle analysis needs to be analyse which is the future scope of the study.

CRediT authorship contribution statement

Deepasree Srinivasan: Writing – original draft, Data curation, Conceptualization. **Ezhilmathi N:** Methodology, Data curation. **Sangeetha R:** Writing – review & editing. **Venkadapriya S:** Writing – review & editing. **Venkatraman V:** Formal analysis.

Consent for publication

Not applicable.

Ethics approval and consent to participate

Not applicable.

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Table 4
Heavy metal analysis of raw material and MSW composite in mg/L.

Parameters	Barium (Ba)	Arsenic (As)	Chromium (Cr)	Cadmium (Cd)	Nickel (Ni)	Copper (Cu)	Mercury (Hg)	Lead (Pb)
Fly-ash	0.15	1.1	0.64	0.07	0.06	0.02	< 0.01	1.26
Bottom ash	0.09	1	0.69	0.04	0.05	0.02	< 0.01	1.34
MSW_10	0.12	0.08	0.02	0.02	0.02	0.02	< 0.01	0.85
MSW_15	0.11	0.03	0.02	0.02	0.02	0.02	< 0.01	0.36
MSW_20	0.05	0.01	0.02	0.02	0.02	0.02	< 0.01	0.14
MSW_25	0.04	0.01	0.02	0.02	0.02	0.02	< 0.01	0.07
MSW_30	0.04	0.01	0.02	0.02	0.02	0.02	< 0.01	0.02
Permissible limit (TCLP regulatory)	100	5	5	1	-	-	0.2	5

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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