Recycling Waste Thermoplastic for Making Lightweight Bricks

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Abstract

Plastics are key resources in circular economy and recycling after the end of useful life with economic value creation and minimal damage to environment is the key to their sustainable management. Studies in a large stream of researches have explored impregnating waste plastics in concrete and reported encouraging results with multiple benefits. The present study makes a critical review of some of these findings and gleans some common useful trends in the properties reported in these studies. The study also presents results of experimental work on bricks made of: non-recyclable waste thermoplastic granules constituting 0 to 10% by weight, fly ash 15%, cement 15% and sand making up the remainder. The bricks were cured under water for 28 days and baked at temperature ranging from 90^{o}C to 110^{o}C for 2 hours. The key characteristics of these bricks are found to be lightweight, porous, of low thermal conductivity, and of appreciable mechanical strengths. Though such bricks hold promise, no similar study appears to have been reported so far. Unlike other processes of making porous bricks, which usually involve incineration to burn combustible materials in order to form pores with implication of high carbon emission, the proposed process is non-destructive in that the bricks are merely baked at low temperature, sufficient to melt the waste plastic that gets diffused within the body of the bricks. The compressive strengths after addition of waste plastic to the extent of 10% by weight is about 17MPa that is in conformity with the minimum specified in the ASTM standards. The bricks are likely to add energy efficiency in buildings and help create economic value to manufacturers, thereby, encouraging the ecosystem of plastic waste management involving all actors in the value chain. A mathematical model is developed to predict compressive strength of bricks at varying plastic contents. The study introduces a new strand of research on sustainable thermoplastic waste management.

Keywords: Recycling thermoplastic, Waste plastic in bricks, Lightweight bricks, Plastic in concrete, Porous brick, Energy efficient construction materials, Sustainable waste management

Introduction

Plastic consumption has grown continuously over the last 50 years. Recovery and recycling have not mirrored the huge consumption leading to dumping in landfill and ocean. Global production of plastic has registered clear increasing trend during the recent years (year 2011: 279mt; 2012: 288mt; 2013: 299mt; 2014: 311mt, and 2015: 322mt) as reported in 'Plastic – the Facts' (2016). The plastic production has registered growth of 4,396% from 1960 to 2013 (Devezas et al. 2017). The growth in production of plastic goods during 2017 is also expected to remain positive. The conveniences with which plastic can be used in multifarious applications, which is only growing with new innovative use such as in filament of 3D printing, are likely to increase consumption in the future. Thus, unless recycling gains momentum, the amount of littered waste is likely to increase compounding the environmental challenge. Growth in recycling plastic after end-of-life is slow resulting in increase in net disposal in the environment. Recycling rate of plastic in the USA from municipal waste shows an increasing trend from 1961 to 2014, but the rate has barely reached 9.3% during 2014 (EPA 2015), whereas, in Europe, it has reached 29.7% in 2014 (Plastics – the Facts 2016).

Thermoplastics constitute about 80% of all plastic consumption and thermoset about 20% (Gawande et al. 2012), some of which are safe to recycle and some are not. Part of it remains littered, part used in illegal landfilling, and rest is incinerated for energy harvesting, giving off significant emission. The cost of emission outweighs the benefits of the energy generated when compared to recycling in terms of implicit abatement of CO_2 emission (Gradus et al. 2017). In 2016, New Delhi in India became the most polluted city in the world due, in large measure, to the incineration of waste materials containing large percentage of waste plastic (Rajput & Arora 2017). Plastic bags choke drainage system, reduce water permeability of land affecting fertility, and increasing cost to Municipal Corporations to manage these wastes (Othman et al. 2013). Unless recycled, natural biological process takes indefinite period of time to degrade them (Kyrikou & Briassoulis 2007, Papong et al. 2014).

Growing stream of literature advocates recycling plastic waste in construction materials particularly in concrete due to synergy between the two (Sivaraja & Kandasamy 2007, Bhogayata and Arora 2011). While mixing plastic in concrete and other construction materials is an environmentally friendly method of pushing the end-of-life by a long period, such addition also imbibes special desirable properties in the end products making favorable economic sense. For example, PET particles in concrete reduce requirement of fine aggregate, increase resistance to corrosion—particularly against sulfuric acid—and make the concrete lighter (Araghi et al. 2015). As such, scholars have explored consequences of adding various forms of plastic wastes in concrete. For example, Rai et al. (2012), Rahmani et al. (2013), Naik et al. (1996), Saikia and Brito (2013, 2014) and Bhogayata et al. (2013) have mixed plastic flakes as fine aggregate, polyethylene terephthalate particles (PET), high density polyethylene waste (HDPE), waste plastics as coarse aggregate, and shredded fibers of polythene bags to partially replace fine aggregate, respectively. Foti (2013), Kou et al. (2009) and Ingrao (2014) have used PET bottle fibers, granulated polyvinyl chloride (PVC) pipe waste and RPET fiber in concrete. In all the above studies, the characteristic features of the end products are satisfactory.

Besides supplementing natural aggregates, plastic impregnated construction materials make buildings thermally more efficient than traditional materials since plastics have low thermal conductivity (TC). The TC of common plastics are in the range of 0.15 to 0.55 $Wm^{-1}K^{-1}$ (Polyethylene terephthalate: 0.15–0.24 Epoxy: 0.17, PVC: 0.19, Acrylic: 0.20, Epoxy glass fibre: 0.23, Acrylic 6: 0.25, High density polyethylene: 0.50), much less than that of conventional concrete with TC of around 1.8 (Sun et al. 2017). Energy from buildings constitutes roughly 33% of total consumption out of which about half is lost through the walls (Wouter 2004). Lower the TC more energy efficient is the building and less is the emission (Galvin 2010) and the world is striving to evolve construction materials of low TC (Bassiouny et al. 2016). Substantial part of the cost of domestic heating or cooling and the resulting emission can be reduced by improving thermal insulation of building walls (Zavadskas et al. 2017). Among the emerging materials for increasing thermal insulation are hollow bricks, perforated bricks, and porous bricks. Porous bricks are produced using combustible materials (Görhan & Şimşek 2013, Bories 2016), a process that can be characterized as destructive and polluting.

Empirical evidences from a large number of studies indicate that the compressive strength of plastic concrete is appreciably high, though addition of plastic is found to reduce the compressive strength to some extent (Sharma and Bansal 2016). We present below a gist of such values as reported in Bhogayata et al. (2013), Saikia and Brito (2013) Rai et al., (2012), Hama and Hilal (2017) and Rehmani et al. 2013). Of course, the absolute values of CS are different in different studies because of the diversity in their choice of waste plastic, the physical characteristics, the constituents and their percentage and key process parameters making it difficult to make a comparison. Some reports suggest that smaller the size of plastic granule higher is the CS (Córdoba et al. 2013) whereas, some provide evidence that variation in CS due to different types of plastic is nominal (Fraternali et al. 2011). The trend of CS with respect to plastic percentage in six different studies are presented in Figure – 1 and the average percentage of reduction in CS vis-à-vis percentage increase in plastic content is presented in Table 1.

Table 1: Average percentage of plastic added vis-à-vis average percentage of CS reduced – collated from six different studies

Plastic percentage (%)	Average CS (MPa)	Percentage decrease of CS (%)
0	49.66	Control
5	43.82	-11.76
10	40.60	-7.34
15	37.32	-8.06

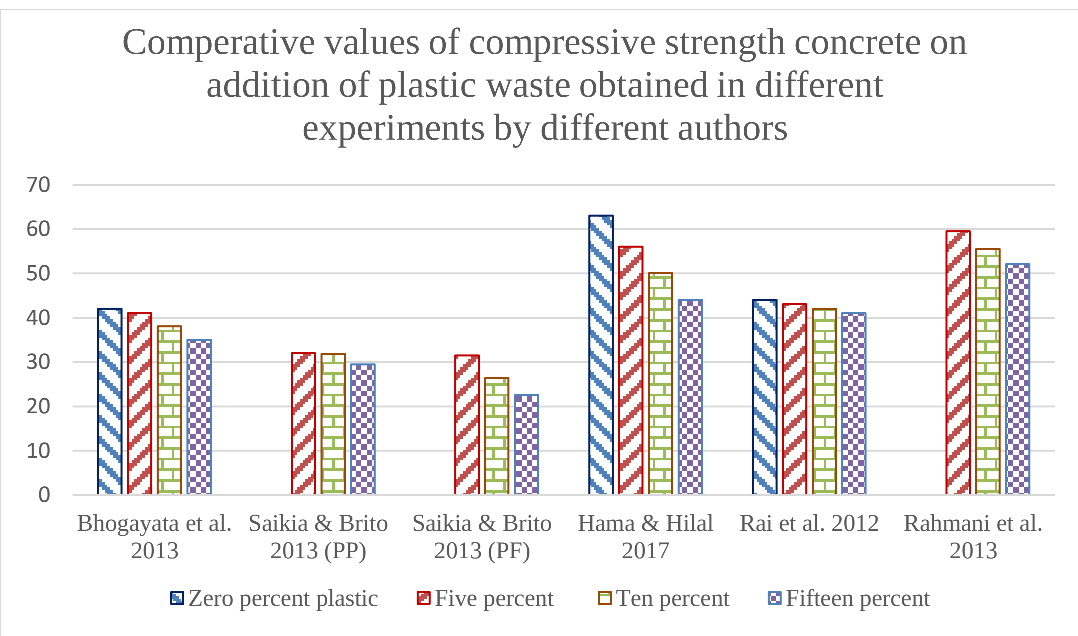

Figure 1: Trend of change of values of CS vis-à-vis percentage waste plastic in concrete observed by six different studies

While appropriate technology can increase recycling of plastic, thereby arresting littering of waste plastics, it can also generate economic value. A lot of researches have made progress in evolving methodologies to reuse waste plastics in concrete mix, bricks, and paver blocks showing promise, though they seem to be still in the realm of research & development (Ismail and Al-Hashmi, 2008). In the absence of a proper system of recycling, plastic wastes will continue to find its way to litter the environment, the oceans, seas and rivers and harm wild life, fisheries and tourism, choke drainage system, obstruct water seepage under the ground, reduce soil fertility.

Large-scale use of recycled plastic in ecofriendly construction materials such as bricks and concrete may lead to sustainable management of this waste material (Hama and Hillal, 2017). Though results in several studies have shown promise, the technology is yet to find adoption in commercial level application (Gu and Ozbakkaloglu, 2016). Further research is necessary for improving properties of the end products and increasing the percentage of plastic in construction materials. The present research introduces new process for incorporating waste thermoplastic to produce self-compacting lightweight and porous fly ash bricks. The results of the study clearly indicate viability of the proposition. The findings pave the way towards sustainable recycling of waste plastic and making them alternative materials for construction industry.

Materials

Every plastic container and bottle statutorily contains one particular symbol also known as resin identification code (RIC) consisting of a triangle and a number with in it ranging from 1 to 7. These symbols contain information on the chemical constituents, toxicity, and the possibility of leaching. The major materials classified under these numbers are: Polyethylene Terephthalate (PET) -1, High Density Polyethylene (HDPE) - 2, Ply Vinyl Chloride (PVC) - 3, Low Density Polyethylene (LDPE) - 4, Polypropylene (PP) - 5, Polystyrene - 6, and other miscellaneous resins including polycarbonate - 7. While plastic with symbols 1, 2, 4, and 5 are safe to be recycled, those with symbols 3, 6 and 7 are unsafe for recycling. The plastic with symbol 7 are particularly unsafe.

We have selected RIC 7 type plastic harvested from computers and peripheral devices. They are assumed to be polycarbonates produced by the reaction of Bisphenol A (BPA) and Phosgene ($COCl_2$). Polycarbonates contain polymers and carbonate group (−O−(C=O)−O−). Being poor in electrical and thermal conductivity and being flame-retardant, it is used in variety of computers, peripherals including CDs, DVDs, electrical and telecommunications hardware, safety goggles, aviation, greenhouses and many more. Thus, their percentage in waste plastic, particularly in E-waste is considerably high. These plastics are best avoided for recycling into products of domestic consumption since BPA is known to cause serious multiple health problems. Impregnating this type of plastic wastes into construction materials may be a safe means of disposal in terms of both arresting their harmful effect and pushing away the end-of-life by a long period while deriving economic values.

Methodology

Waste plastic, understandably at the end-of-useful-life, were harvested from disposed computer peripherals. In absence of a proper machine to grind the plastic into small granules we used hacksaw blade to prepare granules of small particles of roughly up to 2mm size out of cleaned waste plastic. The morphology of the granulated particles are of wide variety and of flaky appearance and thus, a grain size analysis was not meaningful.

Sample blocks of 76mm cube were prepared using 15% portland cement, 0 to 10% waste plastic granules, 15% fly ash, and rest sand of less than 2mm on dry weight basis and water of 25% of the dry mix. No machine compaction was used to compress the mix except self-compaction. The blocks were removed from the mold after 24 hours and were cured under water for 28 days. Two batches of the samples were baked at 90^{o}C and 110^{o}C for two hours. Various mechanical tests were conducted including compressive strength, water absorption rate, apparent porosity, thermal conductivity (Table 2 & Figure 6), and thermo gravimetric analysis.

Results

Table 2: Data on composition of prepared blocks and their mechanical properties

Composition					Properties					
Samp ID	Waste plastic %	Cement %	Fly Aash %	Sand %	Water Absorpn %	Bulk density (gm/cc)	Compressive Strength			Thermal conduc tivity
							Baked at 110^{o}C	Baked at 90^{o}C	Without baking	
1	0	15	15	70	7.71	2.02	29.82	32.04	33.01	0.84
2	1	15	15	69	7.79	1.98	25.90	27.70	29.19	0.79
3	2	15	15	68	7.95	1.94	20.30	27.55	28.33	0.75
4	3	15	15	67	8.26	1.91	19.66	26.18	26.43	0.65
5	4	15	15	66	8.66	1.89	18.46	24.32	24.73	0.61
6	5	15	15	65	9.18	1.84	17.03	22.16	22.67	0.56
7	6	15	15	64	9.49	1.81	16.92	20.44	21.37	0.51
8	7	15	15	63	10.03	1.77	16.56	18.92	20.46	0.48
9	8	15	15	62	10.37	1.74	14.66	18.19	18.98	0.45
10	9	15	15	61	12.74	1.69	14.03	17.45	18.19	0.43
11	10	15	15	60	13.68	1.66	13.54	16.53	17.39	0.40

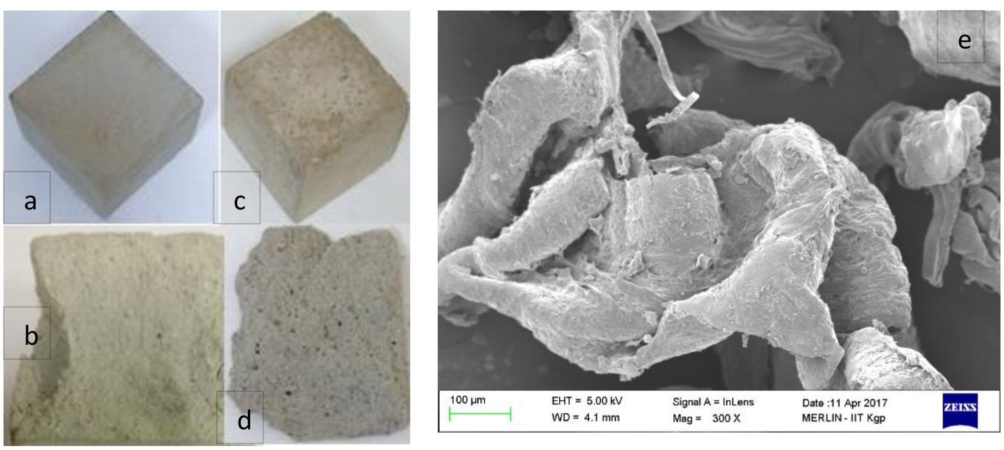

Figure 2: Images of bricks after baking at 90^{o}C: a. & b. Control, c. & d. sample containing 10% plastic waste, e. morphology of unbaked brick sample

In order to model the relation between percentage of plastic and compressive strength holding other factors constant, we fit the data in the following regression equation:

$$CS = \alpha_0 + \alpha_1 w + \varepsilon \qquad \ldots \qquad (1)$$

where CS stands for compressive strength of the blocks, α_0 is the intercept, α_1 is the slope of the linear equation, w stands for percentage waste plastic and ε is the stochastic error term that captures influence of unknown factors.

We fit the data on the above equation in STATA statistical software to receive the following equation:

$$CS = -1.3958w + 25.786 \quad \ldots \quad (2)$$

p-value: 0.000
Adjusted R^2: 84.31%
F-statistic: 48.36 (p-value: 0.000)

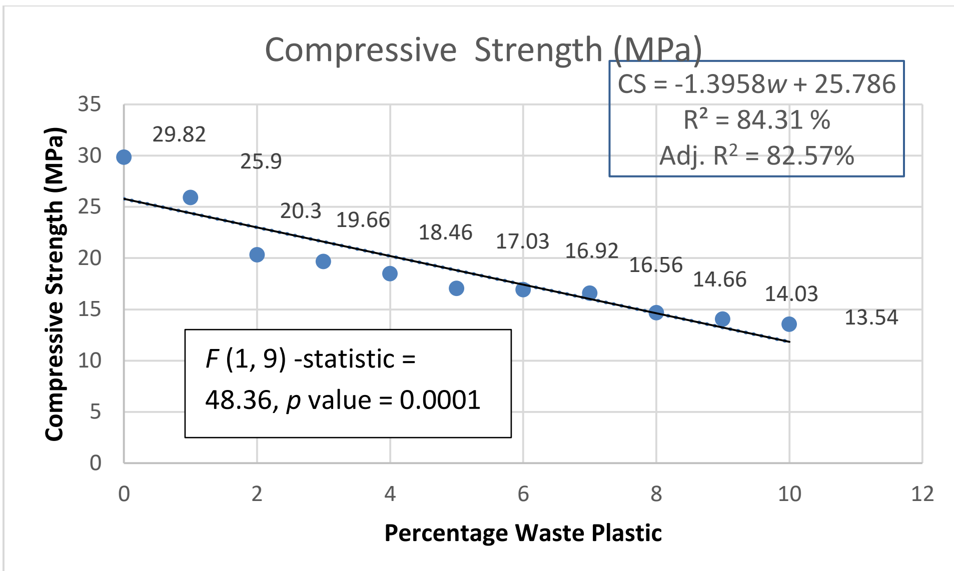

Figure 3: Scatter plot of compressive strengths of blocks of different plastic waste contents

Apparently, the parameter estimates look fine with high value of the coefficient of determination (R^2), significance of the estimates, and the significant value of F-statistic. However, the visual impression of the scatter plot of compressive strength versus percentage of waste plastic in Fig 3 is indicative that their relation may be nonlinear. Thus, the functional form of the Equation (1) may not have been properly specified for a good fit of the data. We, therefore, explore different functional forms of the equation that captures the true relation between the two variables. This is performed using multiple transformation by histograms that shows frequency distribution of different forms of the data to understand the form that is close to normal distribution. This is based on the assumption of regression that the values of the error or disturbance term need to be fairly normally distributed for validity of t-test and f-statistic to judge fitness of the model as per the central limit theorem.

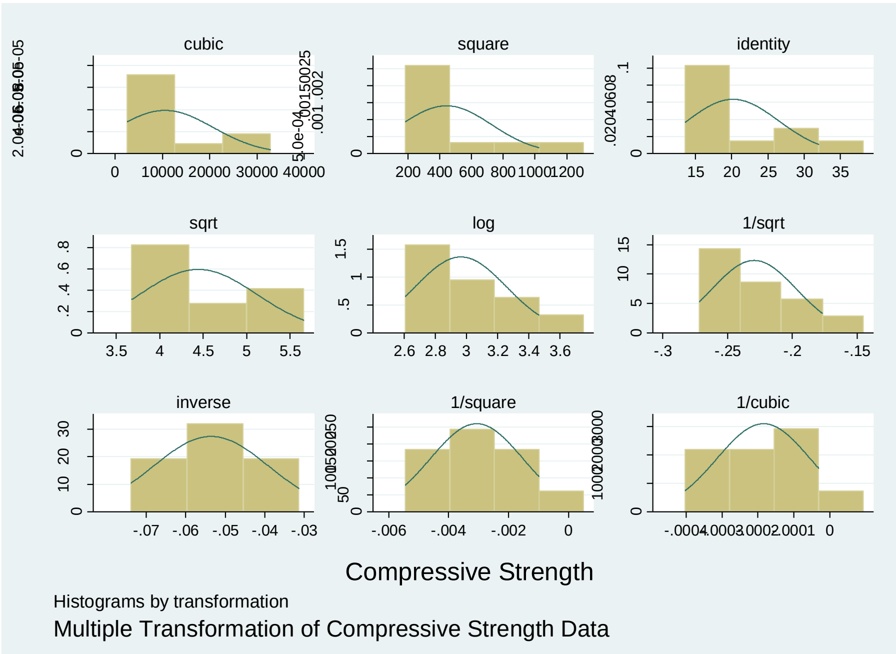

Figure 4: Multiple transformation by histogram of Compressive Strength data

It is evident from the multiple histograms in the Figure 4 that the distribution of the inverse form of the compressive strength data is closest to normal form. We therefore re-specify the Equation (1) as follows:

$$\frac{1}{cs} = \beta_0 + \beta_1 w + \varepsilon \qquad \ldots \qquad (3)$$

Defining $\frac{\mathbf{1}}{\boldsymbol{cs}} = y$ the Equation (3) may be re-written as a linear equation as follows:

$$y = \beta_0 + \beta_1 w + \varepsilon \qquad \ldots \qquad (4)$$

The parameter estimate of the OLS regression of Equation (4) is shown in Equation (5)

$$y = 0.0038w + 0.0374 \qquad \ldots \qquad (5)$$

p-value: 0.000

Adj. R^2: 95.33%

F-statistic: 205.02 (*p*-value: 0.0000)

The improved adjusted R^2 value, F-statistic and t-statistic (14.32 compared to -6.95 in the earlier case) indicate that the data fit much better in Equation (5) than in Equation (2). To put things in right perspective, Equation (5) can be written as:

$$CS = \frac{1}{y} = \frac{1}{0.0038w + 0.0374}$$

or

$$CS = \frac{1}{0.0038w + 0.0374} \qquad \ldots \qquad (6)$$

Or in generalized form as:

$$CS = \frac{1}{M_i w + C_i} \qquad \ldots \qquad (7)$$

We propose that Equation (7) can be used to predict compressive strength of blocks made of waste plastic using cement as binding agent and variety of other filling materials such as fly ash and sand while keeping other factors constant. The parameters M_i and $\mathbf{C}_i$ are characteristic features of specific plastic materials and are required to be empirically estimated. The parameters are found to also vary based on baking temperature. Since we baked the samples at only two different temperatures, it is hard to call it a trend and requires more extensive study. From limited data, it appears that the compressive strengths of the unbaked blocks are less than that of those baked at 90°C but are more than those baked at 110°C.

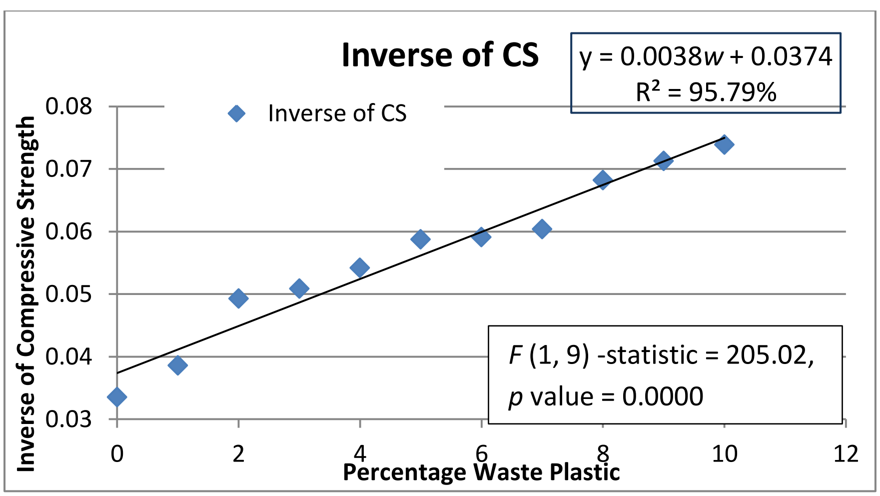

Figure 5: Plot of inverse of compressive strength versus percentage plastic in bricks

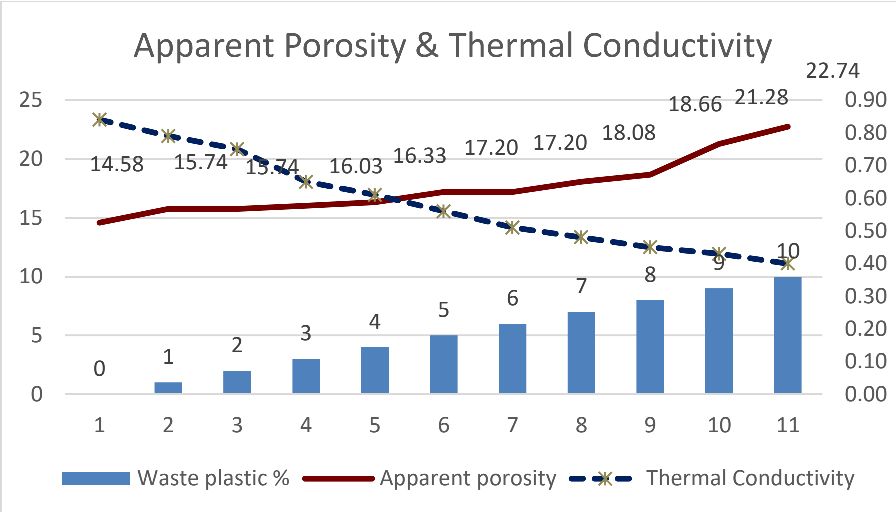

Figure 6: Plot of apparent porosity and thermal conductivity versus percentage plastic in bricks

Limitation of the data

The three batches of blocks were prepared at three different times that may have given rise to some aberrations in the processes and materials. The results are liable to be slightly biased and so are the conclusions. The fact that the control samples in three different sets of experiments displayed different compressive strengths is testimony to such biases. However, the other trends are sharp and inferences drawn are insightful.

Conclusion

The study demonstrates that non-recyclable (and also recyclable) waste thermoplastics can be used to make lightweight, thermally less conductive and porous bricks that can be used to build energy efficient buildings without compromise on mechanical properties. Thus, use of polymer-impregnated concrete or brick not only provides a convenient way of disposing waste plastic but is also a proposition to create economic value in terms of imbibing superior properties in construction materials. The process of making porous bricks enumerated in this paper is nondestructive, whereas many other processes involve the use of combustible materials such as bio-solids that are burnt off during the sintering process resulting in substantial carbon emission.

Exposure to 110°C appears to reduce the compressive strength to a small extent. The compressive strength of samples baked at 90°C are very close to that of unbaked bricks though these bricks are also equally porous. Further experiment may be conducted at lower temperature to explore porosity and other mechanical properties.

The compressive strengths of plastic impregnated bricks reduce with increasing amount of plastic contents. However, CS of bricks with plastic content of up to 10% are observed to conform the ASTM standards. Because of high porosity, water absorption rate is higher compared to control. But these bricks are to be used in specific context where water absorption is not a major concern. Once the process is adopted in practice, the technical advantages and the underlying economic benefits would help in natural evolution of collection and logistic system that will prevent littering of the plastic and unbridle dumping. With the use in bricks, waste plastic will rather become a resource.

The paper presents a mathematical model for predicting compressive strengths with respect to different percentages of waste plastic contents. The framework may be further generalized by estimating the parameters with respect to different plastic materials, cement percentages, baking temperature and other additives.

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