Composite tiles from waste plastics and fly-ash: modelling the influence of composition on mechanical and physical properties

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Abstract: Fly-ash is a waste from coal-based thermal power plant. Grocery bags commonly made from polyethylene and packaging foam which is expanded polystyrene are also two types of waste plastics. All these solid wastes pose an environmental threat. In this article, development of composite tiles from these solid wastes and their physico-mechanical characterisation has been described. Mass ratios of polyethylene to fly-ash (A) and polystyrene to fly-ash (B) were correlated with the respective solvent resistances, tensile and flexural strengths of the tiles through simple equations. The agreement of the proposed models and the experimental data was found to be excellent. Indian standard for the common ceramic tiles is compared with the developed ones. The product is found suitable as a wall tile. This may help in sustainable disposal of these bulk solid wastes whose safe disposal is still a huge problem.

Keywords: waste thermocol; polyethylene bag; fly-ash; composite tiles; mechanical strength; solvent absorption; model.

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1 Introduction

Huge quantities of waste materials are generated worldwide in course of the so-called advent of human civilisation through industrialisation and increase in population. Disposal of waste materials in a sustainable way is a great challenge. For solid wastes, the situation is more difficult since it requires land to dispose of. Many industrial and municipal solid wastes (MSWs) are there; among them fly-ash (FA) and waste plastics are large in volume.

Civilisation demands power and FA is a solid waste generated from thermal power plants when lignite coal with high ash-content is burnt. The ash is captured by the emission-control equipment of a power plant stack. According to a report of the Central Electricity Authority of India published in April 2020, FA generated in India during the first half of 2019–2020 was 129 million tonnes of which 100 million tonnes are utilised (Central Electricity Authority, GOI, 2020). FA causes water, air and soil pollution. In 2020, it was estimated that FA disposal pond took about 65,000 hectares of land (Yousuf et al., 2020) in India. In a country like India where the land-to-population ratio is very low, bulk utilisation of FA is preferred. This situation prevails in other countries like

China or the USA who depend on thermal power. Utilisation of FA is generally made in cement plants (Argiz et al., 2017) and for various construction materials like bricks (Prasanth et al., 2018), paver blocks (Pawar and Bujone, 2017) and a few composite materials (Bamigboye et al., 2019).

Another waste material that has posed a threat to human civilisation is disposed of plastic items. In 2015 the global consumption of plastic was about 298 million tonnes per year. The proportion of plastic waste in MSW of India varies between 3–12%. A global average of plastic consumption is 28 kg per person per year whereas, in India, the figure is 11 (Ministry of Housing and Urban Affairs, GOI, 2019). A recent 2019 report of the PTI shows that India generates 9.46 million tonnes of plastic waste annually, of which 40 percent remains uncollected. Most of the waste plastic still land up in a landfill since source separation of plastic is not yet practised in India and some other countries at large. In 2010, it was estimated that in the US, plastic waste is occupying 20% of available landfill spaces by volume (Choudhary et al., 2014). Another way of disposing of waste plastic is incineration which pollutes the air by discharging dioxin gas and fine particles. After the COVID-19 pandemic, generation of waste plastics including discarded personal protection equipment (PPE) became almost double all over the world (Silva et al., 2021). Grocery items, that were carried in paper bags before the pandemic, are now carried in plastic bags for facilitating sanitisation. Unplanned littering of these waste plastics is not only a big threat to the environment but also to the health and safety of the common people coming in contact with.

Polyethylene (PE) and expanded polystyrene are among the most popular commodity plastics used in daily life. Expanded polystyrene (EPS) foam that is Styrofoam or Thermocol used for bulk packaging and containers whereas polyethylene is generally used as films and carry-bags. Polyethylene is also used for making grocery bags and PPEs are mainly made of polypropylene (PP) and polyethylene terephthalate (PET) (Silva et al., 2021). The best possible way of disposal of waste plastic should be using them in bulk construction materials. For such use, a high temperature is required which eliminates the pathogens, if any.

Research on using waste plastics for road construction (Ministry of Housing and Urban Affairs, GOI, 2019), in concrete blocks (Reddy et al., 2019) and aggregates (Petrella et al., 2020) have already been reported. Although a few reports are available of using FA and waste plastic for preparation of tiles, none of them used two types of waste plastics together with FA.

Konin (2011) used polypropylene-based waste plastic packaging material as supplement or replacement of cement with sand and water to prepare construction tiles. They varied the proportion of waste plastics from 0–50% weight in the total mix. It was observed that tiles containing 40% weight plastic melt were acceptable as roof tiles having sufficient mechanical strength and less water permeability. Sonone and Devalkar (2017) prepared concrete bricks from FA and waste plastics in addition to cement and stone crush. Shredded polyethylene of 0–10% weight was used with 45% weight of FA. Maximum compressive strength obtained was 20.34 MPa (wet) and 21.017 MPa (dry) which were larger than the commercial red clay bricks. Water absorption was also less than the common bricks. Dhawan et al. (2019) prepared paver blocks with waste plastic bags and FA. They used triphenyl phosphate (TPP) flame retardant to reduce the flammability of the blocks caused by the presence of plastics. The tiles were made with various ratios of waste plastic, FA and TPP. Tiles with 75% weight waste plastic, 20% weight FA and 5% weight TPP showed the best performance regarding both fire safety and strength. However tensile strength was the highest for the tiles having no TPP and 90% weight plastic and 10% weight FA. Herki et al. (2013) prepared concrete blocks using waste expanded polystyrene (EPS) after stabilisation with Portland cement, FA and water. They observed a decrease in compressive strength with increase in polystyrene. Jain and Tiwari (2017) also used waste EPS beads to produce lightweight bricks and compared their properties with conventional FA bricks. They observed the bricks are equivalent to conventional second class bricks in terms of strength at a much lower weight.

Aim of the present research was to utilise both of the above bulk solid wastes for the preparation of a composite tile that can be used for construction. For this, the composite material was developed with commercially available carry-bags used for carrying grocery, styrofoam or thermocol thermoformed in the shape of food containers and FA collected from a thermal power plant. The developed material is expected to be an ideal eco-material.

Eco-materials are those that can contribute to the reduction of the environmental burden through their lifecycles. Necessary conditions for eco-materials are energy saving ability, resource-saving ability, reusability, recyclability, structural reliability, chemical stability, biological safety ability, substitutability, amenity and cleanability. Not all the criteria need to be fulfilled for any material to be an eco-material (Shinohara, 2004). Material developed in the present research meets quite a few of the above criteria. If this type of tiles is widely used, the irregular littering of plastic carry bags and thermocol food containers can be managed. The topsoil from which bricks and ceramic tiles are made can be saved and the FA generated from thermal power plants can be disposed of decently.

It was also aimed to find a relationship of the mechanical or physical properties like strength or solvent absorption with the composition of the composite material. A few reports are indeed available on using FA with a particular type of waste plastic as construction materials; however, most of them used a single waste polymer and generally they have produced concrete blocks or bricks. Some of them reported the trend of the mechanical strength of such composites with their composition but none of them tried to fit those data into a mathematical model.

The novelty of this work is in the usage of both types of waste plastics with FA to develop composite tiles and also in the modelling of the strength and swelling data with the respective compositions.

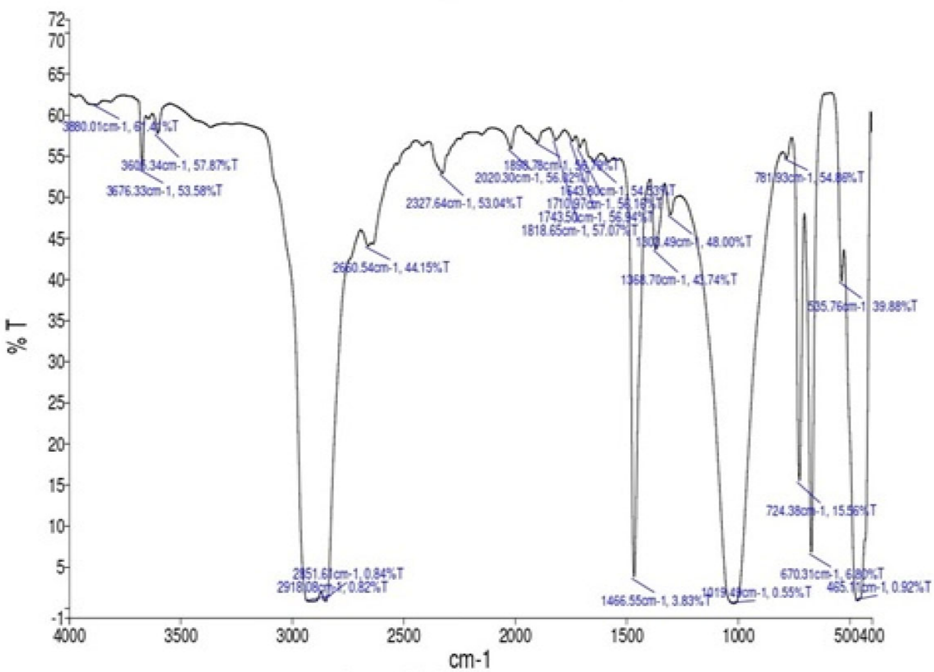
2 Materials and methods

2.1 Materials

- *Plastic waste materials:* Thermocol (expanded polystyrene, PS) plates and containers used for serving food and packaging have been used after thorough cleaning, washing, drying and shredding. Translucent plastic bags (polyethylene, PE) used for carrying grocery from supermarkets are utilised after washing, drying and shredding. FTIR spectroscopic study (Figure 1) of the bag was done in ATR (attenuated total reflectance) mode in a spectrophotometer from Shimadzu (model: IR Affinity-I 8000) within the spectral range of 4,000–400 cm^{-1} using a peak resolution of 4 cm^{-1}. An average of 120 scans has been reported for analysis. The sharp transmission peaks observed at 2,918 and 2,851.6 cm^{-1} are due to asymmetric stretching vibrations of C-H of CH_2 groups, belonging to polyethylene. The sharp peak at 1,466 cm^{-1} marks the bending vibration of C-H, present as a complementary to the earlier stretching vibrations. The transmittances at 1,019 and 724 cm^{-1} characterises the asymmetric and symmetric stretching vibration of Si-O-Si, respectively. Such bonds belong to silica or silicate, possibly present as filler in polyethylene to offer translucency and mechanical strength to the packaging film. Rest of the peaks represents various movements of the bonds which are not much significant.

- *FA:* FA was collected from a nearby thermal power station. Generally FA from lignite coal contains silica (15–45% weight), alumina (10–25% weight), sodium carbonate (0–6% weight), oxides of calcium (15–40% weight), magnesium (3–10% weight), sulphur (0–10% weight) and potassium (0–4% weight). Average particle size range was 50–80 micron (Ghazali and Kaushal, 2015).
- Xylene and Toluene solvents are from SD Chemicals, Mumbai, India; GR grade.

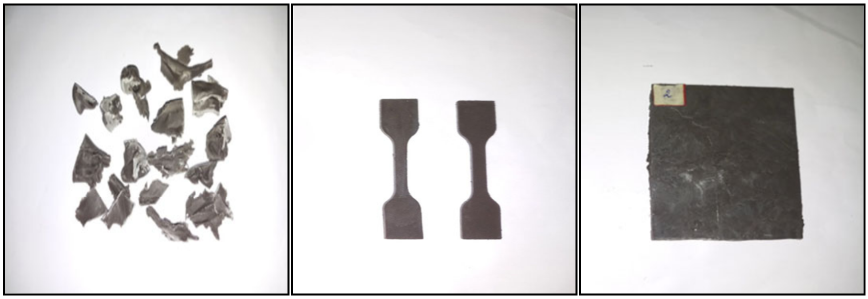
Figure 1 Spectroscopic study of the waste plastic carry bag (see online version for colours)



2.2 *Methods for sample preparation*

Shredded and ground polyethylene films and polystyrene sheets were mixed with FA in different pre-determined compositions by weight. After that, the mixtures were melt-mixed in a Brabender Plasticordor at 130°C using 60 rpm rotor speed to form aggregates of composite materials. The aggregates [Figure 2(a)] were compression-moulded at a temperature of 150°C and with a compressive load of 1,000 KN/m^2 to prepare final product/ samples of different shapes and sizes.

Figure 2 Photographs of the aggregate and samples, (a) aggregate (b) sample for tensile (c) square sample (see online version for colours)



(a) (b) (c)

Dumb-bell-shaped samples [Figure 2(b)] for the study of the tensile strength were prepared from the aggregates by compression moulding. Square (150 mm × 150 mm) tiles of 2.1 mm thickness were also prepared [Figure 2(c)] for other characterisation using a square mould and metal plates. The assembly was heated at 130°C for five minutes and then was subjected to the mentioned load. Silicon oil was used for demoulding after two hours.

2.3 Methods for characterisation

2.3.1 Tensile and flexural strength

Tensile strength was determined by the three-point method using universal testing machine (UTM) (Lloyds) under standard conditions. Flexural strength also known as modulus of rupture or bend strength is a material property, defined as the stress in a material just before it yields in a flexure test. The sample was placed in between two supporting blocks of the MOR testing machine and the load was applied at the centre of the sample. The maximum load at which the sample broke was determined. The MOR was calculated as:

$$MOR = \frac{3WL}{2bd^2} \tag{1}$$

W = load; L = length of the sample; b = width of the sample; d = height of the sample (Callister, 2003).

2.3.2 Swelling test

Since plastic is present in the composite, the swelling test was done with solvent and not with water. For this, samples of specific sizes were collected. The initial weight of the sample was taken and then the sample was dipped into 50 ml toluene solution. Weights of the swelled samples were noted at different intervals of time. Since toluene is a good solvent for both the plastics, the study was only for 10 minutes.

2.3.3 Chemical resistance

Chemical resistance of the sample tiles were evaluated by acid-alkali tests. For these tests, we have selected the two samples with the highest tensile strength and flexural strength values.

2.3.4 Alkali test

Given samples were cut in 1 cm × 1 cm and put into 10% and 20% NaOH solutions. Specimens were put in observation for 24 hrs. After 24 hrs the specimens were removed from the solution, the samples were then dried with tissue paper and the final weights of the specimen were noted.

2.3.5 Acid test

For this test, all the specimen were cut 1cm ×1cm and dipped into the 10%, 20%, 30% sulphuric acid (purity 98%) solution. Specimen put in observation for 24 hrs. After 24 hrs removed from the solution, samples were dried with tissue paper and measured the final weight of the specimen.

2.3.6 Solvent resistance test

For this test solvent was chosen based on polarity. Xylene and acetone were chosen as per the availability. Samples were put in 50 ml of solvent for 24 hrs at 25°C, and the initial and final weight of the samples were recorded.

In all cases, at least four samples were subjected to the test and the average value was reported. Standard deviation between the values is less than 3%.

3 Results and discussion

3.1 Mechanical strength and composition of the composite tiles

Mechanical properties are very often important parameters for identifying the suitability of a material as a construction material. Both the binder and the filler contribute towards the mechanical strength. Here FA is used as a filler and the plastics act as a binder. Again polyethylene (PE) film and expanded polystyrene (PS) behave differently in imparting strength. Hence it would be desirable to predict a correlation between the strength parameters and the composition.

It has already been reported that the tensile strength of a polymer sample filled with spherical filler particles can be expressed as a power equation as below (Wypych, 2016):

$$\sigma_c = \sigma_p \left(1 - a\varphi_f^b + c\varphi_f^d\right) \tag{2}$$

where

σ_c tensile strength of the resultant polymer composite

σ_p tensile strength of the polymer matrix

φ_f volume fraction of the polymer material

a, *b*, *c*, *d* constants depending on the nature of fillers; a is related to stress concentration, *c* and *d* are related to particle size of the fillers.

It is therefore pertinent to assume that not the absolute value, but the ratio of the binder and filler is eventually responsible for the mechanical properties. Hence the observed values are expressed as a function of the ratio of the binder and filler. In this case polyethylene bags and polystyrene foams are acting as binders whereas FA is acting as filler.

Two ratios were defined (A and B) based on the composition of the polymer composite. A is the weight-ratio of the polyethylene bag is to the FA; B is the weight-ratio of the polystyrene foam is to the FA.

Tensile and flexural properties of the composite tiles are recorded in Table 1.

When tensile strength ST is plotted against A (PE/FA), it was observed that tensile strength increases slightly up to a certain value of the PE/FA ratio. After that, it decreased. For the B (PS/FA) versus ST curve, tensile strength remained almost unchangedup to a particular value of PS/FA ratio, after that it decreased (Figure 3). Among the components, both polystyrene and FA are considered as a brittle material. The brittle matrix-filler composites are generally strong with less elongation (Sim et al., 2020). Combined and interacting effects of all the components are responsible for the trend.

Figure 3 Influence of composition on tensile and flexural strength, (a) PE/FA ration vs. tensile strength (b) PS/FA ration vs. tensile strength (c) PE/FA ratio vs. flexural strength (d) PS/FA ratio vs. flexural strength

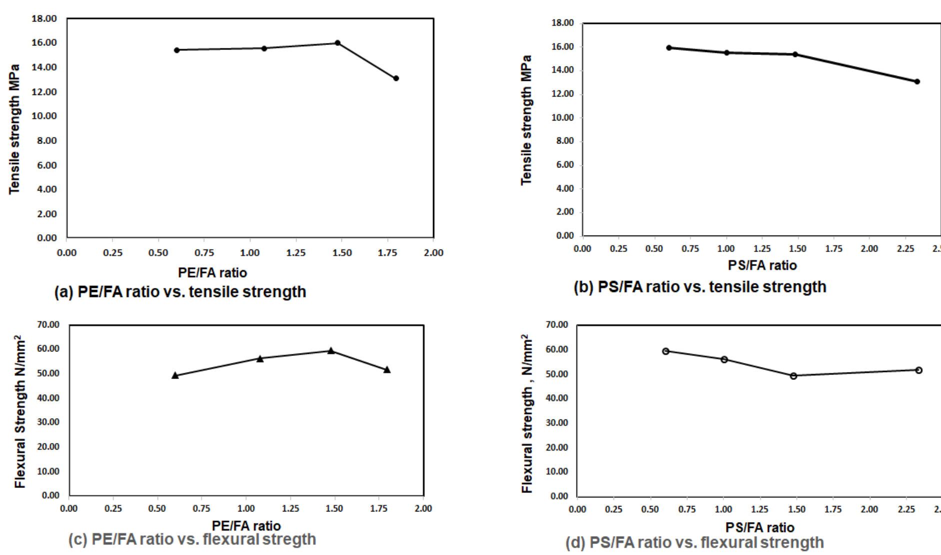


Table 1 Tensile and flexural properties of the composite tiles with compositions

			Tensile properties				Flexural properties			
Sample	*A = PE-/FA*	*B = PS/FA*	*Average area (mm^2)*	*Average thickness (mm)*	*Average load at break (KN)*	*Average tensile strength (ST) (MPa)*	*Area (mm^2)*	*Thickness (mm)*	*Load (MPa)*	*Average flexural strength (SF) (MPa)*
1	1.077	1.000	9.630	1.93	0.1497	15.515	321.8	1.58	0.196	56.44
2	1.795	2.333	12.577	2.25	0.1592	13.061	263.2	1.58	0.1764	51.81
3	0.600	1.477	13.034	2.30	0.1621	15.385	295.4	1.67	0.1862	49.43
4	1.477	0.600	11.106	2.05	0.1853	15.957	275.9	1.58	0.2058	59.51

It appears that ratios of the individual polymer binders and the filler have their respective influences on the tensile strength of the composite material. Hence to study the combined effect of both the plastics relative to FA on the strength of the material, it is proposed that the tensile strength is related to the composition as below:

$$S_T = K_T A^{\alpha} B^{\beta} \quad (3)$$

where K_T is proportionality constant, α and β are exponents related to A and B. Taking the logarithm of both sides and fitting of data into a multivariable linear equation results in the following correlation:

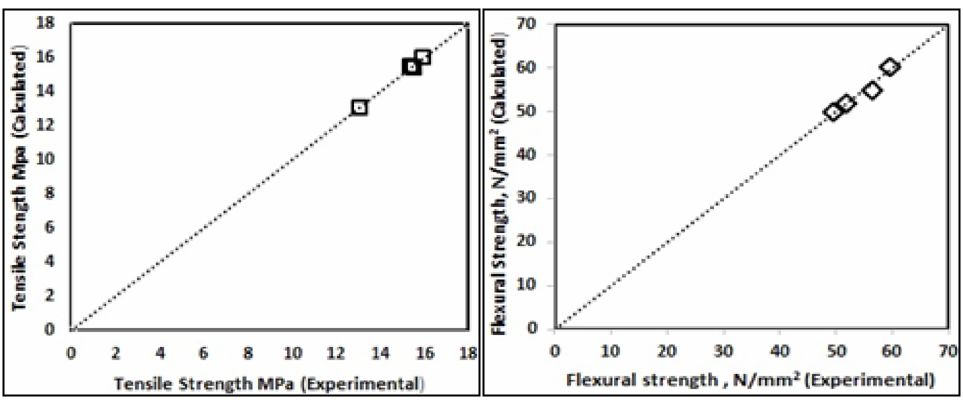
$$S_T = 15.504 A^{-0.095} B^{-0.136} \quad (R^2 = 0.9966) \quad (4)$$

Similarly, for flexural strength, a correlation is proposed with composition as follows:

$$S_F = 54.711 A^{0.088} B^{-0.121} \quad (R^2 = 0.9593) \quad (5)$$

where S_F is the flexural strength. Following are the parity diagrams (Figure 4) that show the validity of the proposed relations in the experimental range.

Figure 4 Parity diagram for, (a) calculated vs. experimental tensile strength (b) calculated vs. experimental flexural strength model



(a) (b)

Trends of the flexural strength with the individual ratios A and B are plotted (Figure 3) and it was observed that flexural strength increased with increase in the PE/FA ratio (= A) up to 1.47 then when the ratio increased to 1.79, it decreased. On the other hand, with increasing value of the ratio PS/FA (= B), flexural strength decreased up to the value of B = 1.47 and it again increased when the value of B increased to 1.79.

3.2 *Influence of composition on solvent swelling*

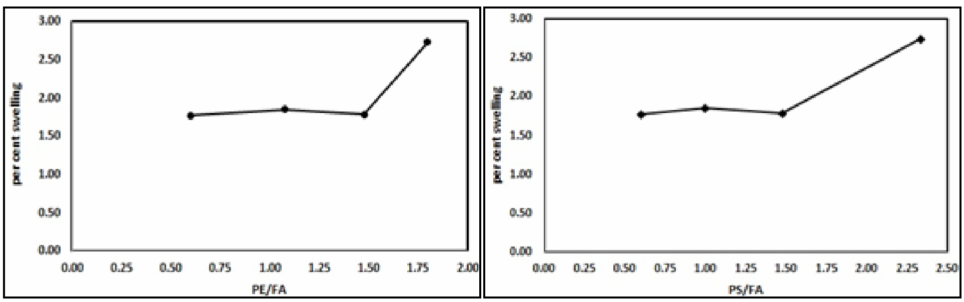
In this composite, plastics are soluble in the toluene solvent and FA is insoluble in it. With an increase in PE/FA ratio, percent swelling remains almost unchanged up to a certain value of about 1.5 (Figure 5). After that, it abruptly increased. The same trend is observed for the PS/FA ratio against percent swelling curve. That is, maximum swelling occurs expectedly where the total plastic/FA ratio is the maximum since both the plastics are soluble in toluene.

Percent swelling was also modelled by the power equation in the same way as it was done in cases of equations (3)–(5). The equation in this case became:

$$P_{sw} = 1.8325 A^{0.2832} B^{0.2772} \quad (R^2 = 0.9987) \tag{6}$$

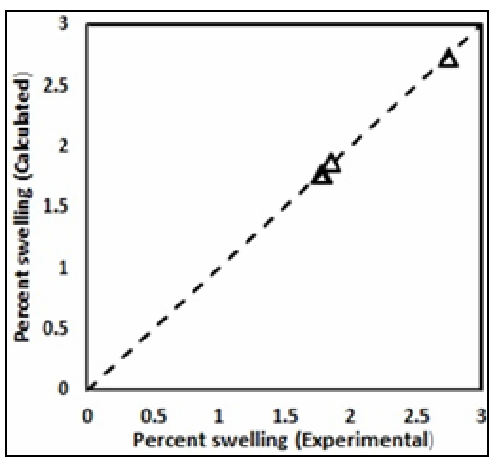
where P_{sw} is the percent swelling, *A* and *B* are the ratios mentioned before.

Figure 5 Influence of composition on solvent swelling, (a) PE/FA ratio vs. percent swelling (b) PS/FA ratio vs. percent swelling



(a) (b)

Figure 6 Parity diagram for swelling model



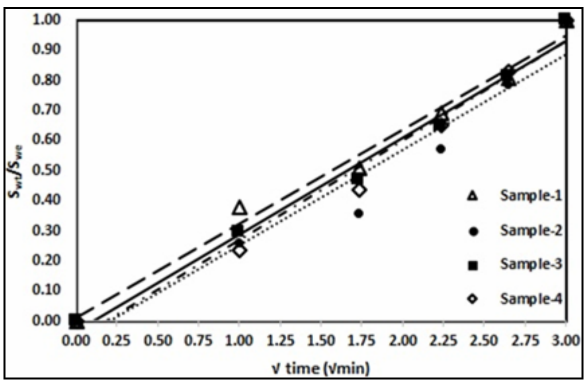
Parity diagram (Figure 6) shows that the model equation agrees well with the experimental data.

The swelling kinetic data are reported in Table 5. The nature of the time-swelled weight curve indicates that the swelling is diffusion (Fickian) controlled (Muñoz and García-Manrique, 2015).

Table 2 Kinetic data for swelling of the composites

Sample	Sample 1	Sample 2	Sample 3	Sample 4
Initial weight (g)	1.1234	1.1902	1.1556	1.1423
Final weight (g)				
Average thickness *h* (mm)	1.94	2.25	2.28	2.03
Time (min)	Solvent absorbed in swelled sample S_{wt} (g)			
0	0	0	0	0
1	0.0079	0.0084	0.0061	0.0048
3	0.0106	0.0117	0.0096	0.0089
5	0.0144	0.0187	0.0133	0.0133
7	0.0168	0.0256	0.0167	0.0169
9	0.0208	0.0326	0.0205	0.0204
% swelled	1.8515	2.739	1.7339	1.7858

Figure 7 Plot for determination of diffusivity



Diffusivities of the solvent through the composite material were calculated using the kinetic parameters obtained by plotting (S_{wt}/S_{we}) against $\sqrt{t}$, where S_{wt} = solvent absorbed (g) at any time *t* and S_{we} = solvent absorbed (g) at equilibrium. Diffusivity was calculated using the following formula (Muñoz and García-Manrique, 2015):

$$D = \pi \left(\frac{kh}{4S_{we}} \right)^2 \tag{7}$$

Table 3 Kinetic parameter and diffusivity with composition

A = PE-PP/FA	*B = PS/FA*	*Kinetic parameter (min)*$^{-0.5}$	R^2	*Diffusivity cm*^{2}*/s*
1.077	1.000	0.3136	0.9856	0.028
1.795	2.333	0.3175	0.9429	0.016
0.600	1.477	0.321	0.9843	0.042
1.477	0.600	0.3317	0.9768	0.356

In the sample having total plastic is the maximum compared to the FA, diffusivity is the minimum. It indicates better adsorption of the plastics molecules over the FA particles thereby restricting the solvent diffusion.

3.3 Solvent and chemical stability

As described before, the stability of the composite tiles was tested in p-xylene, acetone, acid and alkali. It was observed that the samples did not show any deformation even after 24 hours with any of the chemicals or solvents.

3.4 Comparison with standard ceramic tiles

There is no standard available for such a composite tile. Indian Standard (BIS, 2006) for ceramic tiles was referred to for comparison. A few properties have been compared as below since all tests for ceramic tiles are not applicable for polymer composite tiles.

According to the Table 11 of the Indian standard, water absorption by weight should be equal to or less than three whereas the present composite tile shows complete water resistance and toluene (solvent) absorption is maximum 2.39%. There is no standard value for breaking load of 3 mm thick tile, which is the thickness of the present product, but the acceptable breaking load for 7.5 mm thick tile is 600 N. The breaking load reported for the present set of the tile of 3mm thickness is 117–218 N. It is expected that a 7.5 mm thick tile would comply with the standard value. According to the standard, acceptable flexural strength should be around 38 N/mm^2; it is 50–60 N/mm^2 for the tiles developed by us. To be applied as wall tile, the bonding with the wall was tested using toluene and the tiles adhered well with the concrete wall.

4 Conclusions

Lightweight (1.3 g/cm^3) composite tile was developed out of three solid waste materials – FA, styrofoam and plastic grocery bags by compression moulding. It showed excellent mechanical strength and chemical resistance and can be used as a wall tile. However the strength and solvent swelling was found to be dependent on the composition of the composite; rather, on the ratio of the plastics and FA. Mathematical models relating the compositions and properties were proposed and validated by experimental data. If such type of tiles are commercially manufactured, these results may be utilised to determine the correct proportions of the plastics and FA. This process needs no sophisticated technology or instrument, hence is suitable for bulk production by small and medium scale industries. This may be a means for sustainably disposing of the solid wastes with the generation of employment.

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