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Eco-efficiency of phosphogypsum waste and sisal fiber in the production of non-fired tile

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ABSTRACT

Phosphogypsum (PG) is an industrial by-product and it has the binding properties to produce non-fired tile. Sisal fibers were supplemented with phosphogypsum to enrich the strength of the tile. In this study, the eco-friendliness of utilizing phosphogypsum with Sisal fiber in non-fired has been assessed to find the environmental impact of PG tile and compared with conventional tile. The physiochemical properties of phosphogypsum and Sisal fiber were analyzed. The strength characteristics of the phosphogypsum and Sisal combined tile have been test verified by pressing hydration process. The ideal water content and fiber content for different pressing pressures have been determined from the experimental investigation. Phosphogypsum tiles consisting of 6 wt.% sisal fiber exhibited maximum bending stress of 16.5 MPa under 15 MPa loading. Production of non-fired tile largely reduces the energy consumption and environmental impacts over conventional tile production.

Keywords: Phosphogypsum; Industrial by-product; Sisal fiber; Non-fired tiles; Eco-friendly building material.

1. INTRODUCTION

Agriculture is the backbone of every country. To increase the yield lot of chemical fertilizers are used to supplement the soil nutrients. phosphate fertilisers are suggested by experts in modern agriculture to enrich the phosphate levels. PG is a key by-product of phosphate fertiliser production. As a result of sulphuric acid reaction with phosphate rock phosphogypsum (PG) is produced [1–5]. About 4.3 -5.2 tons of PG is created from 1 ton of phosphoric acid reaction with phosphate. Globally, every year 252 million tonnes of PG is formed. However, only 10–15% of the total quantity produced is utilized for several purposes. Disposal of PG on soil may deposited and transferred into food. If PG is disposed into water it may diluted and results in ground and surface water contamination [6–13].

Nearly 4.5 -5 tons of PG is formed from one ton of phosphoric acid consumption during the production of fertilizers. However, 12 – 15% of the total quantity produced has been used for soil stabilization, plastering, building material production etc. [14–19]. Presently, disposing of this waste in a legal way has become crucial task for the fertilizer industry. Moreover, dumping this waste requires large dumping yards [20–22]. Dumping this waste in open yards is also not environmentally compatible. Inappropriate disposal of phosphogypsum causes serious menace to the atmosphere and human beings [23–29].

Phosphogypsum obtained resides radioactive elements such as Pb210, Po210, Ra226, U238, and U234 which may cause skin burns, cancer and cardiovascular disease to human beings. Though phosphogypsum contains radioactive elements, it can be used because the total toxic elemental concentration was lower than the allowable toxic element concentration prescribed by the EPA . Many researchers have done their research in this area and concluded that using phosphogypsum for the production of building material has no adverse effects on human health and its usage is already in vogue [30–36], Influence of PG in the rheology of cementitious paste was evaluated and they revealed that there is no health risk found in using PG from the point of view radioactive elements.

The construction sector provides a better chance for mitigating the impact of phosphogypsum (PG) on the environmental by utilizing it for the production of construction materials [37–43]. Currently, ceramic tiles are largely used and they attain high strength through the sintering process. Ample quantities of gases

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are released in sintering which results in air pollution. Ceramic tile manufacturing poses a severe threat to the environment and its production becomes indispensable [44–51]. This serious issue triggered the thought of utilizing PG in tile production. Hence an attempt has been made to produce non-fired tile using PG by pressing the hydration process and the impact of PG tile on the environment has been assessed and the same is compared with conventional tile.

2. MATERIALS AND TEST DETAILS

Non-fired PG tile production with Sisal fiber is a novel approach. Since it is a new approach, existing literature on environmental impact study of PG tile is limited. Hence, the current study was categorized into two phases. In the first Phase (Phase I), the strength features were test verified. In Phase II, the eco-friendliness of PG tile during its production was evaluated and compared with the conventional tile.

2.1. Constituent materials

The XRD pattern of PG used in this study is illustrated in Figure 1. The chemical composition of PG and Sisal fiber are shown in Table 1. Preferably, use as a general framework the following sequence.

The XRD pattern exhibits that the key constituent present in phosphogypsum is $CaSO4·2H_2O$. Sisal fibre was infused to improve the tensile strength of the material. The physio-mechanical properties of Sisal fiber are furnished in Table 2.

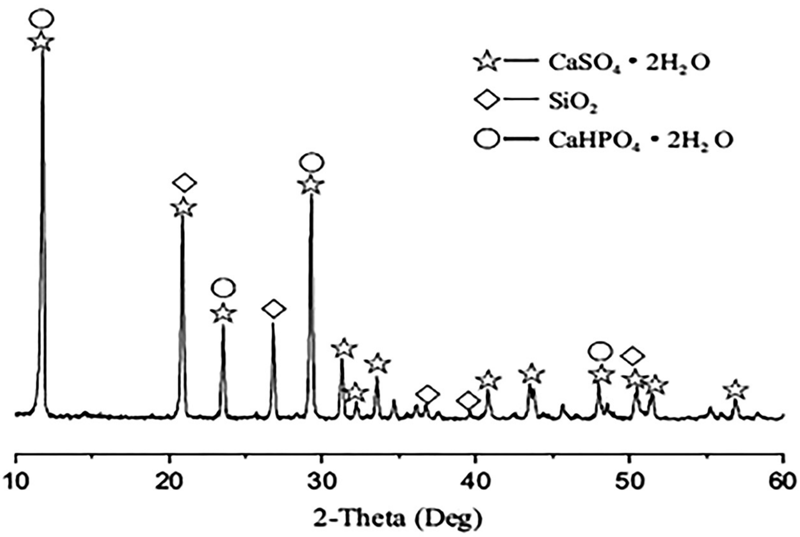

Figure 1: XRD of phosphogypsum.

Table 1: Chemical compositions of PG (wt%) & Sisal fiber.

PG		SISAL FIBER	
CONSTITUENT	PERCENTAGE	CONSTITUENT	PERCENTAGE
CaO	30.79	Cellulose	62.4
Fe_2O_3	0.24	Hemi cellulose	14.3
SiO_2	8.63	Login	19.3
MgO	0.27	Pectin	2.7
Al_2O_3	0.52	Minerals and waxes	1.3
P_2O_5	0.81	–	–
K_2O	0.08	–	–
TiO_2	0.05	–	–
Na_2O	0.11	–	–
SO_3	39.58	–	–
Loss of ignition	18.92	–	–

Table 2: Physio-mechanical properties of Sisal fiber.

PROPERTY	VALUE
Fiber diameter (mm)	0.3
Density (g/cm^3)	1.21
% of elongation	1.57
Young's modulus (GPa)	64.1
Tensile strength (GPa)	2.92
Poison's ratio	0.19

Table 3: Mix proportioning of PT-series mixes.

MIX ID	PHOSPHOGYPSUM (KG)	WATER (LITERS)
PT-10	12	1.2
PT-20	12	2.4
PT-30	12	3.6
PT-40	12	4.8

Table 4: Mix proportioning of PTF-series mixes.

MIX ID	PHOSPHOGYPSUM (kg)	SISAL FIBER (kg)	WATER (LITRES)
PTF-2	12	0.24	3.6
PTF-4	12	0.48	3.6
PTF-6	12	0.72	3.6
PTF-8	12	0.96	3.6
PTF-10	12	1.2	3.6

2.2. Preparation of Sisal fiber added phosphogypsum based non-fried tile

The pressing hydration process was used to produce sisal fiber added phosphogypsum tile. Under the loading pressures of 10, 15, and 20 MPa tiles were prepared. The following steps are involved in the production of tile:

To transform the carbon into minerals to eliminate CO_2 release at the time of calcination at 150°C (for 2 hours), NaOH was added with a molar ratio of 2.

Samples of size 1000 × 1000 × 10 mm were prepared using 12 kg of phosphogypsum. Water to binder ratio of 10 to 40 wt.% by mass of PG was used to get the mix.

Sisal fibre was blended with the mix. The content of fiber varied from 0 to 10 wt.% of PG.

Prepared mixes were pressed at 10, 15, and 20 MPa for 2 minutes. While pressing, PG is transformed into di-hydrate PG. The higher tensile strength and percentage of elongation make sisal fiber suitable for reinforcing phosphogypsum tiles.

2.3. Test methods and mix proportions

Bending stress was assessed as per IS 13630 (part 6): 2006. Tiles of size 230 × 300 × 10 mm were prepared. Two series of mixes (PT and PTF) were prepared. Mix ratios of the PT and PTF series are furnished in Table 3 and Table 4 respectively.

2.4. Assessment of eco-friendliness of PG tile

The environmental footprints concerned with the production of PG tile with sisal fiber have been assessed. By and large, the following stages are considered for assessment (i) Cradle to grave (a full life span) (ii) Cradle-to-gate studies (middle stage) (iii) Specific portion of the life span [27]. Owing to less availability of data, the process involved in the Cradle-to-gate stage has been considered for the environmental impact associated with the production of Sisal fiber incorporated PG tile. This product-level analysis helps to establish the possibilities and necessary improvisations needed to enrich the environmental performance of the Sisal fiber incorporated PG tile towards sustainability.

2.4.1. System boundaries

In this study, the system boundaries deliberated are the processing of raw material and production of ceramic tile (cradle-to-gate approach) for the conventional as well as PG tile. The system boundaries considered in the production of conventional tiles are shown in Figure 2.

System boundaries deliberated in this study are collection, treatment, and manufacturing of PG tile. Since it is a new attempt, analysing the environmental footprint associated with the production of PG tile is quite critical. Hence, mainly production phase was considered. The data concomitant to production was considered for the environmental impact assessment. The system boundaries considered for the production of PG tile are shown in Figure 3.

2.4.2. Comparison of the environmental impact of conventional and PG tile

The environmental impact of conventional and PG tile has been estimated by considering the resource consumption, wastes produced and emissions caused during the production. The data related to all the stages of the unit process were considered. The avowed functional unit is reliant on the environmental footprint of the material. Hence, 1 m^2 was chosen as a functional unit in this study. In the case of ceramic tile, the inputs related to the functional unit are the collection of raw material, processing and energy consumed during production. The outputs related to the functional unit are product, waste generated during production, and pollutants released

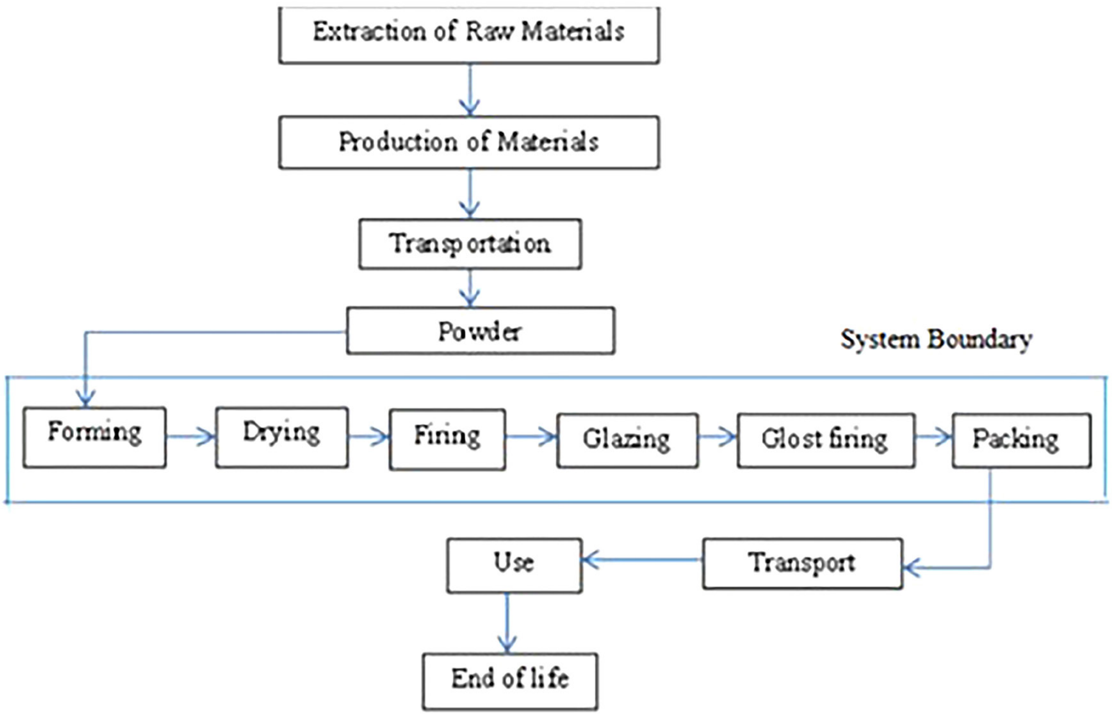

Figure 2: System boundaries of the ceramic tile production process.

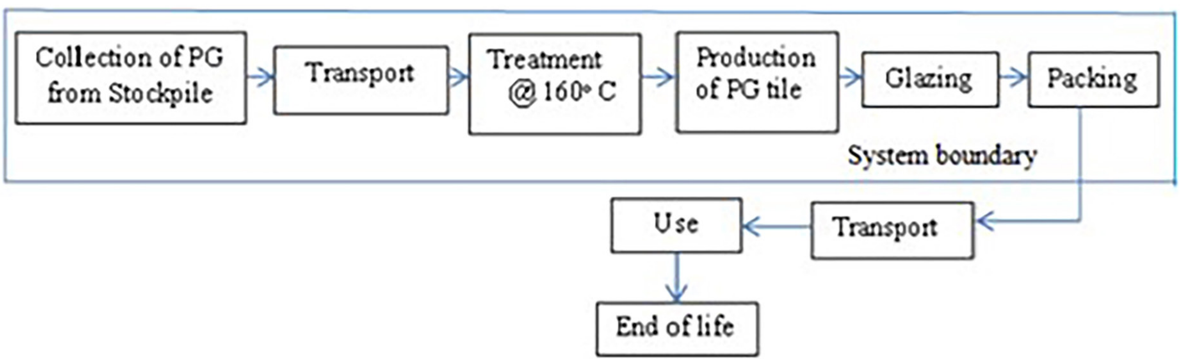

Figure 3: System boundaries of the PG tile production process.

into the environment. The data required for the production of ceramic tile was dealt with extensively by Tikul (2014) [32].

Tikul conducted a study to compute the environmental impact concerning ozone layer depletion, global warming and acidification during production of 1 m^2 ceramic tile. The manufacturing of ceramic tile involves several processes. Every process consumes a substantial amount of energy and it is taken in to account for environmental impact assessment. For 1 m^2 ceramic tile production, 16.8 kg of raw material is consumed for the production of 10.7 kg of ceramic tile. Production plants that use electrical energy for biscuits and glazing firing were taken into account for analysis. In PG tile production, 17.68 kg of raw material is consumed for 1 m^2 tile and 11.6 kg of PG tile is produced. Based on existing and experimental data, inventory analysis was carried out to compute the air pollution and energy consumption of the tile production.

3. RESULT AND DISCUSSIONS

3.1. Effects of water content on bending strength

Different water-to-binder ratios has been used to produce PG tile against various loading pressures (10, 15, and 20 MPa). Figure 4 illustrates the test results of bending strength values of PG tile for different water-to-binder ratios. The maximum strength was exhibited at 15 MPa. 30% water addition by mass of PG increased the bending strength from 9.6 to 11.3 MPa. Beyond 30% water addition, a decrease in bending strength was observed. The strength attainment may be owing to the lubrication effect of water. The presence of water enriches the filling density of phosphogypsum and eases the delamination of dehydrated particles in the mix. Test results indicated that 30 wt.% has been reckoned as the ideal water content.

The excess water in mix i.e. >30 wt.% may increase di-hydrate crystals which have less bonding in tandem with other particles results in lower bending strength.

3.2. Effects of fiber addition on bending strength

The influence of sisal fibre addition (0-10%) on the bending strength was experimentally verified. Figure 5 shows the test results. The incorporation of fibre content shows an escalating trend bending strength increase

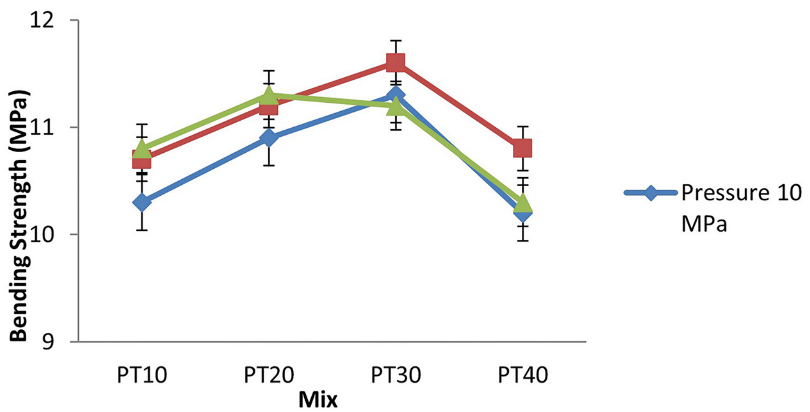

Figure 4: Bending strength versus water content.

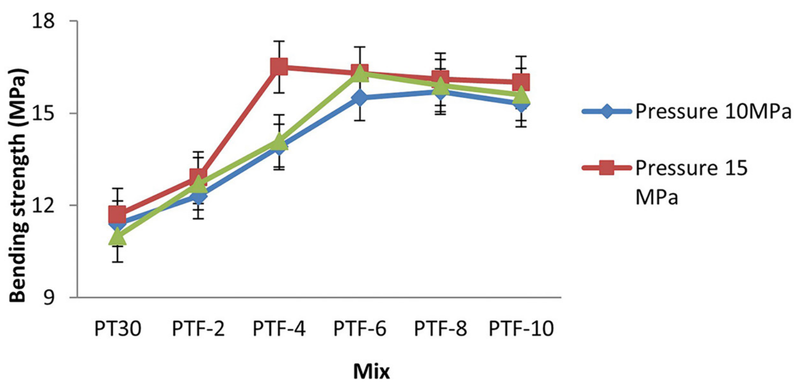

Figure 5: Influence of fibre on bending strength.

Table 5: Energy consumption per m^2 conventional tile produced (Tikul, 2014) [32].

UNIT PROCESS	ELECTRIC ENERGY		FUEL		TOTAL ENERGY (MJ)
	(KWH)	MJ	LITER	MJ	
Glazing preparation	0.19	1.74	0.66	24.03	25.77
Formation	0.36	3.15	–	–	3.15
Sintering	0.23	1.91	–	–	1.91
Surface glazing	0.09	0.80	–	–	0.80
Firing	0.46	4.39	–	–	4.39
					36.02

Table 6: Energy consumption per m^2 PG tile produced.

UNIT PROCESS	ELECTRIC ENERGY		TOTAL ENERGY (MJ)
	(KWH)	MJ	
Treatment	0.19	1.89	1.89
Production	0.31	3.06	3.06
Glazing	0.24	2.41	2.41
			7.36

from 11.7 to 16.5 MPa for fibre addition up to 6% by mass of PG. Later decrease in bending strength was observed for fiber addition of 8 and 10 wt.%.

During the pressing stage, fibers having Poison's ratio of 0.19 were strongly integrated with di-hydrated PG increasing the bonding of the mix. Hence higher bending strength was found in the mix. Fibre content beyond 8% tends to intensify the bending strength. Higher length-to-diameter affects the proliferation nature of the fibre. Therefore the bending strength is reduced [17].

3.3. Environmental impact analysis of conventional tile Vs PG tile

The environmental impact of ceramic and PG tile was assessed. Environmental impacts such as Acidification, Ozone depletion layer and Global warming have been considered (for 1 m^2 of tile). Besides, the energy consumption of tile production is also calculated. All the necessary data have been collected for assessment.

Based on studies, Tikul assessed that the production of $1m^2$ ceramic tile causes Ozone layer depletion of (2.38 × 10-7 kg CFC11-eq) and acidification of (0.21 kg SO_2-eq). During ceramic tile production, 22.8 kg of CO_2 was emitted which resulted in Global warming but there is no gas emissions due to the non-firing of PG tile. However, in the aspect of environmental impact, PG offers a great scope in reducing environmental pollution. As far as the energy consumption point of view concern, ceramic tile consumes more energy. During production (glazing, forming, drying, biscuit and glost firing process) ceramic tile ingests energy of 36.02 MJ but PG tile incurred only 7.36 MJ of energy. The various energy consumption levels during the production of conventional and PG tiles are furnished in Table 5 and Table 6.

The environmental impact analysis indicated that the production of PG tile by "pressing hydration process" can considerably lower the impact on the environment of tile production. Especially in the reduction of energy demand, global warming, and resource depletion. From the experimental investigation, it is corroborated that PG tile production only consumes 20% of the total energy incurred during the making of conventional tile. The avoided CO_2 emissions ensured by the PG tile are related to the addition of a carbon sequestration agent (Na(OH)), which reduces the CO_2 emission during the production of PG tile.

4. CONCLUSION

The experimental investigation has proved the viability of producing non-fried PG tile with Sisal fiber. The test results fortified the following conclusions.

Based on the extensive study it was exhibited that 30% water content by the weight of PG is the optimal percentage of water to produce PG tile without detrimental to the bending strength.

The optimal loading pressure was found to be 15 MPa for the production of PG tile. The PG tile produced for the optimal fibre content of 6% and 30% water content by mass of PG obtained 16.5 MPa. The produced tile satisfied the standard requirements of Indian Standards (≥15 MPa).

The below-mentioned limitations are drawn from the eco-sustainable perspective of PG tile production:

Environmental impact analysis helps to identify the bottlenecks in the development of a new greener product. Utilizing industrial by-products as raw material (PG) is a paradigm shift in eco-sustainable building material production. The production of PG-based wall tile by pressing hydration process evidenced a lower environmental footprint like global warming, acidification and ozone layer depletion than the conventional tile with similar strength and durability performance.

The higher environmental impacts in terms of toxicity, resource depletion, and chemical smog are mostly due to the conventional tile production process. Compared with the conventional production process of tile, the pressing hydration process reduces 80% of the cumulative energy demand and avoids abiotic resource depletion.

The input data considered for impact analysis are case-specific. Potential upscaling not only has positive results but also some variation may present in the expected results due to variations in batching of PG. Hence, this analysis has some limitations in assessing the environmental effects of a product. However present study revealed that usage of PG tile considerably reduces the environmental impact. For accurate environmental analysis, an exact dataset should be obtained from the industry by considering the probable environmental effects at a holistic system level.

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