



Effect of mix proportion on the strength and durability of plastic and sand composite for construction applications

Yusuf Olawale Babatunde¹ · Ridwan Ademola Ibrahim¹ · Daniel Oluwafemi Oguntayo^{2,3}

Received: 29 April 2022 / Accepted: 9 September 2022 / Published online: 21 September 2022
© Springer Nature Switzerland AG 2022

Abstract

The management of solid waste continues to be a major challenge, particularly in the urban agglomeration in developing and underdeveloped countries in the world. One type of solid waste that is of national and global concern is waste plastic. It has become necessary to find a sustainable way for its disposal. This study sought to explore the potential of recycling waste plastic as a binder to produce composite for construction purposes. Polyethylene Terephthalate (PET) type of plastic was employed in this study. Melted waste PET plastic was mixed with sand at three different compositions of 1:1, 1:2, and 1:3. The influence of the varying mix compositions on the morphology, strength, and durability of the composite was investigated. The highest compressive strength of 11.5 N/mm² was obtained from a mix ratio of 1:2. Meanwhile, the results of the post-elevated compressive strength showed a slight reduction in strength. The water absorption for the composite was below 1%. However, the scanning electron microscopy images showed sand reinforcing the waste plastic by filling voids, thereby enhancing its strength properties. The results obtained will provide a guide for designing plastic–sand composite for construction applications such as low bearing block walls.

Keywords Waste PET bottles · Strength · PET-Sand composite · Durability · Morphology

Introduction

The continuous increase in the global waste plastic generation posed a serious threat to the environment, human health, and the ecosystem [4, 20, 27]. Plastic is the second most generated municipal waste in the world after food and fruit waste [7]. Unprecedented disposal and inefficient management of waste plastics have been a global concern [30], most especially, in developing countries where there are weak waste management mechanisms, low rates of collection and recycling [13, 24]. There is growing interest in the recycling of waste plastic as construction materials. Utilization of recycled waste plastic in construction would contribute to green construction and sustainable

infrastructural development. This approach would diminish the traditional culture of incineration and landfills. There are different categories of plastic, and their level of recyclability can be known by their resin code [25]. Plastic with recyclable arrows and Resin Identification Code (RIC) on the container are known to be recyclable. The lower the resin code, the more likely it is to be recyclable [28]. Polyethylene Terephthalate (PET) plastic-type dominates the single-use waste plastic generation stream. It is widely used for plastic beverage bottles, water bottles, trays, jars, etc. [1, 16, 21]. PET plastic contains atomic species of Carbon, C, Hydrogen, H Oxygen, O; thus, there won't be release of noxious gases when melted [19]. Different research studies have incorporated waste plastic as partial or full replacement of aggregates in concrete mix [5, 12, 18, 23]. Their findings showed that less than 15% of aggregates can be added into concrete mix without significant impact on the strength properties [11]. Increase in the utilization of waste plastic in construction sector motivates this study. Cement is a prominent material in construction industry. About 1.5 billion tons of cement are consumed in concrete industry annually [23]. The ever-increasing cost of construction is partly associated with the rising cost of cement, owing to

✉ Yusuf Olawale Babatunde
babatundeyusuf990@gmail.com

¹ Department of Civil Engineering, University of Ilorin, Ilorin, Nigeria

² Landmark University SDG 11 (Sustainable Cities and Communities Research Group), Omu-aran, Nigeria

³ Department of Civil Engineering, Landmark University, Omu-aran, Nigeria



Fig. 1 Drying of Sand

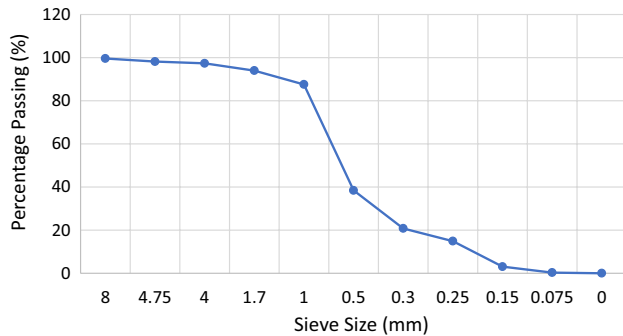


Fig. 2 Sieve analysis of sand

its high energy consumption and production cost [6, 10, 26]. Alternatives are being sought in the use of agricultural and industrial waste materials. Hence, this study focuses on the use of waste PET plastic as the only binder in a lightweight composite for certain construction applications and circular economy.

Materials and methods

Sand

The sand was locally sourced from a river at the University of Ilorin, Ilorin, Nigeria. It was air-dried under ambient temperature (as shown in Fig. 1) to remove absorbed water from the pores of the sand and to prevent the presence of lumps in the sand–plastic composite. From visual inspection, the sand has brownish color, odorless and free from impurities. It is not too coarse, as it did not hurt when rubbed on the palm. Laboratory tests of sieve analysis, bulk density, water absorption, moisture content, and specific gravity were carried out in accordance with ASTM D422-63, ASTM D1895-17, ASTM D570-98, and ASTM D4643-00, respectively, and are presented in Fig. 2 and Table 1.

Waste plastic

This study uses a Polyethylene Terephthalate (PET) type of plastic. It was locally sourced from a waste plastic recycling company at *Sobi* area, Ilorin, Nigeria. At the recycling company, the waste plastic was sorted, washed, and shredded into small sizes between 6.35 and 20 mm as shown in Fig. 3. Specific gravity, bulk density, water absorption of the waste plastics were determined in accordance with ASTM standards and are presented in Table 1.

Sample preparation and laboratory investigation

The materials: waste PET plastic and sand, were batched by volume for three different mix ratios of 1:1, 1:2, and 1:3. The batched waste PET plastic was introduced into an aluminum bucket and then placed in a carbonization chamber to melt. Carbonization chamber is a semi-closed open system with a chimney to lead out the gas produced during the melting of the plastics. PET plastic has a melting point

Table 1 Physical properties of the materials

S/N	Tests	Sand		Waste PET plastic
		Values obtained	Standard	
1	Bulk Density (g/cm ³)	1.471	1.4–1.68	0.810
2	Specific gravity of sand	2.604	2.6–2.8	1.053
3	Water absorption of sand (%)	1.894	< 3%	0.000
4	Moisture content of sand (%)	0.901	–	–
5	Co-efficient of curvature of sand	1.500	1–3	–
6	Co-efficient of uniformity of sand	2.667	< 4 = Uniformly graded > 4 = Well or gap grade	–
7	Fineness modulus of sand	2.940	2.2–3.2	–



Fig. 3 Shredded waste PET plastic

of 260 °C at the range of 20 °C. Waste PET plastic was melted at a temperature between 260 and 300 °C. Since the process of the melting wasn't timed, to know if the plastic has completely melted, a long steel rod of 16 mm diameter was used to stir the sample of fire to feel the presence or absence of lumps. Hence, dictating the time of the completion of melting. The batched sand was gradually mixed with the melted waste PET plastic to give a homogenous mortar-like composite. The mixing of the sand with melted plastic was done inside the bucket while on fire. The composite was filled into 100×100 mm molds and 70×70×280 mm beams and cast samples are shown in Fig. 3. After 2 h, the samples were demolded and air-cured in the laboratory at an ambient temperature of 24 °C. Waste PET plastic is a thermoplastic with the ability to solidify when cooled due to the reversible chemical bonds among its molecules. The morphology of the waste PET plastic and sand composite was analyzed using JEOL JCM—7000 benchtop Scanning Electron Microscopy (SEM) with Neoscope software. High vacuum observation conditions and an acceleration voltage of 15 kV were set to take images at several magnifications and speeds. Strength properties of compressive and flexural strength of the hardened waste PET plastic and sand composite were determined in accordance with ASTM C39/C39M—18 and ASTM C78. However, samples were fully immersed in water and the corresponding water absorptions were determined after 1, 6, 24, and 48 h in accordance with ASTM D5229. In order to determine the post-elevated temperature compressive strength of waste PET plastic and sand composite, each mix ratios samples of 100×100 mm cube size was exposed to an elevated temperature of 200 °C for 2 h. An Electric furnace with temperature control was employed and set to 200 °C. After the furnace has reached the required temperature, the samples were placed in the furnace. Changes in density of the composite samples at

20 min, 40 min, 1 h, and 2 h were measured. The samples were allowed to cool for 24 h, and the residual strength of the composite samples was determined and strength loss was computed (Fig. 4).

Results and discussions

Compressive strength test

Figure 5 shows the compressive strength results of the waste PET Plastic and Sand composite against the curing days. It can be observed that the compressive strength of waste PET plastic and sand composite increases as the curing days increase for all the mix proportions. For instance, the 28 days' compressive strength is 13–44% more than that of 7 days. Similar rising trend in strength as curing days was reported by Thiam et al. [29]. They opined that polymers' degree of crystallinity and solidification increases as the duration of cooling increases. Waste PET plastic is a polymer material with reversible chemical bonds, it solidifies when cool and bonds with the sand particle, thereby enhancing cementation or strength ability. Meanwhile, the 28 days compressive strength result of 9.0 N/mm², 11.5 N/



Fig. 4 Cast composite samples

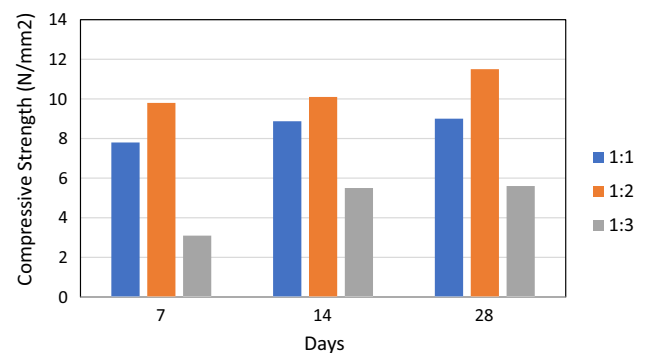


Fig. 5 Compressive strength results of Waste PET Plastic and Sand Composite

mm^2 , and 5.6 N/mm^2 was obtained for waste PET plastic and sand composite at mix ratios 1:1, 1:2, and 1:3, respectively. The addition of sand increased the strength up to twice the proportion of plastic. When the quantity of sand is increased to three times higher than the plastic, the plastic was insufficient to bind the sand. Hence, the lower adhesive binding force between the two constituent materials. This can be explained to be a result of the higher presence of cracks in the composite as shown in SEM images. Plastic melts and expands when heated and contracts and solidifies when cools, provided the melting point range was not exceeded. The mixing of plastic and sand to give a homogeneous paste elongates the duration of exposure of plastic to heat. The more the content of sand, the higher the duration. The higher temperature difference and duration creates tensile stress, weakens the interfacial transition zone between constituent materials, causes cracks, increases porosity, and subsequently decreases strength properties. Contrarily [8, 14, 17], reported an increase in strength up to 1:3 mix ratio before a significant drop in strength at 1:4 mix ratio of plastic and materials. However, BS 5628-1:1992, prescribed the 28 days characteristic strength of masonry block made with cement and sand at 1:2.5 and 1:3.5 mix ratio to be 4.5 N/mm^2 and 6.5 N/mm^2 , respectively. Thus, waste PET plastic and sand composite at 1:1, 1:2, and 1:3 of plastic & sand composite can be used for building blocks strength-wise.

Flexural strength test

Flexural strength is a strength property of the composite against bending stress. Figure 6 depicts the flexural strength of waste PET plastic and sand composite. The result indicated that the flexural strength increases as the content of sand in the composite increases. Waste PET plastic and sand composite at mix ratio 1:3 showed significantly higher values of 39% and 21% than mix ratios 1:1 and 1:2, respectively. The sand tends to reinforce the composite and thereby enhancing its resistance to bending. The resistance of a

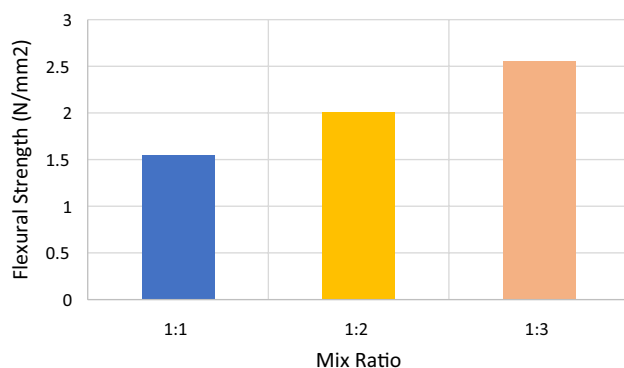


Fig. 6 Flexural strength of waste PET plastic and sand composite

composite depends on the individual strength of constituent materials [2, 3]. According to BS 5628-1:1992, the characteristic flexural strength of a mortar brick with water absorption of less than 7% and the plane of failure perpendicular to the bed joint should be at least 1.5 N/mm^2 . Meanwhile, the obtained flexural strength values of waste PET plastic and sand composite for all the mix proportions are above the specified 1.5 N/mm^2 .

Water absorption test

Figure 7 presents the water absorption of the waste PET plastic and sand composite at different mix proportions. Generally, the water absorption of the composite is less than 1%, irrespective of the mix proportion. This can be attributed to the hydrophobic property of the waste PET plastic and which coats the sand particle, preventing the ingress of water through the pores of the sand. The results indicated that the water absorption increases as the duration of the composite in water increases. Likewise, the water absorption increases as the dosage of sand in the composite increases. The result is in agreement with the report of [9, 15], and [29]. The increment can be explained to be due to the hydrophilic property of sand [2] and the lower presence of waste PET plastic to coat the sand particles. More so, the cracks created by higher temperature difference at a 1:3 mix ratio increase the porosity of the composite [29].

Fire resistance

The durability of the waste PET plastic and sand is evaluated based on resistance to fire. Figure 9 presents the changes in weight of the waste PET plastic and sand composite at different time duration, when exposed to elevated temperatures. The result indicated slight changes in the weight of all composites, irrespective of the mix ratio. For instance, the weight loss for waste PET plastic and sand of mix ratios 1:1, 1:2, and 1:3 is in the range of 0.07–0.2, 0.1–0.2 and

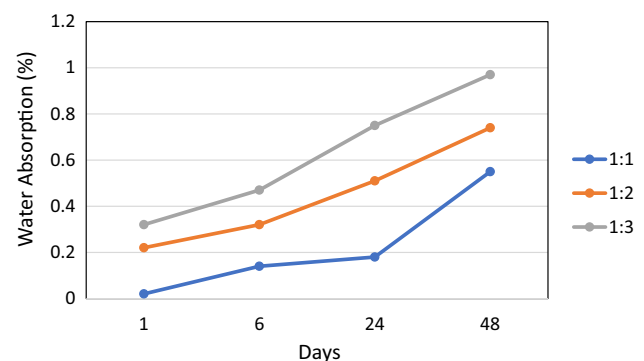


Fig. 7 Water absorption of waste PET plastic and sand composite

Table 2 Residual compressive strength at post-elevated temperature

Mix ratio	Initial compressive strength (N/mm ²)	Post-elevated temperature compressive strength (N/mm ²)	Compressive strength loss (N/mm ²)
1:1	9.0	7.2	1.8
1:2	11.5	10.0	1.5
1:3	5.6	4.0	1.6

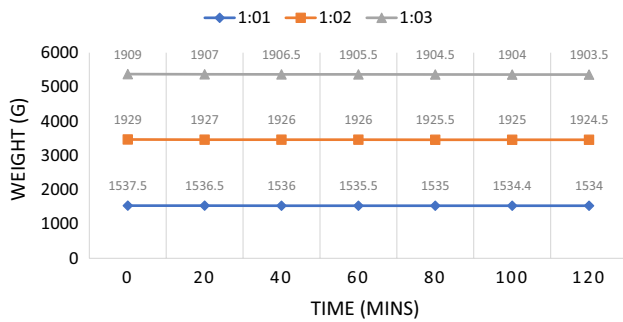
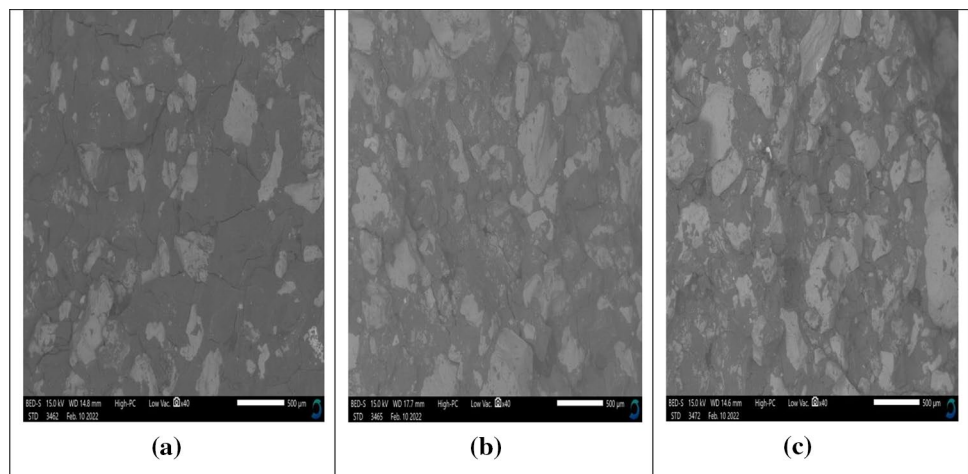


Fig. 8 Post-elevated temperature weight loss

0.1–0.2%, respectively. Upon expiration of 2 h exposure to elevated temperature, residual compressive strength was determined and the results are presented in Table 2. The results showed that there is a compressive strength loss of 1.8, 1.5, and 1.6 N/mm². It can be observed that the 1:1 mix ratio with less quantity of sand gave higher compressive strength loss. Plastic has low fire resistance and which could have led to that result. However, the presence of sand in the composition serves as an insulation for the composite. The higher bonding forces in the mix ratio of 1:2 could be attributed to the lower compressive strength loss. Such strength reduction was reported by Ingabire et al. [14]. After exposure of the paver samples to a 35 °C temperature environment for 12 h, the compressive strength was reduced by

Fig. 9 SEM images for waste PET plastic and sand composite at mix ratio **a** 1:1, **b** 1:2, **c** 1:3



18%, 14%, and 26% for mix ratios 1:3, 1:4, and 1:5, respectively (Fig. 8).

Morphological properties

Figure 9 shows the SEM images of the waste PET plastic and sand composite. The sand is randomly distributed within the plastic. The plastic coats and binds the sand particles together. More so, the sand fills the voids and reinforced the plastic to improve its resistance to load. As shown, waste PET plastic and sand composite at mix ratio 1:3 has a clustered presence of sand due to the high volume of sand and little plastic causing weaker bonding of plastic and sand particles. The lack of adhesion of the sand particle to the melted plastic results in discontinuity in the form of debonding. As a result, the stress transfer at the sand particle/plastic contact is therefore ineffective [22]. This must have influenced the lower compressive strength result of the mix. As seen for 1:2 composite mix, the sand is well distributed and interlocks well within the plastic to give better adhesive force and interactions at the interfacial transition zone, thereby enhancing its higher strength values.

Conclusions

From this study, the following conclusions were drawn:

- i. Waste PET plastic and sand composite at mix ratios 1:1, 1:2, and 1:3 gave 28 days compressive strength values of 9.0 N/mm², 11.5 N/mm², and 5.6 N/mm², respectively, and which can be used for certain construction applications such as low bearing block walls.
- ii. Waste PET plastic and sand composite at mix ratios 1:1, 1:2, and 1:3 gave 28 days flexural strength values of 1.545 N/mm², 2.003 N/mm², and 2.551 N/mm², respectively, and which meets up with minimum of

- 1.5 N/mm² specified for mortar brick by BS 5628–1:1992.
- iii. The water absorption for all the mix proportion of waste PET plastic and sand composite is less than 1%. Hence, it can be applied in areas where waterproofing is required.
 - iv. The sand in the composite serves as an insulator thereby reducing the susceptibility of the composite to fire.
 - v. The results obtained will provide a guide for designing plastic–sand composite for construction applications such as low bearing block walls.
 - vi. Since the time for the melting process cannot be ascertained, it is recommended that a rotating stirrer can be mounted on top of the chamber. Furthermore, for a large quantity that can be used for construction application, the melting and mixing process is best carried out in a rotary furnace. The rotation of the furnace will enhance the mixing process.

Compliance with ethical standards

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

References

1. Adeniran AA, Shakantu W (2022) The health and environmental impact of plastic waste disposal in south african townships: a review. *Int J Environ Res Public Health* 19(2):779. <https://doi.org/10.3390/ijerph19020779>
2. Agyeman S, Obeng-Ahenkora NK, Assiamah S, Twumasi G (2019) Exploiting recycled plastic waste as an alternative binder for paving blocks production. *Case Stud Constr Mater*. <https://doi.org/10.1016/j.cscm.2019.e00246>
3. Akinwumi II, Domo-Spiff AH, Salami A (2019) Marine plastic pollution and affordable housing challenge: shredded waste plastic stabilized soil for producing compressed earth bricks. *Case Stud Constr Mater*. <https://doi.org/10.1016/j.cscm.2019.e00241>
4. Aina KS, Oladimeji AO, Agboola FZ, Oguntayo DO (2022) Dimensional stability and mechanical properties of extruded-compression biopolymer composites made from selected Nigerian grown wood species at varying proportions. *Sci Rep* 12:10545. <https://doi.org/10.1038/s41598-022-14691-z>
5. Aldahdooh MAA, Jamrah A, Alnuaimi A, Martini MI, Ahmed MSR, Ahmed ASR (2018) Influence of various plastics-waste aggregates on properties of normal concrete. *J Build Eng* 17:13–22. <https://doi.org/10.1016/j.jobe.2018.01.014>
6. Ali Shar I, Ayoub Memon M, das Bheel N, Aizaz Dayo A, Ahmed Memon F, Bheel N, Hussain Shaikh Z (2019) Use of wheat straw ash as cement replacement material in the concrete. In: International conference on sustainable development in civil engineering, MUET, Pakistan. <https://www.researchgate.net/publication/339434609>
7. Almeshal I, Tayeh BA, Alyousef R, Alabduljabbar H, Mohamed AM (2020) Eco-friendly concrete containing recycled plastic as partial replacement for sand. *J Market Res* 9(3):4631–4643. <https://doi.org/10.1016/j.jmrt.2020.02.090>
8. Aneke FI, Awuzie BO, Mostafa MMH, Okorafor C (2021) Durability assessment and microstructure of high-strength performance bricks produced from pet waste and foundry sand. *Materials* 14(19):5635. <https://doi.org/10.3390/ma14195635>
9. Aneke FI, Shabangu C (2021) Green-efficient masonry bricks produced from scrap plastic waste and foundry sand. *Case Stud Constr Mater*. <https://doi.org/10.1016/j.cscm.2021.e00515>
10. Bheel N, Ibrahim MHW, Adesina A, Kennedy C, Shar IA (2021) Mechanical performance of concrete incorporating wheat straw ash as partial replacement of cement. *J Build Pathol Rehabil*. <https://doi.org/10.1007/s41024-020-00099-7>
11. Boucedra A, Bederina M, Ghernouti Y (2020) Study of the acoustical and thermo-mechanical properties of dune and river sand concretes containing recycled plastic aggregates. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2020.119447>
12. Dawood AO, AL-Khazraji H, Falih RS (2021) Physical and mechanical properties of concrete containing PET wastes as a partial replacement for fine aggregates. *Case Stud Constr Mater*. <https://doi.org/10.1016/j.cscm.2020.e00482>
13. Dumbili E, Henderson L (2020) The challenge of plastic pollution in Nigeria. In: *Plastic waste and recycling*. Elsevier, pp 569–583. <https://doi.org/10.1016/b978-0-12-817880-5.00022-0>
14. Ingabire D, Ntihemuka F, Mugabo G, Isabane RS, Turatimana T (2018) Recycling High-Density Polyethylene (HDPE) into construction materials as a key step in plastic waste reduction: case of Kigali City. *Rwanda J Eng Sci Technol Environ*. <https://doi.org/10.4314/rjeste.v1i1.2s>
15. Jacob-Vaillancourt C, Sorelli L (2018) Characterization of concrete composites with recycled plastic aggregates from post-consumer material streams. *Constr Build Mater* 182:561–572. <https://doi.org/10.1016/j.conbuildmat.2018.06.083>
16. Kankam KC, Sasah J, Meisuh BK (2019) Study of recycled polyethylene plastic waste as binder in building block for greener construction. In: *International conference on trends & innovations in management, engineering, science and humanities*, 168
17. Kaveh B, Zakwan Arab M, Klalib Aoun H, Arab Z, Kemp T (2020) Performance of concrete with recycled plastic waste. <https://www.researchgate.net/publication/343263792>
18. Kumar Agarwal L, Felix S, Agarwal S (2019) Strength and behavior of concrete contains waste plastic (high density PVC) aggregates as partial replacement of coarse aggregates. *Int J Eng Res Technol (IJERT)* 8(6). www.ijert.org
19. Kumar R, Kumar M, Kumar I, Srivastava D (2020) A review on utilization of plastic waste materials in bricks manufacturing process. *Mater Today: Proc* 46:6775–6780. <https://doi.org/10.1016/j.matpr.2021.04.337>
20. Kumar R, Verma A, Shome A, Sinha R, Sinha S, Jha PK, Kumar R, Kumar P, Shubham, Das S, Sharma P, Prasad PVV (2021) Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. In: *Sustainability (Switzerland)* (vol 13, Issue 17). MDPI. <https://doi.org/10.3390/su13179963>
21. Li X, Ling TC, Hung Mo K (2020) Functions and impacts of plastic/rubber wastes as eco-friendly aggregate in concrete—A review. In: *Construction and building materials* (vol 240). Elsevier Ltd. <https://doi.org/10.1016/j.conbuildmat.2019.117869>
22. Mohandesi JA, Refahi A, Meresht ES, Berenji S (2011) Effect of temperature and particle weight fraction on mechanical and micromechanical properties of sand-polyethylene terephthalate composites: a laboratory and discrete element method study. *Compos B Eng* 42(6):1461–1467

23. Needhidasan S, Vigneshwar CR, Ramesh B (2020) Amalgamation of E-waste plastics in concrete with super plasticizer for better strength. *Mater Today: Proc* 22:998–1003. <https://doi.org/10.1016/j.matpr.2019.11.253>
24. Olofinnade O, Chandra S, Chakraborty P (2020) Recycling of high impact polystyrene and low-density polyethylene plastic wastes in lightweight based concrete for sustainable construction. *Mater Today: Proc* 38:2151–2156. <https://doi.org/10.1016/j.matpr.2020.05.176>
25. Rai A, Truman C, Gilles H, Patel S (2014) Resourceinnovation hub at the 27th avenue campus: circular economy businesses. <https://doi.org/10.13140/2.1.1398.9449>
26. Shafiq N, Hussein AAE, Nuruddinal Mattarneh H MF (2018) Effects of sugarcane bagasse ash on the properties of concrete. *Proc Inst Civ Eng: Eng Sustain* 171(3):123–132. <https://doi.org/10.1680/jensu.15.00014>
27. Shilpa K (2019) *Green Building Technology*, p 2
28. SL Recycling (2021) SL Recycling Limited. Retrieved from SL Recycling Limited Web Site. <http://www.slrecyclingltd.co.uk>
29. Thiam M, Fall M, Diarra MS (2021) Mechanical properties of a mortar with melted plastic waste as the only binder: influence of material composition and curing regime, and application in Bamako. *Case Stud Constr Mater*. <https://doi.org/10.1016/j.cscm.2021.e00634>
30. Tearfund and Crudan (2019) Follow the plastic. Research Report on Plastic Waste in Jos, North Central Nigeria, p ii

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.