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Sustainable building materials using textile effluent treatment plant sludge: a review

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A huge quantity of textile effluent sludge is generated from 21 076 textile units of India and dumped in large areas, leading to contamination of soil, surface water and groundwater. Hence, effective management of this sludge is important for its reuse and safe disposal. Considering the utilization of this waste in construction activities, the current paper explores the potential of textile sludge produced from textile industry effluent treatment plants. Many researchers have attempted to reuse this sludge for the development of sustainable construction materials and suggested its optimum usage as a partial substitution for fine aggregate, cement and clay with or without additives for the manufacturing of non-structural building components. This paper provides a critical review of the production of non-structural elements – namely, sustainable building blocks, clay bricks, mortar and paver blocks – using textile effluent treatment plant sludge and recommends optimum ranges of 5–30, 5–40, 5–50 and 20–40%, respectively. The prominent gaps are suggested as the outcome of studies such as techno-economic feasibility of the product, thermal and energy building simulation along with the life-cycle assessment and fatigue life assessment of the developed paver blocks.

1. Introduction

Due to rapid industrialization in developing countries and subsequent increase in human activities, there is a continuous accumulation of industrial wastes, which are becoming increasingly difficult to manage day by day. A great area is utilized in dumping these industrial wastes, which may lead to contamination of soil, surface water and groundwater.¹ Hence, recycling these wastes into an innovative material could be a practical solution to the problem of landfilling and reduce its impact on the environment. Also, urbanization in urban/rural areas has increased the demand for construction materials, and thus, the demand for new construction materials that are economically feasible is increasing exponentially. According to a report, there will be a galloping demand for construction materials to alleviate the housing shortage.² As per the report of the Ministry of Urban Housing and Poverty Alleviation (technical group) of an estimation of the urban housing shortage³ and the report of the working group on the rural housing shortage,⁴ in 2012, India's total urban housing shortage was 18.78 million, while the rural housing shortage was projected to be 43.9 million (Figure 1(a)).^{3,4} It is worth noting that 90% of this shortage pertains to the socially deprived and the lower-income classes of the society. This massive number is a cause for concern. One of the reasons behind it is the high cost of building materials. Thus, an economically weaker sector cannot afford the high construction cost. To meet these demands, there is a need for an increase in the production of materials, which leads to another issue – namely, carbon dioxide (CO₂) emissions. Figure 1(b) shows that the production of steel, cement, bricks and lime has increased from 2000 to 2020. Hence, increases in the consumption of energy and carbon dioxide emissions can therefore be seen (Figures 1(c) and 1(d)).² In India, the construction sector emits around 22% of the total emission

of carbon dioxide annually, out of which 80% results mainly from the industrial processes involved in the production of steel, cement, bricks and lime. Therefore, there is a need to develop sustainable, economically viable and modular construction materials to meet the ever-increasing demand for construction materials without exploiting the available natural resources. This will help reduce carbon dioxide emissions and provide an alternative solution for solid waste management. Many researchers have incorporated various wastes to develop sustainable construction materials, such as ladle furnace slag, blast slag, iron (Fe) tailings, zinc (Zn) tailings and several sewage sludges. Such wastes can end up being a sustainable solution to disposal and environmental issues.

India is the world's second largest manufacturer and exporter, with a huge raw material base and strength. India accounts for 5% of the world's clothing and apparel trade. The textile industry accounts for 2% of the gross domestic product and 15% of the nation's export earnings.⁵ About 21 076 textile units are spread all over India.⁶ A large quantity of water is utilized by textile industries during the production of textiles. As a result, a significant quantity of industrial wastewater is produced, which needs to be treated appropriately before its safe disposal. This industrial wastewater is treated in effluent treatment plant units.

During this effluent treatment process, a large amount of sludge is generated in various stages or processes – namely, chemical coagulation (i.e. addition of chemical coagulants), flocculation (i.e. formation of flocs) and liquid or solid separation.¹ It is estimated that in India the textile industry generates an abundant quantity of textile effluent treatment plant (TETP) sludge – namely, around

Figure 1. (a) Housing shortage in India; (b) material production in India; (c) energy consumption in India; (d) carbon dioxide emission in India

70–80 Mt/day.^{7,8} It sometimes contains heavy metals, impurities and inorganic salts, which are then disposed of in landfills, thereby causing environmental pollution. Hence, many researchers have attempted to reuse and recycle this sludge to develop cost-effective sustainable construction materials that can reduce the toxic effect on groundwater and soil, incurred due to leaching out of heavy metals, and also provide an economic solution to fulfill the demand for construction materials. The present study delineates past research studies on the utilization of TETP sludge into environmentally friendly, modern, sustainable construction materials and identifies the prominent areas for further research. Using low-cost effluent sludge waste as a base material for manufacturing sustainable construction materials would not only solve the environmental pollution problem but would also make the construction facilities sustainable and cost effective.

2. Development of sustainable construction materials using TETP sludge

2.1 Methodology for the development of sustainable construction materials

Figure 2 shows the methodology for the development of sustainable construction materials such as mortar, concrete, clay

bricks and paver blocks. To start with, a sample of open-air-dried textile sludge sample from the textile industry is collected and then dried in an oven at a temperature of 105°C until the net weight becomes steady⁶ or the sample can be used directly. To decrease the size of large and irregular particles, the dried samples are then crushed. Similarly, other raw materials such as cement, fine aggregate, coarse aggregate and clay are collected (Tables 1 and 2). Characterization of the collected raw materials is then carried out using scanning electron microscopy (SEM), X-ray fluorescence (XRF), X-ray diffraction (XRD), thermogravimetric analysis or thermal gravimetric analysis (TGA) and so on. The raw materials are then mechanically/hand-mixed until a homogenous mixture is obtained. The mixture is then pressed or molded as per the requirements at various proportions (Tables 3–6). The specimens are then dried in the open air or the oven, depending on the type of product developed. The dried specimens or products are then fired in a kiln or cured as per the requirements. To determine the mechanical properties of the developed sustainable materials, samples of specimens are then subjected to various tests such as compressive strength, density, split tensile strength, flexural strength, water absorption, shrinkage and porosity tests as specified in the various standards depending on the type of development of

FA, fine aggregate; CA, coarse aggregate; XRD, X-ray diffraction; XRF, X-ray fluorescence; SEM, scanning electron microscopy; TGA, thermogravimetric analysis; CS, compressive strength; FS, flexural strength; WA, water absorption; AR, abrasion resistance; STS, split tensile strength

Figure 2. Methodology for development of sustainable construction material based on the literature^{1–65}

sustainable materials. Subsequently, characterization of the developed product can then be carried out. A demonstrative real-life model can then be prepared using a developed sustainable construction material to monitor the performance.

2.2 Material characterization

2.2.1 Scanning electron microscopy

SEM analysis helps analyze the morphological characteristics of the material. TETP sludge has been found to consist of particles

Table 1. Various elemental analyses carried out by past researchers

Number	Test	Equipment	Description
1	Scanning electron microscopy ^{6,10–12,20,34,66}	Hitachi S-3000H, ⁶ JSM-6510LV microscope, ¹³ Shimadzu SS 550 microscope, ²⁰ Hitachi model S-3400N ⁶⁶	Examines the morphological characteristics of pure clay samples, textile sludge samples, ³⁴ bricks replaced with sludge, ⁶ mortar specimens and sludge-incorporated mortar specimens ^{12,13}
2	Fourier transform infrared (FTIR) spectroscopy analysis ⁶	FTIR spectroscope (FTIR-2000, PerkinElmer) using the potassium bromide (KBr) pellet method ⁶	Detects the surface functional groups of pure clay samples, textile sludge samples and bricks replaced with textile sludge ⁶
3	X-ray fluorescence (XRF) ^{10,11,15–18}	Phillips PW 2404 XRF spectrometer, ¹¹ Edax Inc. Eagle III XRF spectrometer, ¹⁵ Hach spectrophotometer, Shimadzu XRF-1800 XRF spectrophotometer, ¹⁶ Phillips PW 1480 XRF spectrometer ¹⁸	Detects the chemical composition of textile sludge ^{11,18} and its inorganic elements, particularly the heavy metals present in it ¹⁶
4	Thermogravimetric analysis ^{11,15,17,20,41}	PerkinElmer Diamond thermogravimetric and differential thermal analyzer, ¹⁵ PerkinElmer TGA7 analyzer, ¹⁹ Shimadzu TA-50 equipment (Tokyo), ²⁰ TG-DTA 2000 SA ⁴¹	Helps understand the effect of temperature on textile mill sludge and soil ^{11,19,41}
5	Atomic absorption spectrometry ^{12,19,21,66}	Atomic absorption spectrophotometer, ^{12,66} ThermoSolar 2ASS spectra atomic absorption spectrophotometer ¹⁹	Determines heavy metals in raw materials ¹⁹ and detects lead (Pb), chromium (Cr), copper (Cu) and zinc content in sludge-incorporated mortar ¹²
6	X-ray diffraction ^{13–15,36,64,66}	X'Pert HighScore Plus, ¹³ X'Pert Pro (PANalytical B.V.), ¹⁵ X'Tra X-ray diffractometer ⁶⁶	Determines the mineralogical composition of textile sludge ^{14,36,64} and phase changes in specimens prepared using it ^{13,15,66}
7	Energy-dispersive X-ray spectroscopy ^{30,66}	Horiba EX-205 ⁶⁶	Determines the elemental composition of textile sludge ³⁰ and the samples prepared using it ⁶⁶
8	Spatial scale surface morphological analysis ⁴¹	JXA-8900JR electron probe microanalyzer ⁴¹	Investigates the effect of sludge and waste glass additions on brick specimens ⁴¹

Source																		
1	7	9	11	14	16	17	18	19	26	30	32	34	36	37	41	63	64	67
Oxide composition																		
Titanium dioxide (TiO ₂): %	—	—	—	—	—	1.3	3.6	—	0.5	—	—	—	<0.0003	—	3.1	—	0.4	—
Manganese (II) oxide (MnO): %	—	—	0.6	—	—	—	—	—	0.8	—	—	—	—	—	0.1	—	—	—
Magnesium oxide (MgO): %	0.2	—	9.5	—	—	—	1.3	—	—	3.0	—	—	0.6	3.1	1.9	—	0.8	—
Sodium oxide (Na ₂ O): %	—	—	—	—	—	—	11.2	—	—	—	—	—	0.5	0.5	12.8	—	1.6	—
Potassium oxide (K ₂ O): %	—	—	—	—	—	—	3.9	—	—	—	—	—	0.5	0.6	1.0	—	0.4	—
Phosphorus pentoxide (P ₂ O ₅): %	—	—	—	—	—	3.5	8.4	—	—	—	—	—	—	—	2.9	—	4.8	—
Sulfur trioxide (SO ₃): %	10.3	—	—	—	—	—	29.2	—	—	—	—	—	—	8.4	3.0	—	—	—
Calcium oxide (CaO): %	39.6	—	22.1	—	—	23	2.6	28.4	0.9	—	—	3.7	4.1	31.5	2.8	108.22 mg/l	1.7	—
Iron (III) oxide (Fe ₂ O ₃): %	43.8	—	—	—	—	NA	3.3	9.1	60.5	1.9	—	13.2	6.6	11.1	10.7	—	0.1	—
Silicon dioxide (SiO ₂): %	2.6	—	15.2	—	—	15.2	29.1	7.1	3.4	53.2	—	3.3	4.0	32.5	10.3	—	2.9	—
Aluminum oxide (Al ₂ O ₃): %	0.2	—	3.6	—	—	3.6	4.5	0.7	6.2	0.2	—	1.0	0.2	9.8	44.2	—	10.3	—
Trace element (heavy metal) content																		
Cadmium: mg/kg	4.0	—	5.2	—	BDL	5.6	—	5.6	—	BDL	1.4	—	—	—	—	3.9	0.1	BDL
Copper: mg/kg	57.5	—	225.5	—	87.4	58	—	119	—	87.4	28.7	—	—	—	—	57.5	0.0	87.4
Chromium: mg/kg	3.0	—	231.5	—	34.4	10	—	358	—	34.4	6.1	—	—	—	—	3.0	<0.01	34.4
Zinc: mg/kg	91.6	—	186.5	—	82.7	131	—	190	—	82.7	229.2	—	—	—	—	91.6	0.1	82.7
Nickel: mg/kg	0.7	—	89.7	—	30.8	32	—	—	—	30.8	—	—	—	—	—	—	<0.01	30.8
Lead: mg/kg	12.1	—	44.8	—	101.1	12	—	—	—	101.1	29.4	—	—	—	—	0.7	<0.01	101.1
Ferrous (Fe ²⁺): mg/kg	180.5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	12.1	—	—
Magnesium: mg/l	154.3	—	—	199	—	—	—	—	—	—	—	—	—	—	—	154.3	—	199
Total volatile solids: %	31.9	—	36.6	—	—	—	—	—	—	7.8	—	—	—	—	—	31.9	—	—
Density: kg/m ³	2.4	—	916.2	1350.0	810	—	—	—	—	—	—	1080	—	—	—	—	—	810
Specific gravity	2.4	—	0.9	1.3	2.2	—	—	2.3	1.1	2.4	—	1.1	1.8	—	—	2.4	—	2.2
pH	9.1	—	8.7	6.5	9.4	—	—	—	—	9.2	8.5	6.5	—	—	—	9.1	—	9.4

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Table 3. Development of sustainable cement sludge blocks/mortar

Source	Type of product	Size of sample: mm	TETP sludge replaced with	Used: %	Curing	Various tests conducted
Patel and Pandey ⁹	Cement–sludge blocks	70.6 × 70.6 × 70.6	Cement	30–70	Moist condition: 24 h at room temperature (27–29°C) and relative humidity (RH) of 92% Water tank: 28 days	CS, BD, LT
Jahagirdar <i>et al.</i> ¹⁰	Cement–sludge blocks	70.6 × 70.6 × 70.6	Cement	20–90		CS, BD, LT
Rahman <i>et al.</i> ¹²	Mortar specimens	50.8 × 50.8 × 50.8, 304.8 × 25.4 × 25.4	Cement/sand	10–50 and 20–80	28 days	CS, WA, FS, LT, porosity
Goyal <i>et al.</i> ¹³	Cement–sludge pastes and cement–sludge mortar mixes	70.6 × 70.6 × 70.6	Cement	5–20	Moist curing: 28 days followed by air curing	CS, STS, WA, RCPT, sorptivity test
Vellingiri <i>et al.</i> ¹⁴	Mortar cubes	70.6 × 70.6 × 70.6	Cement	10–30	28 and 56 days	CS, WA
Patel and Pandey ²¹	Cement–sludge blocks	70.6 × 70.6 × 70.6	Cement	30–70	14 and 28 days (at ambient temperature, RH of 70%)	BD, CS, LT
Jeevanandam <i>et al.</i> ²²	Cement–mortar cubes	70.6 × 70.6 × 70.6	Cement	10–60	7, 14 and 28 days (at ambient temperature, RH of 60%)	CS, LT, pH, electrical conductivity
Arul <i>et al.</i> ²³	Cement–mortar cubes	70.6 × 70.6 × 70.6	Cement	5–30	7, 14 and 28 days	CS, WA, BD

BD, block density; CS, compressive strength; FS, flexural strength; LT, leachate test; RCPT, rapid chloride permeability test; STS, split tensile strength; WA, water absorption

Table 4. Development of sustainable concrete

Source	Type of product	Size of sample: mm	TETP sludge replaced with	Used: %	Curing: days	Various tests conducted
Balasubramanian <i>et al.</i> ¹	Solid concrete blocks	400 × 150 × 200	Cement	10–30	3, 7 and 28	CS, WA, BD, moisture movement
Rahman <i>et al.</i> ¹²	Concrete specimens	152.4 × 152.4 × 152.4	Sand	20–100	28	CS, FS, WA, LT, porosity
Arul <i>et al.</i> ²³	Concrete cubes	150 × 150 × 150	Cement	5–30	7, 14 and 28	CS, STS, FS, WA, BD
Zhan and Poon ²⁶	Concrete blocks	70 × 70 × 70, 25 × 25 × 285	Sand	5–30	Wrapped with plastic films for moist curing: 7 and 28	CS, ST, LT
Loganayagan <i>et al.</i> ²⁷	Concrete blocks	150 × 150 × 150	Sand	5–20	7 and 28	CS
Altidis <i>et al.</i> ²⁹	Concrete specimens	50 diameter by 10 height	Sand	3–7	Moist chamber: 7 and 28	CS, WA
Anandh <i>et al.</i> ³¹	Concrete specimens	150 × 150 × 150, 200 × 100, 500 × 100 × 100	Cement	5–30	—	FS, CS, STS
Kaur <i>et al.</i> ³³	Concrete specimens	150 × 150 × 150, 70.6 × 70.6 × 70.6	Sand	5–55	7, 14 and 28	CS, AR, acid attack
Kulkarni <i>et al.</i> ³⁴	Concrete blocks	150 × 150 × 150	Sand	4–36	—	CS, BD
Sandesh <i>et al.</i> ³⁶	Concrete blocks	—	Cement	5–10	3, 7 and 28	CS, STS, FS, WA
Kaur <i>et al.</i> ³⁸	Concrete blocks	150 × 150 × 150	Sand	15–55	Curing tank: 7, 14 and 28	CS
Mariappan <i>et al.</i> ⁵³	Concrete specimens	150 × 150 × 150, 100 × 100 × 500	Cement	10–20	—	CS, STS, FS
Joseph and Kumar ⁵⁴	Concrete specimens	150 × 150 × 150, diameter 150 and length 300	Cement	5–15	28	CS, STS
Pradeepa <i>et al.</i> ⁵⁶	Concrete blocks	150 × 150 × 150	Sand	5–15	Curing tank: 7, 14 and 28	CS
Prabhu <i>et al.</i> ⁵⁷	Concrete blocks	150 × 150 × 150	Sand	30–50	Curing tank: 28	CS, FS
Kaur and Singh ⁵⁸	Concrete blocks	100 × 100 × 100	Cement	5–35	Curing tank: 7, 14 and 28	CS
Sakthivel <i>et al.</i> ⁵⁹	Concrete specimens	150 × 150 × 150	Sand	10–30	—	CS, STS

AR, abrasion resistance; BD, block density; CS, compressive strength; FS, flexural strength; LT, leachate test; ST, shrinkage test; STS, split tensile strength; WA, water absorption

Table 5. Development of sustainable clay bricks

Source	Type of product	Size of sample: mm	TETP sludge replaced with	Used: %	Drying	Firing	Various tests conducted
Balasubramanian <i>et al.</i> ¹	Clay bricks	190 × 90 × 90	Clay	10–30	—	—	CS, WA, efflorescence
Begum <i>et al.</i> ⁶	Clay bricks	210 × 100 × 75	Clay	3–50	Open atmosphere: 24 h	1000°C – brick kiln	CS, WA, WL, efflorescence, density
Jahagirdar <i>et al.</i> ¹¹	Clay bricks	70 × 70 × 70	Clay	5–35	Air-drying in lab: 2 days; and sunlight: 4 days	600, 700 and 800°C – muffle furnace (8, 16 and 24 h)	CS, WA, density, efflorescence
Anwar <i>et al.</i> ¹⁶	Clay bricks	121 × 114.3 × 70	Clay	0.5–5.25	Air-drying: 10 days	1050°C – Hoffman kiln burning 8 days	CS, WA, LT, ST
Jahagirdar <i>et al.</i> ¹⁷	Clay bricks	70 × 70 × 70	Clay	5–35	Air-drying in lab: few days; and sunlight: 4 days	600, 700 and 800°C – muffle furnace (8, 16 and 24 h, respectively)	CS, WA, density
Jewaratnam and Samat ¹⁸	Clay bricks	100 × 100 × 15	Clay	5–20	Oven: 24 h at 105°C	950 and 118°C – chamber furnace	CS, WA, ST, density
Baskar <i>et al.</i> ¹⁹	Clay bricks	70 × 70 × 70	Clay	3–30	Open atmosphere: 24 h; and oven: 6 h at 110°C	200–800°C – muffle furnace (2–8 h)	CS, WA, ST
Priyadharshini and Kavisri ³⁹	Clay bricks	90 × 90 × 190	Clay	5–20	Open atmosphere: 10–12 days	900°C – muffle furnace	CS, WA, density, efflorescence
Mary and Sreeja ⁴⁰	Clay bricks	75 × 33 × 33	Clay	0–6.66	Sunlight: 4 days	400, 500 and 600°C – muffle furnace	CS
Rahman <i>et al.</i> ⁴¹	Clay bricks	ø30 × 30 height	Clay	10–40	Open atmosphere: 1 day; or oven: overnight	1150°C – muffle furnace (2 h)	CS, WA, WL, LT, ST
Anwar <i>et al.</i> ⁴²	Clay bricks	121 × 114.3 × 70	Clay	0.5–5.25	Air-drying: 10 days	1050°C – Hoffman kiln (8 days)	CS, LT, WA, ST
Hossain <i>et al.</i> ⁶¹	Clay bricks	150 × 75 × 25	Clay	10–50	Air-drying and sunlight	450°C – muffle furnace (24 h)	WL, WA, FS, WA, ST, density, bending modulus, impact strength, electrical resistivity

CS, compressive strength; FS, flexural strength; LT, leachate test; ST, shrinkage test; WA, water absorption; WL, weight loss

Table 6. Development of sustainable paver blocks

Source	Type of product	Size of sample	TETP sludge replaced with	Used: %	Curing: days	Various tests conducted
Balasubramanian <i>et al.</i> ¹	Pavements blocks	Hexagonal shape of 39 000 mm ²	Cement	10–30	—	CS, WA
Patel <i>et al.</i> ⁷	Rubber mould paver blocks	60 mm thick	Cement	5–40	28	CS, WA, AR
Narayan and Supriya ⁴⁵	Paver blocks	200 × 100 × 60 mm	Cement	10–30	7 and 28	CS, WA
Velumani and Senthilkumar ⁴⁶	Paver blocks	Zigzag pattern (229 × 110 mm)	Cement	10–35	Water tank: 28	CS, WA, FS, AR
Indumathi <i>et al.</i> ⁴⁷	Paver blocks	—	Cement	20–60	7, 14 and 28	CS
Kishore ⁴⁸	Paver blocks	200 × 120 × 80 mm	Cement	10–40	—	CS, WA, FS
Jayakumar <i>et al.</i> ⁶²	Paver blocks	200 × 120 × 60 mm	Cement	10–40	7 and 28	WA, CS, FS, RCPT

AR, abrasion resistance; CS, compressive strength; FS, flexural strength; RCPT, rapid chloride permeability test; WA, water absorption

of various shapes and sizes⁹ and is fibrous.⁶ The particles present in sludge have been found to be larger than clay particles.⁶ Sludge particles show predominance of spherical particles in the form of agglomerates with a diameter ranging from 1 to 40 μm .⁹ Analysis of textile mill sludge using the electron-dispersive technique under SEM also exhibited the absence of heavy metals.^{10,11} Mercury (Hg) and molybdenum (Mo) were discovered but in a smaller amount – namely, below 0.4%.¹¹

SEM images also showed that samples of textile-sludge-incorporated clay bricks had more pore spaces than samples of crushed brick powder obtained from pure clayey brick. Consequently, the quantity of absorbed water increased.⁶ A mixture of granular and fibrous materials was seen in SEM images of bricks with 15% sludge.

In cement sludge mortar specimens, the major products that were found in the control sample (100% cement and 0% sludge) were calcium silicate hydrate (CSH) gel and calcium hydroxide ($\text{Ca}(\text{OH})_2$). However, when cement was replaced with textile sludge in greater quantities, a more porous microstructure was found, with ettringite and voids, and a lower amount of CSH gel. The surface structure of the cement sand mortar was seen to be homogeneous and dense.¹² However, higher heterogeneity in the structure was seen due to the addition of sludge in the composition. This heterogeneity in the microstructure of the mortar caused a significant reduction in the strength. Lack of hydration was also clearly observed in textile sludge mixes.

2.2.2 X-ray diffraction

Analysis of XRD peaks showed that textile effluent sludge mostly consists of calcite (CaCO_3), quartz (SiO_2), ferric oxide, vaterite (CaCO_3), calcium hydroxide and gypsum ($\text{Ca}(\text{SO}_4)(\text{H}_2\text{O})_2$).^{9,13,14} The presence of calcium (Ca) compounds and gypsum in textile sludge confirms its potential as a construction material.

Microstructural analysis of mortar specimens after a compressive strength test showed CSH, calcium silicates (C_3S and C_2S), portlandite, calcite and quartz.¹³ The addition of textile sludge in mortar mixes showed no noticeable qualitative changes in the phases of cement hydration products. The hydration of mortar mixes was affected by the percentage increase of textile sludge from 0 to 20%. When textile sludge was incorporated into the composition, the peaks of calcium carbonate and calcium silicates were found to have higher intensities, while the hydration products, such as CSH and calcium hydroxide, had lower intensities. It was observed that the addition of 20% textile sludge resulted in lesser hydration reaction and lesser pozzolanic action at later ages, hence leading to a loss in the performance of mortars as confirmed by the strength tests and permeation behavior of the specimens. Thus, optimum replacement of up to 5% textile sludge in cement mortar mixes was suggested.

The XRD pattern of a cement sludge specimen with 40% textile sludge showed peaks of unreacted C_2S and C_3S along with

ettringite peaks.⁹ In the XRD pattern, the portlandite peak was seen absent, thereby indicating hydration retardation. Gehlenite hydrate peaks have also been observed. Thus, it can be inferred that the addition of sludge above 40% resulted in hydration retardation and resulted in an adverse effect on gel formation.

Peaks of quartz along with traces of microcline (KAlSi_3O_8) and hematite (Fe_2O_3) were detected in the XRD pattern of sludge-incorporated clay bricks for a sludge proportion of 20%, which was found similar to the chemical composition of soil and textile sludge.¹⁵ Hence, an optimum mix of 20% textile sludge is being suggested for the manufacturing of bricks.

2.2.3 X-ray fluorescence

Elemental analysis such as determination of carbon (C), hydrogen (H), nitrogen (N) and sulfur (S) contents¹⁵ and the main chemical composition of raw materials such as textile sludge and soil can be carried out using the XRF technique. Toxic metals such as arsenic, chromium, cadmium and lead were observed in textile sludge but at a lower concentration.¹⁶ Many researchers have found that textile sludge contains a smaller quantity of silicon dioxide (SiO_2) than ordinary Portland cement and fly ash, thus indicating its lack of binding properties.^{10,11,17} Meanwhile, the presence of a significant amount of aluminum oxide (Al_2O_3), calcium oxide (CaO) and iron (II) oxide (FeO) indicates its potential as a building material. Therefore, to enhance its binding properties, the addition of fly ash is recommended, as it contains a significant amount of silicon dioxide.¹⁰ The presence of a significant amount of sulfur trioxide (SO_3) in textile sludge has also been reported in other research studies,¹⁸ which indicates good binding properties when incorporated into building materials. This indicates that the chemical composition of textile sludge varies by industry. It also varies with the chemical used and dosage applied during the treatment process of textile wastewater.¹⁶ Thus, by looking at the results of XRF analysis, it can be concluded that TETP sludge has the potential to be used in developing sustainable construction materials.

2.2.4 Thermogravimetric analysis

Thermogravimetry (TG) provides information on the thermal behavior of raw materials such as textile sludge and clay¹⁹ and samples of textile-sludge-incorporated products such as clay bricks. Three distinct patterns of variance in weight loss with temperature were seen in a TG plot of textile sludge. There were three different peaks at 295, 380 and 790°C with respect to the derivative weight loss. The presence of volatile organic matter in textile sludge may be the reason for this weight loss. Similarly, three main peaks in the TGA curve of the textile sludge sample, corresponding to weight loss, were observed.²⁰ The first one occurred until 223°C, and it corresponds to the loss of physically adsorbed water. A further weight loss of 75% was observed until 304°C, which corresponds to the dehydration of hydroxides and the presence of a high water content. Lastly, a weight loss near 600°C was observed, and it can be attributed to the presence of volatile constituents. In the DSC curve of the sludge sample, there

was also a pronounced endothermic peak at 100°C, which is related to water loss in the sample. Whereas, a smaller portion of weight loss was reported in another research study at a similar range of temperatures – that is, 400–800°C.¹⁵

Thus, from the TGA curves of textile sludge, it can be inferred that the burning of volatile matter present in textile sludge might affect the strength, density and water absorption of sludge-incorporated sustainable materials due to an increase in the pores of materials. Similar results have been reported by past researchers, such as voids being observed in sludge-incorporated clay bricks due to the burning of organic matter present in TETP sludge.^{11,17} With the increase in temperature, the weight of TETP sludge was found to reduce, resulting in a porous brick structure with lower compressive strength and increased value of water absorption. A weight loss of 30–40% was observed within the temperature range 600–800°C due to the presence of organic matter. Thus, for the development of sustainable construction materials, optimal usage of TETP sludge was suggested by past researchers.

2.3 Study of sustainable mortar incorporating TETP sludge

In Figure 3, maximum strength was observed in control specimens compared with a specimen cast with textile sludge. As the percentage substitution of textile sludge as a partial replacement of cement in cement–sludge specimen/mortar is increased, the compressive strength decreases.^{9,13,21–23} A maximum of 62% reduction in strength is observed. It is evident from Table 2 that textile sludge contains a lower amount of calcium oxide compared with cement, due to which the hydration process slows down and results in an increase in the setting time, thus contributing to the reduction in the compressive strength of the mortar specimens. Furthermore, it does not show adequate pozzolanic activity and binding capacity due to the lower amount of silica present;¹² thus, satisfactory later strength was not

Figure 3. Compressive strength and density of cement–sludge mortar

observed.¹³ SEM images have also confirmed the heterogeneity of the microstructure of the mortar leading to a reduction in strength¹² (Table 2). The presence of zinc and lead in textile sludge also affects the strength of a specimen, as it affects the hydration reactions that are responsible for the development of strength; hence, lower strength is observed.⁹ Moreover, a high volatile content in textile sludge is decomposed after a definite compressive strength is achieved.¹² However, considering the requirement of the strength of construction materials, blocks produced using textile sludge accomplish the requirements of non-structural works as specified by the Bureau of Indian Standards (BIS).^{9,14,21,22}

When it comes to the block density of specimens, blocks cast with 100% cement – that is, without sludge – showed a maximum density (Figure 3).¹⁴ With the increase in the percentage substitution of textile sludge in the mixes, the density started reducing.^{10,21} The lower density may be due to the lower specific weight of sludge compared with that of cement.¹⁰ The bulk density of specimens is also observed to increase up to an optimal amount of replacement by textile sludge, after which it starts to decrease.²³ Hence, optimum usage of textile sludge is suggested by many researchers.

It can be seen from Figure 4 that the water absorption value of sustainable material is lower than that of the control sample. Thus, improvement in the value of water absorption is observed,²³ as sludge appears to fill the voids of the mixtures. A maximum reduction of 71% is observed. It is also observed that after utilizing the optimum quantity of TETP sludge, the value of water absorption increases; hence, optimum utilization of textile sludge is suggested.¹³ It is seen that with the inclusion of textile sludge above 5% level in mortars, the value of water absorption increases.¹³ The increased replacement of sludge in mortar lowers

Figure 4. Water absorption of cement–sludge mortar

the hydration reaction and results in inadequate pozzolanic action, thus affecting the water absorption value; hence, an optimum level of 5% is suggested.¹³ A variation in the results was seen due to the variation in the mix design carried out by the researchers. Mix design plays an important role in achieving the desired properties of sustainable materials. Thus, it can be concluded that with the proper utilization of TETP sludge and mix design, a new sustainable mortar can be developed with enhanced properties.

The toxicity characteristic leaching procedure of cement–sludge blocks was investigated in past studies to obtain the concentration of heavy metals in the leachate of the developed product, and the results showed negligible leaching of heavy metals.^{9,12,21} The heavy metal concentrations in the leachate were below threshold limits when compared with the regulatory limits of the US Environmental Protection Agency (EPA) and Department of Environment in Bangladesh.

2.4 Application of TETP sludge to develop sustainable concrete

From Figure 5, it is observed that the compressive strength of the concrete decreases with the increase in the percentage of textile sludge when used as a partial replacement for cement or aggregate.^{12,23–32} A maximum reduction of 50% is observed when compared with the test samples. A reduction in strength is observed because the sludge is finer than cement particles, and its hydroscopic nature causes it to increase in volume;³³ thus, during mixing, demand for water increases to maintain workability,²⁷ hence affecting the water–cement ratio. The presence of chlorides and sulfates in textile sludge also diminishes the quality of concrete.²⁴ Although the strength of concrete is decreased, the obtained strength fulfills the requirements of many non-structural materials¹² or components as specified in many standards – namely, ASTM and Indian standards. Therefore, many researchers have suggested the optimal quantity of

textile sludge that can be used in concrete (Figure 5). An increase in the strength of concrete due to partial replacement with textile sludge has also been reported in some research studies.^{34,35} A maximum percentage increase of 11% is observed compared with the control sample, which may be due to the presence of some percentage of silica and calcium content in TETP. The use of TETP-compatible superplasticizers in concrete mix also enhances the compressive strength of concrete.³⁶ A concrete mix design parameter such as water content in combination of TETP and cement may be the cause of this increased strength. As mix design involves mixing of various ingredients in suitable proportions in which each ingredient has unique properties and these properties vary from source to source, the proportion of each ingredient affects the strength of the developed concrete. Besides, the suitability of the admixture used in the mix also improves the properties of concrete. Thus, by looking at the results, it may be inferred that with the appropriate mix design, there is a possibility to develop sustainable concrete with enhanced properties (Figures 6 and 7). A similar trend is observed for the split tensile strength and flexural strength of textile-sludge-incorporated concrete. The increase in strength may be due to the cohesive nature of textile sludge.²³ A maximum increase of 6% and a decrease of 28% are observed in split tensile strength compared with the control sample. Similarly, a 15% increase in flexural strength and a reduction of 16% are observed. Water absorption and quantity of sludge added are directly proportional with each other.^{37,38} The porosity of the specimen increases with an increase in the content of textile sludge in the concrete; subsequently, density is reduced and water absorption capacity increases (Figure 5). A maximum increase of 21% and a reduction of 40% in water absorption capacity are observed compared with the test samples. The toxicity characteristic leaching procedure was performed by past researchers using fractured particles of sludge-incorporated concrete blocks as per the US EPA method, the Japan Society of Civil Engineers standard leaching test method and so on.^{12,26} It was found that none of the samples exceeded the

Figure 5. Compressive strength and water absorption of concrete blocks or bricks

Figure 6. Split tensile strength of concrete blocks or bricks

Figure 7. Flexural strength of concrete blocks or bricks

threshold values, as given by the US EPA and the Department of Environment in Bangladesh.

2.5 Utilization of TETP sludge to develop sustainable clay bricks

From Figure 8, it is seen that the compressive strength of textile-sludge-incorporated clay bricks decreases with the percentage increase in the composition of the textile sludge when partially replaced with soil.^{1,6,11,15,17–19,39} A maximum percentage decrease of 35% is observed when compared with control bricks. The chemical characterization of textile sludge shows the presence of organic matter; this volatile organic matter is volatilized during the burning process, hence resulting in a volumetric increase in pores.^{6,17,18} This causes porosity in the

Figure 8. Compressive strength and water absorption of clay bricks

bricks, and the percentage of weight loss increases in textile sludge bricks (Figure 9). A maximum weight loss of 83% is observed, due to which the strength of bricks reduces.¹¹ In some of the other studies, it is also observed that bricks developed with textile sludge exhibited higher compressive strength compared with control bricks^{40–42} and the maximum increase in percentage is 90% (Figure 8). A gradual increment in strength was observed at an optimum quantity of sludge and then decreased after reaching that quantity. Hence, optimum utilization of sludge in bricks is suggested for the production of good bricks. It has been found that an optimum quantity of TETP sludge in the bricks has satisfied the norms of first-class bricks of the Indian standards,⁶ class III brick strength of 3.5 N/mm² or more¹⁷ of IS standards¹¹ and ASTM standards.⁴²

The density of bricks/blocks is affected and is found to reduce with a percentage increase in the quantity of textile sludge (Figure 10).^{6,11,17,18} A maximum decrease of 14% in density is observed.

Water absorption is directly proportional to the quantity of textile sludge added to the compositions.¹⁹ A maximum increase in water absorption capacity of 80% is found when compared with the test sample (Figure 8). A higher amount of void spaces in the microstructure of textile-sludge-incorporated bricks subsequently increases the consumption of water; thus, the water absorption capacity increases.^{6,11,16,18,42–44} The water absorption capacity of green bricks is lower than that of burnt clay bricks.⁴² The addition of glass in combination with sludge could result in reducing the water absorption capacity of bricks by clogging their voids⁴¹ (Figure 9). It is also observed that the firing temperature and its corresponding duration play a vital role in the development of strength. Strength increases with the increase in firing temperature and firing duration^{11,18,19} (Figure 11). Shrinkage of the sludge-incorporated clay bricks is found to increase with the increase in sludge content.

Figure 9. Firing temperature and weight loss of clay bricks

Figure 10. Density of clay bricks

Figure 11. Shrinkage of clay bricks

Toxicity characteristic leaching procedure tests performed on sludge-incorporated bricks indicated that most heavy metals were not detectable in the leachates of the brick product,^{15,16,42} and the levels of the few detectable heavy metals were found to satisfy the standard regulations – namely, Dutch regulations. The reduction in heavy metal concentrations in the developed product may be due to dilution of the concentration of heavy metals present in the raw material during the blending process and due to evaporation of heavy metals present in the brick product during the firing process.

2.6 Development of paver blocks using TETP sludge

The maximum compressive strength of paver blocks was found to decrease with an increase in the percentage substitution of textile

sludge with cement (Figure 12).^{45–48} A maximum reduction of 11% is observed compared with test blocks. IS 15658:2006 recommends a minimum strength of 30 MPa for paver blocks in building premises and public gardens/parks⁴⁸ (Figure 12). It can be seen that the maximum compressive strength reported by many past researchers was above 30 MPa, which fulfills the requirement of BIS.

As far as flexural strength is concerned, it decreases with the increase in the amount of sludge added as a partial replacement of cement (Figure 13).^{45,46}

Loss of thickness was observed in sludge-incorporated blocks when sludge was used as a partial replacement of cement.⁴⁶

Figure 12. Compressive strength and water absorption of paver blocks

Figure 13. Flexural strength and abrasion resistance of paver blocks

The losses observed were within 2–2.5 mm, which satisfies the recommendations of IS 1237:1980.⁶⁸

The water absorption of each block tested is less than 10%, which fulfills BIS requirements.¹

3. Discussion

An abundant quantity of around 70–80 Mt of TETP sludge is generated per day in India,^{7,8} which is disposed of in landfills, subsequently causing environmental pollution. Thus, extensive literature studies were performed pertaining to the development of sustainable construction materials. Table 1 shows the various types of equipment utilized by various researchers for the chemical characterization of TETP sludge and the developed sustainable products. It is seen that the composition of sludge varies from place to place and depends on the type of treatment process involved. Enormous variations in the chemical composition of sludge were observed. Sludge waste has silicon dioxide in a larger amount, which shows its siliceous nature. The presence of a high calcium and magnesium content indicates its potential as a partial replacement for the manufacturing of sustainable construction material. The presence of metals such as aluminum (Al), iron and calcium is indicative of the oxide composition of base-clay materials. Heavy metals such as cadmium and chromium were found to be within regulatory limits. Thus, sludge can be used directly as a raw material without creating any negative impact on the environment. The present paper reviewed that various researchers have substituted TETP sludge in various optimum proportions ranging from 0 to 50% and adopted various methodologies for the development of sustainable concrete, bricks, mortars and paver blocks (Figure 2). The common parameter tests that were performed by researchers were compressive strength, water absorption and density tests, for investigating the properties of the developed product (Tables 3–6). It is discovered that the concrete produced by using TETP sludge showed appreciable strength up to a certain limit, but after reaching the optimum limit of replacement, the strength started reducing. A similar trend was observed for other developed sustainable products such as mortar, bricks and paver blocks with various other mechanical tests. The maximum compressive strength was observed in the control samples. It was observed that the compressive strength of block with an optimum quantity of sludge¹ satisfied the minimum required strength of 4 N/mm² for grade D, load-bearing units of IS 2185(Part 1):1979.⁴⁹ Also, blocks developed with sludge satisfied ASTM C 129-75 standards for non-load-bearing concrete masonry units.⁵⁰ Clay bricks developed with the optimum quantity of sludge were found to have compressive strength greater than 3.5 N/mm² as specified in IS 1077:1979 for bricks in load-bearing units.⁵¹ The value of water absorption of blocks developed by many researchers was less than 10%, which meets the requirements of BIS.⁴⁹ The water absorption value of bricks was found to be less than 20%, as prescribed in IS; for paver blocks, water absorption values were less than 10%, which meet the requirements of BIS.⁵² As far as block density is concerned, the blocks achieved

Figure 14. Percentage substitution of TETP sludge recommended by various researchers⁶⁹

a density greater than 1800 kg/m³.⁴⁹ As per ASTM C 129-75 standards, the developed blocks were categorized as normal weight.⁵⁰ Researchers have suggested utilizing an optimum quantity of sludge to achieve desirable properties in sustainable material. Optimum replacement percentages ranged from 5 to 30% for mortar, from 5 to 40% for concrete, from 5 to 50% for clay bricks and from 20 to 40% for paver blocks (Figure 14). This indistinctness in the optimum replacement percentage is due to the variations (Table 2) in the chemical composition of sludge and variation in the type of product. When looking at the performance of the developed sustainable construction material, it can be said that with the proper mix design, TETP sludge has the potential to be used in creating structural or non-structural building components that will help meet the increasing demand for construction material. Also, with the optimum usage of TETP sludge ranging from intermediate to higher limits (Figure 14), production of cement can be minimized; thus, reduction in the consumption of natural resources can be achieved. Consequently, carbon dioxide footprints will be substantially reduced.

4. Conclusion

The various methodologies pertaining to the development of sustainable construction materials such as mortar, concrete, clay bricks and paver blocks have been extensively reviewed. Various microscopic examinations and physicochemical and mechanical tests involved in the development of TETP-sludge-incorporated sustainable material have been studied in accordance with the reviewed literature and standards. From this review study, the following conclusions have been drawn.

- The chemical composition of TETP sludge shows its potential to be used in developing sustainable construction materials.

- Usage of TETP sludge as an alternative raw material to cement, fine aggregate and clay in the construction industry is feasible without compromising the quality and strength as prescribed by many standards – namely, IS 2185(Part 1):1979, IS 1077:1979 and ASTM C 129-75.
- The optimum ranges for the development of mortar, concrete, clay bricks and paver blocks are 5–30, 5–40, 5–50 and 20–40%, respectively.
- When looking at the replacement percentages, it can be concluded that a maximum of up to 40% TETP sludge with proper mix design can be used as a substitute with or without additives for the manufacturing of structural or non-structural building components, which would provide a cost-effective solution to fulfill the demand for construction materials and also provide an alternative solution to the problems arising due to direct disposal of TETP sludge on land.
- Many researchers have utilized TETP sludge as a partial replacement for cement, fine aggregates and clay for the development of sustainable construction material. However, the thermal and functional performance of TETP-sludge-incorporated small-scale models under real-life conditions was not commonly observed in past studies.
- The techno-economic feasibility of the developed product can be explored using cost–benefit analysis for its commercial applications.
- Thermal and energy building simulation along with life-cycle assessment are the prominent areas for further research.
- Fatigue life assessment of developed paver block might prove an important aspect of the design of TETP-sludge-incorporated pavements.

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