Case Studies in Construction Materials 18 (2023) e02200

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Performance of recycled Bakelite plastic waste as eco-friendly aggregate in the concrete beams

Mohan R [a], Vijayaprabha Chakrawarthi [a], T. Vamsi Nagaraju [b], Siva Avudaiappan [c,d,e,*], T.F. Awolusi [f], Ángel Roco-Videla [g,**], Marc Azab [h], Pavel Kozlov [i]

[a] Department of Civil Engineering, Alagappa Chettiar Government College of Engineering and Technology, Karaikudi, Tamil Nadu, India
[b] Department of Civil Engineering, SRKR Engineering College, Bhimavaram 534204, India
[c] Departamento de Ingeniería Civil, Universidad de Concepción, Concepción 4070386, Chile
[d] Centro Nacional de Excelencia para la Industria de la Madera (CENAMAD), Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago 8331150, Chile
[e] Department of Physiology, Saveetha Dental College and Hospitals, SIMATS, Chennai 600077, India
[f] Department of Civil Engineering, Afe Babalola University, Ado Ekiti, Nigeria
[g] Facultad de Salud y Ciencias Sociales, Universidad de las Américas, Providencia, Santiago 7500975, Chile
[h] College of Engineering and Technology, American University of the Middle East, Egaila 54200, Kuwait
[i] Polytechnic Institute, Far Eastern Federal University, Vladivostok 690922, Russia

ARTICLE INFO

Keywords:
Bakelite
Stress-strains
Shear behavior
Recycle waste
Durability

ABSTRACT

The use of plastic waste as a partial or complete replacement for coarse aggregate in concrete mixtures has been studied in recent years. However, the quality and quantity of coarse plastic waste particles have been a challenge. This study aims to investigate the mechanical performance of concrete with Bakelite plastic waste as a partial replacement for coarse aggregate. Six different concrete mixtures with various Bakelite dosages, ranging from 0 % to 10 %, were tested. The results indicate that the addition of Bakelite plastic alters the behaviour of the concrete and reduces compressive and flexural strengths at lower dosages. The inclusion of Bakelite waste in concrete mixtures generally leads to a decrease in compressive and split tensile strength, with the exception of the mixture containing 6 % Bakelite, which showed increased strength. Although there is a slight reduction in flexural strength, Bakelite waste prevents sudden specimen breakage and maintains specimen integrity. The ultimate load capacity of reinforced concrete beams with Bakelite waste is generally lower compared to the control beam, except for the 8 % waste Bakelite beam which demonstrated a similar ultimate load capacity of 60 kN. Although managing Bakelite waste can be difficult because it can lead to the creation of microplastics in landfills over time, utilizing Bakelite waste in concrete can be a sustainable method of waste management. The innovative use of Bakelite waste as a partial replacement for coarse aggregate in concrete offers a sustainable solution to the problem of waste management and addresses the environmental concerns related to the disposal of non-biodegradable plastics. This research provides a practical

* Corresponding author at: Departamento de Ingeniería Civil, Universidad de Concepción, Concepción 4070386, Chile.
** Corresponding author.
E-mail addresses: mohan2006132@gmail.com (M. R), vijayaprabha.struct@gmail.com (V. Chakrawarthi), varshith.varma@gmail.com (T.V. Nagaraju), savudaiappan@udec.cl (S. Avudaiappan), awolusitf@abuad.edu.ng (T.F. Awolusi), aroco@udla.cl (Á. Roco-Videla), marc.azab@aum.edu.kw (M. Azab), opiv.uvc@yandex.ru (P. Kozlov).

https://doi.org/10.1016/j.cscm.2023.e02200
Received 14 March 2023; Received in revised form 15 May 2023; Accepted 5 June 2023
Available online 7 June 2023

solution for developing eco-friendly and cost-effective construction materials while promoting sustainable waste management practices.

1. Introduction

Ensuring that every nation's citizen lives in a sustainable and clean environment is one of the most critical challenges facing governments today [1]. The rise in construction activity has exponentially increased the demand for river sand, depleting and exploiting natural sand resources and having negative environmental repercussions like river edges slipping and a falling water table [2,3]. So, finding a different binding substance that may be used in place of river sand while making concrete is crucial. Moreover, the most significant component of concrete by volume is composed of coarse and fine aggregates, which give the material its stiffness and dimensional stability [4,5]. However, one tone's coarse and fine aggregate requires roughly 0.081 GJ/t and 0.083 GJ/t of energy, respectively [6]. Thus, alternatives to fine and coarse aggregates are crucial in the current situation.

Due to rising industrialization and urbanization, dumping and landfilling recycled products pose a serious risk to human health and the environment. The first synthetic plastic, Bakelite, was made through a polycondensation reaction of formaldehyde, and phenol is one form of a hazardous industrial product. [7,8]. Bakelite is a thermoplastic, sometimes known as a thermosetting polymer or a polymer-based substance [8,9]. Due to its thermal resistance and electrical nonconductivity, Bakelite plastic was used to create the E-elements [10,11]. As a result, many heavy metals, electronic components, glassware, ferrous, polymers and nonferrous metals, hazardous chemicals, cell phone casings, housewares, plastic containers, pipe stems, and other plastic materials are made of synthetic Bakelite plastic [12].

Landfilling is still a typical technique for Bakelite plastic waste, although when biodegradation does not continue, landfills do not offer an environmentally favourable alternative [13]. To mitigate Bakelite plastic waste dangers, it is crucial to employ Bakelite plastic waste components and to minimize, reuse, and recycle waste [14]. According to statistics, India manufactured 318 million tonnes of plastic in 2020 and generated 80,000 tonnes of Bakelite waste, with an estimated rise to 70,00,000 tonnes by 2050 [15]. Several of these were burned in kilns and disposed of in landfills, potentially causing environmental deterioration and posing a health risk to the workers handling them. The most often utilized materials are plastic and rubber [16,17]. By 2030, it is hoped that Bakelite scrap from commercial items would be recycled and collected in 60 % of all instances. [18], despite controlled procedures in industrialized countries. The plastic and rubber subsectors comprise 8.33 % of the total zone, and they represent almost 15 % of all recyclable materials [19]. Plastic garbage can be produced in the electrical, home, and professional sectors. This source accounts for 20–30 % of the resource recovery facility's supply [20]. Concrete is utilised more than any other material in the construction industry. [21,22]. Concrete is accessible and useful for many different uses. The demand for building project aggregates is anticipated to grow 2.4 % annually to 46.3 billion metric tonnes in 2023 due to a continuous rise in global building activity, making India one of the top aggregate consumers worldwide [23,24]. In addition, cement sales have increased worldwide in all non-building sectors where aggregates are required for continuing infrastructure projects [25,26]. Therefore, it is crucial to develop alternative materials due to the future demand for construction and the diminishing supply of natural building materials. The enormous demand for naturally occurring aggregate raises serious questions about the availability in long-term development for natural aggregate for [27–29]. By substituting wasted Bakelite material for natural aggregate when making concrete, the environment is therefore protected, and concrete is now a durable and advantageous building material for the environment [30,31]. Stresses on concrete, such as extreme heat and cold, can cause it to crack and deteriorate [30,32,33]. Plastics have recently raised concerns due to their breakdown and influence on the environment. It is utilized to decrease the effects of these problems because it degrades and is widely accessible. For the past few years, various applications have extensively used plastic materials as a concrete matrix and reinforcing [34–36]. Synthetic polymers are one of the extensively used plastics because of their low density, low cost, ease of production, and better mechanical properties than ceramics and metals [37,38]. E-waste management poses substantial issues in terms of recycling and disposal [39]. Even though recycling e-waste helps reduce the amount of waste dumped in landfills, improper recycling can pose serious risks to nearby communities and workers. These hazards include being exposed to dangerous materials like heavy metals during recycling. Additionally, improper e-waste disposal in landfills or incinerators can cause dangerous substances, like heavy metals, to leak into the environment. Innovative waste management techniques, such the use of reused plastic in the construction sector, have been created to address the problem of e-waste [40–43]. Recycling plastic waste while producing valuable resources for the construction sector is a sustainable method of handling plastic waste [41–43].

There is an enormous amount of literature on the use of recycled plastic waste in concrete. Waste plastic products cannot always be cementitious binders or aggregates [30]. The repeated drop weight test, described in the ACI 544–2R, is the first method of determining concrete's impact resistance. Investigational tests can be carried out to ascertain the number of strikes necessary to damage testing samples to a specific level. Each impact is recorded to produce a quantitative estimate of the energy absorbed by the specimen at the specified level of discomfort. So, by performing impact tests under ACI 544 [44] criteria, it is possible to compare the impact resistance of different materials. Concrete's workability is impacted by the size and shape of recyclable plastic particles, according to Siddique et al. [45]. More studies evaluate the impact of aggregates and cement replacement by plastic waste and fibers in concrete. For example, the use of wet-grinding plastic waste (WGPW) as additive in Portland cement was investigated by He et al. [46]. The authors showed that WPWC additive enhanced the early strength of mortar and improved the hydration of cement, while reducing the permeability and the electric flux of cement mortar. Another attempt made by Zeyad et al. [47] to study the effect of coarse aggregate replacement on the mechanical properties and resistance to radiation of ultra-high performance concrete. The authors found that

Ilmenite aggregate and steel fibre enhanced considerably the compressive strength of concrete. The use of dry crushed pomegranate peel waste (PW) as a thermal insulator to produce lightweight clay bricks was studied by Maafa et al. [48]. The results showed that the use of PW increased thermal conductivity, water absorption, density, and shrinkage, while decreasing the compressive strength of clay bricks. In another study done by Al-Tayeb et al. [49], the replacement of coarse aggregate with plastic waste improved the impact resistance and energy absorption of concrete beams.

Ghanim et al. [50] investigated the use of rubberized concrete with hybrid polypropylene and steel fibers. They found that the addition of crumb rubber improves fracture characteristics but decreases compressive and tensile strengths.

The use of Bakelite plastic waste as a partial replacement for coarse aggregate in concrete is a novel approach to managing plastic waste and creating sustainable construction materials. This method not only provides an effective solution to plastic waste disposal but also reduces the demand for natural coarse aggregates, which are finite resources. Additionally, the study's findings indicate that concrete containing Bakelite waste can achieve desirable compressive and flexural strengths at a specific dosage, making it a viable alternative to traditional concrete.

1.1. Research significance

Previous attempts to recycle various materials for use in concrete are mentioned, including plastic waste, which was claimed to improve the strength of polymer concrete [30,51–53]. Recycled Bakelite was also studied as a potential coarse aggregate, but further research is needed to establish its applicability and recycling potential. This study aims to recycle Bakelite waste as a partial replacement for coarse aggregate in concrete and contribute to conservation efforts while reducing energy consumption and environmental pollution. The findings are expected to assist the building sector and inspire further research on the use of Bakelite in concrete.

2. Materials

In this study, ordinary Portland cement (IS 53-grade) was used as a cementitious material meeting the standard specifications of IS 12269 [54]. River sand and crushed granite coarse aggregates were used as the filler materials. Moreover, plastic waste Bakelite was used as a partial replacement of the coarse aggregate in the percentages of 2, 4, 6, 8, 10 by dry weight of the granite aggregate. The grain size distribution of the aggregate and Bakelite was shown in the Fig. 1. The waste Bakelite can be properly identified and used as building materials. Plastic waste is one of the biggest environmental recycling products. Most plastic garbage is gathered from workplaces, retail locations, educational facilities, and other industries. The requirement for a solution can be determined by looking at the present trend of reusable materials. Depending on the desired particle size, the waste from the manufacture of Bakelite is gathered, crushed, and ground. Fig. 2 shows the granite aggregates and Bakelite aggregates. The Bakelite aggregate concrete exhibits compressive and tensile strength of 37 MPa and 2.5 MPa, respectively in this study. Specific gravity of the sand, granite aggregate, Bakelite aggregate are 2.63, 2.68, and 1.42, respectively. For 1 m^3 concrete, the proportion of the cement, fine aggregate, and coarse aggregate are 380 kg, 665 kg, and 1110 kg, respectively as presented in Table 1. In the concrete mix, water-cement ratio of the blends was maintained as 0.5.

3. Test setup and instrumentation

After procuring the raw materials, the specimens were prepared and tested. The mechanical properties include the compressive strength of cubes and cylinders, the cylinders' split tensile strength, and the beams' flexural strength were evaluated. In addition, a physical observation was made to assess the crack pattern of the beams.

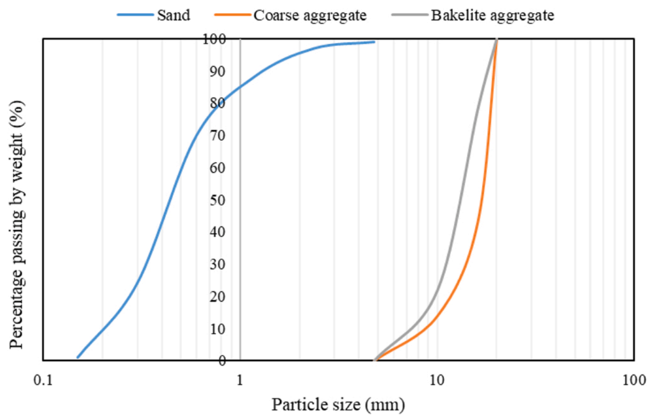

Fig. 1. Particle size distribution of aggregates.

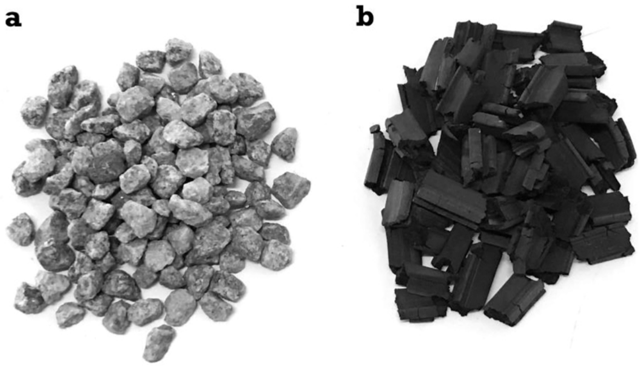

Fig. 2. Aggregates (a) granite (b) Bakelite.

Table 1
Mix proportion for concrete mix.

Specimens	Bakelite (%)	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Bakelite (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)
C	0	380	665	0	1110	190
Sp1	2	380	665	22.2	1087	190
Sp2	4	380	665	44.4	1065	190
Sp3	6	380	665	66.6	1043	190
Sp4	8	380	665	88.8	1021	190
Sp5	10	380	665	111.0	999	190

3.1. Compressive strength test

Concrete cubes have undergone compression testing under IS 516-1999 [55]. A compression testing equipment with a 2000 kN capability was used to test each concrete cube specimen. Applying compressive load at 140 kN/min or 140 kgf/cm^2/min until the specimen fails makes it feasible to determine the crushing strength of concrete cubes. The cubes were evaluated at 7 and 28 days of curing. Similarly, on days 7 and 28, cylinders were tested. The specimen's plane surfaces were compressed while sandwiched between two plates of the compression testing apparatus. For each specimen, three cubes are tested, and the average values are chosen. A compression testing equipment with a 2000 kN capacity was used to perform compressive strength tests on concrete cylinders with a 150 mm diameter and 300 mm length (see Fig. 3).

3.2. Split tensile strength and modulus of rupture tests

Concrete cylinders' split tensile strength is tested by applying a compressive force at 140 kgf/cm^2/min or 140 kN/min until the specimen fails. The cylinders underwent testing after 28 days of curing and a brief drying period. On the 28th day, cylinders were tested. The specimen's lateral sides were compressed while sandwiched between plates of the compression testing apparatus. The cylindrical specimens with a 150 mm diameter and 300 mm length were used for the splitting tensile strength. A

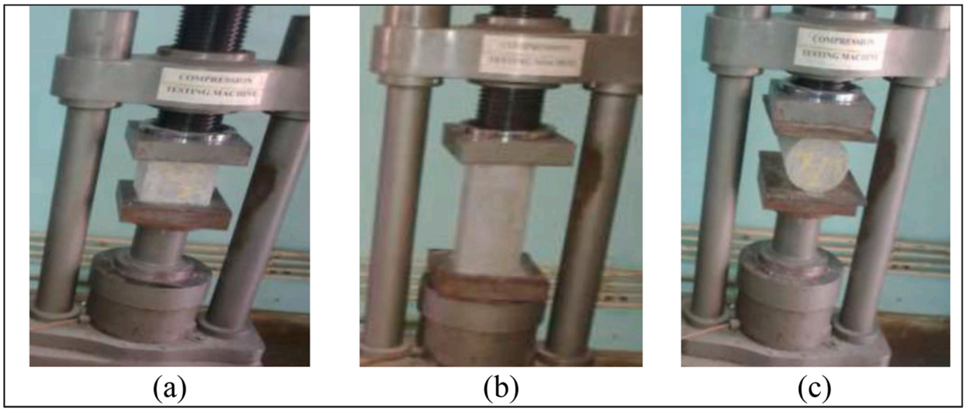

Fig. 3. View of specimens testing (a) compression on cube, (b) compression on cylinder, and (c) split tensile on cylinder.

500 mm × 100 mm × 100 mm prism was used to measure the rupture modulus.

3.3. Durability test

150 × 150 × 150 mm concrete cubes that have been cast and are curing in water for 28 days. According to ASTM [C1898–20] standards, the cured specimens underwent chemical resistance testing. The test solutions were of 5 % hydrochloric acid (HCl). According to ASTM guidelines, distilled water was also employed as a control solution. Once the specimens had been steeped in the solution for 7 and 14 days, their weight was recorded. Each immersion period ended with visually inspecting the test specimen's appearance, cleaning under running water, hasty drying with a paper towel, and weight measurement.

3.4. Shear behaviour

Beams measuring 100 mm × 150 mm × 1700 mm are used as test specimens; they are supported by four high-yielding strength distorted (HYSD) bars, two of which are under tension and two in compression. Additionally, HYSD bar stirrups measuring 90 mm in length and 6 mm in diameter were added to strengthen it against shear forces. Fig. 4 displays the details of the reinforcement. In an open curing tank with ambient lighting, all the specimens underwent a 28-day curing process. Fig. 5 depicts the schematic view of the reinforcement setup. All beams underwent reaction loading frame testing. The beams' spans were maintained at 2000 mm with supported ends, and they were tested with loading at two-point applied at one-third of the spans on a beam. As illustrated in Fig. 4d, three linear variable differential transformers (LVDTs) were mounted at the midspan, third span, and fourth span to measure the deflections of the beam.

Four strain gauge buttons were attached to the specimens, and maximal compressive and tensile strains were calculated using a mechanical strain gauge. Deflection, strain, and crack were recorded for each 2 kN load increment, with data logged using proSoft software.

All beams were tested in a 500 kN loading frame with a constant 1500 mm span and two-point loads applied at one-third intervals through a stiff beam. Three LVDTs were used to measure deflections at the centre, 1/3rd, and 1/4th of the span.

The beam was placed perpendicular to the applied stress without eccentricity for a flexural test on a 1000 kN universal testing machine. The specimens were loaded at a constant rate until failure, with the crack initiation and location recorded to determine the modulus of rupture.

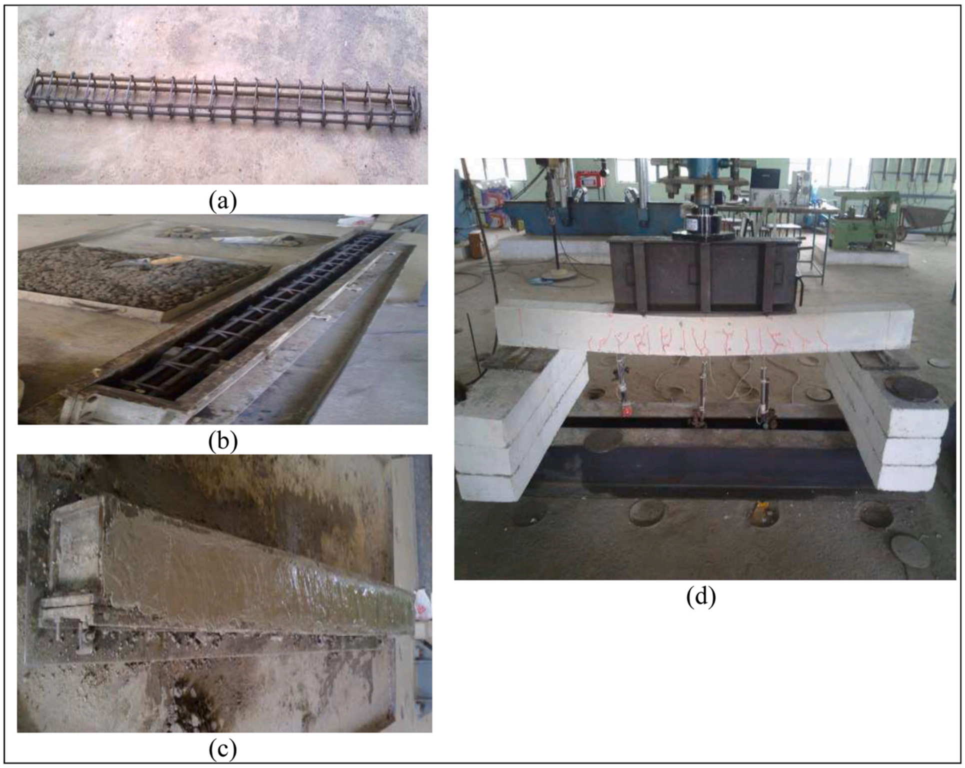

Fig. 4. Preparation and testing of the concrete beam: (a) steel reinforcement detail, (b) Formwork and reinforcement placement, (c) casted beam, and (d) testing of beam.

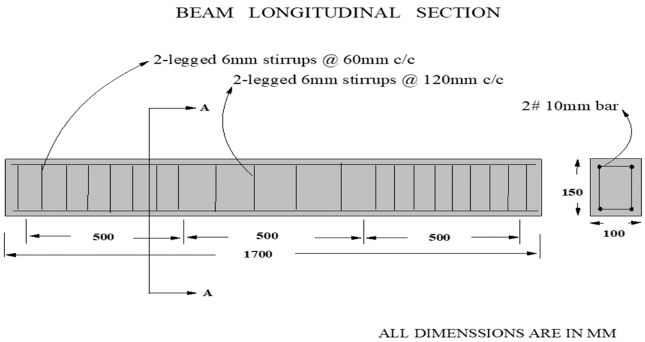

Fig. 5. Schematic view of the reinforcement setup.

4. Results and discussion

4.1. Compressive strength of cubes and cylinders

As anticipated, all concrete combinations' compressive strengths rose between 7 and 28 days of curing period. According to all the concrete's compressive strength results, the concrete made with Bakelite waste aggregate as a partial replacement for the natural aggregate had the most significant reduction in compressive strength because, in comparison to the natural aggregates, the aggregate waste particles from Bakelite have a poor angular shape and a smooth surface texture. As a result, this combination of Bakelite aggregate and the cement matrix is expected to interlock poorly. Also, due to the hydrophobic properties of Bakelite and the cement mortar, sand, and recycled Bakelite waste aggregate particles, the fall in compressive strength for Bakelite concrete was typically caused by a weak bond. Also, in the case of the Sp4 mix, the efficient distribution of Bakelite's fine and coarse particles results in greater strength. As seen in Figs. 6–7, the formation of voids upon adding Bakelite waste in lower and higher contents may cause a decrease in strength. The visual examination of broken specimens revealed that the failure planes could not be identified along the Bakelite interfaces, which suggests that the cement mortar and Bakelite aggregates will be well-bonded. Additionally, the Bakelite particles were evenly dispersed throughout the specimens, indicating acceptable homogeneity and the absence of any particles that appeared to be floating on the specimens' top surfaces. Bakelite is harder and denser than plastics like polyethylene, polypropylene, and polystyrene [56,57]. Researchers in the past that utilized waste Bakelite aggregate in concrete reported a substantial loss in strength compared to natural aggregates [30,51]. Waste Bakelite found in concrete was the subject of research. Although there has been an increase in Bakelite plastic, there has been a noticeable drop in compressive strength. However, there are three advantages to partially replacing granite aggregate: mechanical performance, chemical resistance, and low cost. Bakelite concrete can therefore be utilized to create low-weight concrete constructions [51].

Furthermore, the 28 days compressive strength results obtained for the cubes specimens were compared with that of cylindrical specimens and according to previous literatures the ratio between the strength test of cubes and cylinder is approximately 1.25. Details of this comparison is presented in Fig. 8. The coefficient of determination obtained were above 0.9 which indicates a close relationship between the predicted and the experimental results.

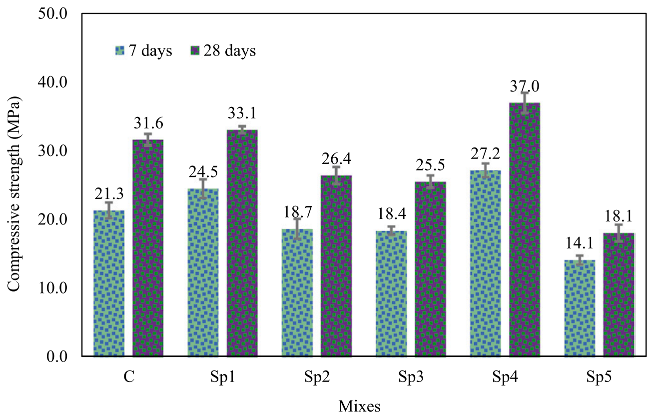

Fig. 6. Compressive strength of Bakelite concrete cube specimens.

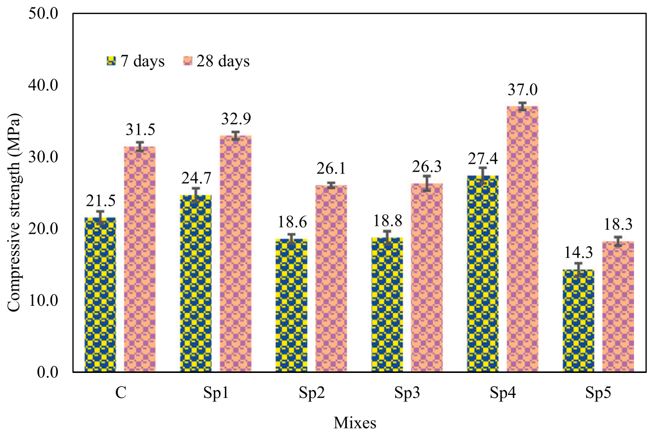

Fig. 7. Compressive strength of Bakelite concrete cylindrical specimens.

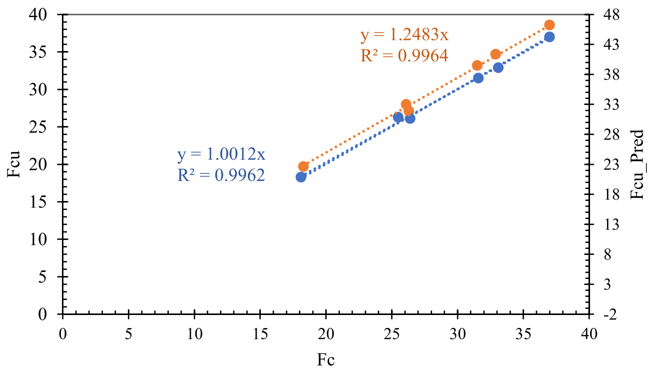

Fig. 8. Comparison between compressive strength of cylinder and cube specimen.

4.2. Split tensile strength

Fig. 9 shows the results of the split tensile strength testing for the Sp1, Sp2, Sp3, Sp4, and Sp5 Bakelite plastic concrete mixtures. These findings indicate that the amount of Bakelite waste plastic in concrete mixtures at 28 days of curing age decreases the split tensile strength. This phenomenon can be related to the weakening of the bond between the cement paste's surface and waste plastic fragments and to the hydrophobic properties of plastics, which may prevent cement from fully hydrating. As a result, the hydration gradually increased. Moreover, the split tensile strengths of the concrete composites made from waste plastic were similar to those of earlier research works [30,51]. A relationship between the split tensile strength and compressive strength in comparison with the split

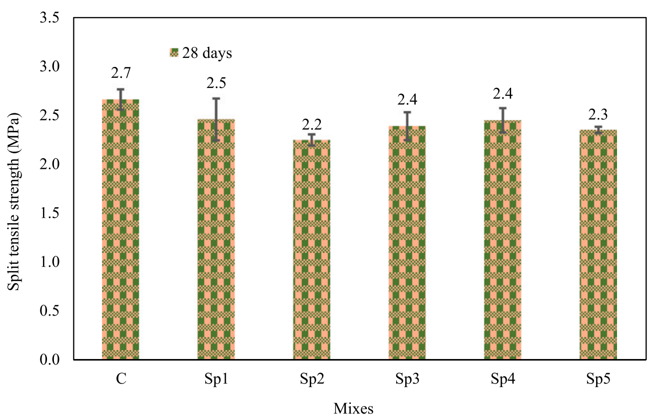

Fig. 9. Split tensile strength of Bakelite concrete cylindrical specimens.

tensile strength obtained using ACI 318–99 equation is presented in Fig. 10. The results of the coefficient of determination indicates a weak relationship between split tensile strength, compressive strength and ACI 318–99 equation.

4.3. Modulus of rupture

The results show that the flexural strength of cylinders containing waste plastic, such as Sp1, Sp2, Sp3, and Sp5, is lower than that of the control specimen, as seen in Fig. 11. This is because the bond between the waste plastic and concrete components for flexure is inadequate. In contrast, the Sp4 specimen's strength is slightly lower than that of the control concrete. This is because the high compressive strength in the compression zone prevents the beam from cracking.

A relationship between the modulus of rupture and compressive strength in comparison with the modulus of rupture obtained using ACI 318–99 equation is presented in Fig. 12. The results of the coefficient of determination indicates a close relationship between modulus of rupture, compressive strength and ACI 318–99 equation.

4.4. Influence of hydrochloric acid on Bakelite blended concrete weight loss

Standard-size cubes were left to cure in acid solutions for 7 and 28 days, respectively, to measure the weight loss in hardened concrete. The reduction of the hardened mass, as seen in Fig. 13, was considered when determining the concrete's ability to withstand acid attacks. Concrete contains a higher amount of Bakelite, which prevents acids from penetrating. Therefore, the bonding and pore structure are weakened by the decreased percentage of Bakelite (Sp1 and Sp2 mixes) latex.

4.5. Load-deflection behaviour of Bakelite concrete beams

Table 2 shows that two specimens among the beams have the maximum load-carrying capacity, which is the control specimen and Sp4. The Sp1 and Sp5 beam specimens exhibited a less load-carrying capacity and poor performance, while the remaining beams had similar load-carrying capacities and can be grouped into the same category.

Bakelite concrete graphs and regular concrete graphs differ significantly from each other from the load-deflection curves of concrete beams shown in Figs. 14–16. Compared to Bakelite concrete graphs, regular concrete graphs have a substantially higher initial rigidity. This is another representation of Bakelite concrete's lower modulus of rupture, which was already covered in the rupture section. Because the stiffness of the specimens rises with the addition of waste plastic, their mid span (L/2), one-third span (L/3), and quarter span (L/4) deflections are fewer than those of the control specimen. Although there is less deflection, Sp3 and Sp4 specimens carry the same load as the control specimen. A lesser ductile phenomenon is shown in the graphs with Bakelite content. Once approaching the breaking threshold, the concrete control graphs perform substantially better than Bakelite concrete in giving ample forewarning. Contrarily, Bakelite-containing concretes fail suddenly without taking on any additional weight after reaching their ultimate point.

4.6. Stress-strain behaviour of Bakelite concrete beams

Fig. 17 displays the stress-strain curves for various concrete compositions. Fig. 17 shows that the specimen concrete's strain rate in the compression zone is approximately identical to that of the control specimen and lower. This might be caused by discarded plastic, which makes specimens more rigid. Due to the reinforcement, the tensile strain displayed by the Bakelite specimens behaves linearly up until severe fracture. The graphs' initial stiffness is nearly the same, but the final point differs depending on the amount of Bakelite present when the flexural strength change occurs. In general, specimen beams are under less strain than the control beam. Fig. 18 shows that the Sp4 specimen initially has more strain than the control specimen. The reduction in strain rate during the final stage may be caused by the higher compressive strength of the concrete in the compression zone, which prevents the beam from straining. In

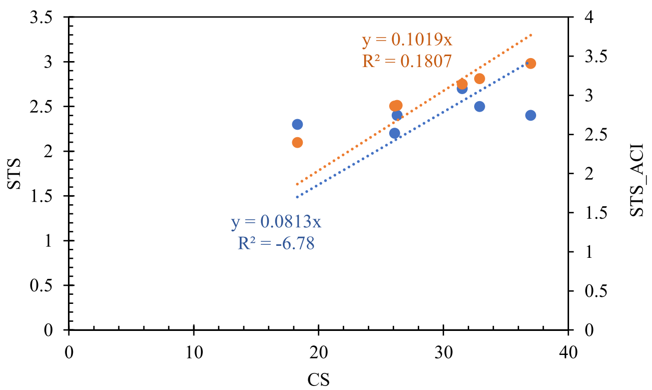

Fig. 10. Relationship between split tensile strength and compressive strength.

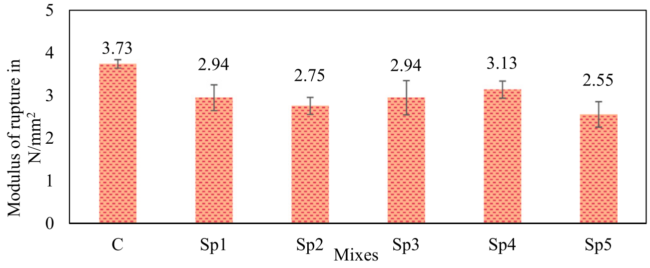

Fig. 11. Modulus of rupture of Bakelite concrete specimens.

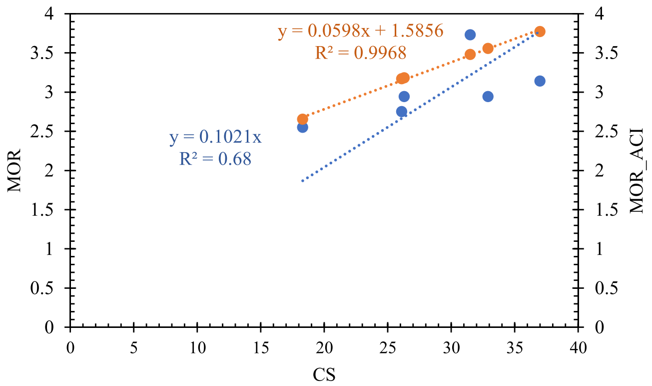

Fig. 12. Relationship between modulus of rupture and compressive strength.

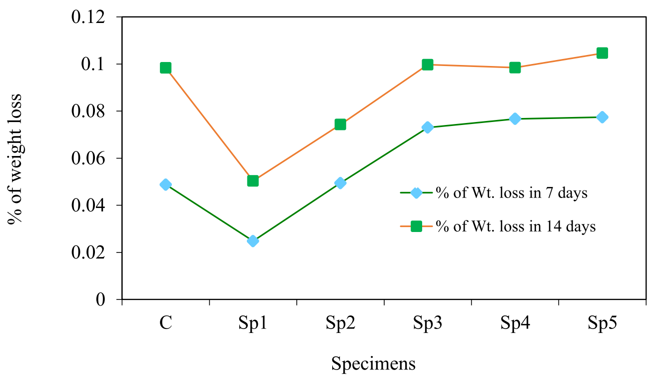

Fig. 13. Percentage mass loss of Bakelite concrete specimens exposed to HCl.

Table 2
Ultimate load and deflection of beams.

Specimen	Ultimate failure load, Pu (kN)	Ultimate failure moment (kN-m)	Ultimate Deflection (mm)			First cracking load (kN)
			L/2	L/3	L/4	
C	60.78	15.19	23.77	20.62	17.79	10
SP1	41.39	10.34	24.27	19.18	16.92	8
SP2	52.79	13.19	21.71	17.26	15.84	16
SP3	57.24	14.31	20.59	16.48	15.55	14
SP4	60.39	15.09	18.56	14.17	14.94	14
SP5	44.27	11.06	18.30	16.03	13.24	10

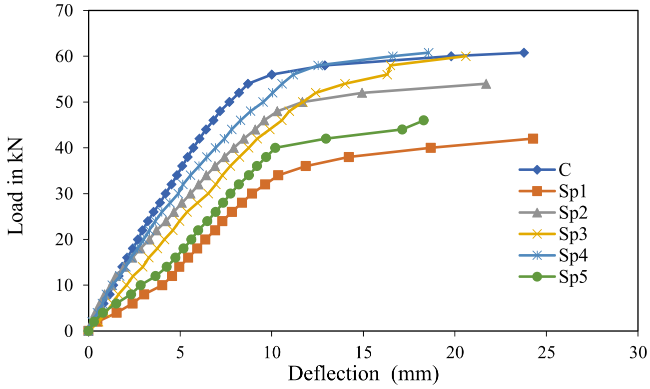

Fig. 14. Deflections of specimens at mid span.

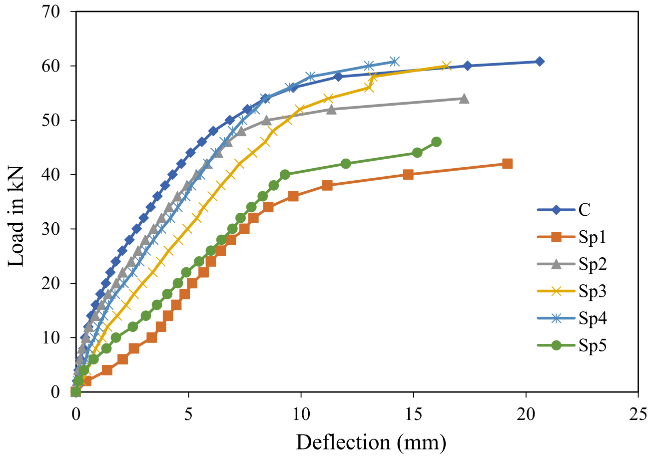

Fig. 15. Deflections of specimens at one-third span.

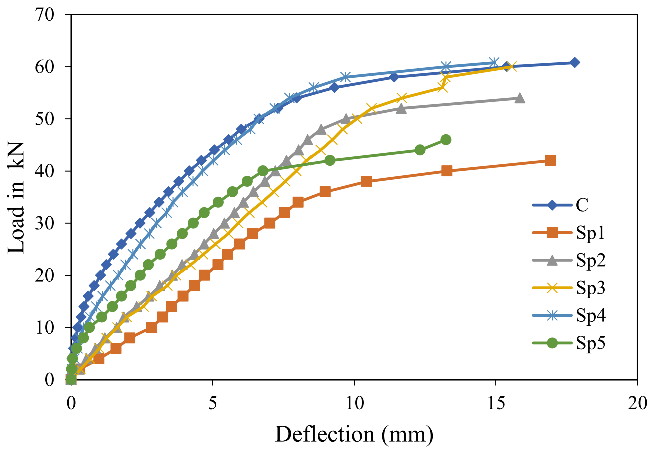

Fig. 16. Deflections of specimens at one-fourth span.

contrast to the other plastic waste concrete studied by Prasittisopin et al. [58] for expanded polystyrene (EPS) concrete, Choi et al. [59] for polyethylene terephthalate (PET) concrete, and Dulsang et al. [60] for ethylene vinyl acetate (EVA) concrete, Bakelite plastic concrete exhibits a different behavior. This is due to the Bakelite plastic being more rigid.

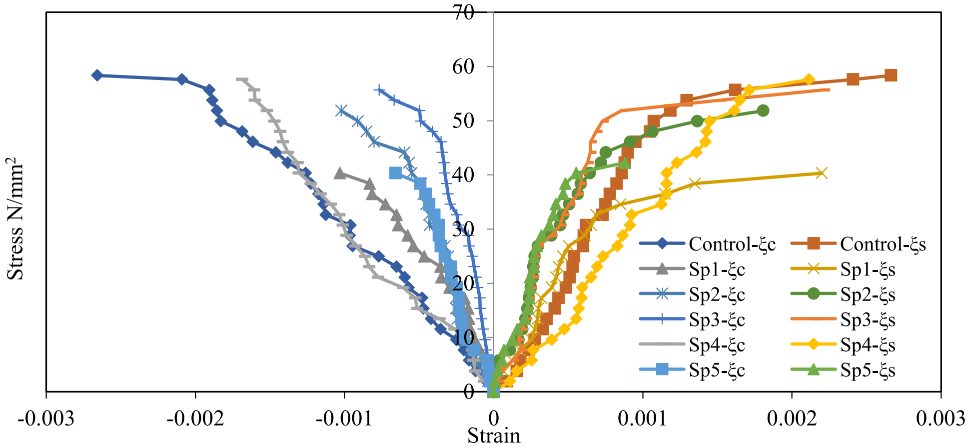

Fig. 17. Stress-strain behaviour of beams.

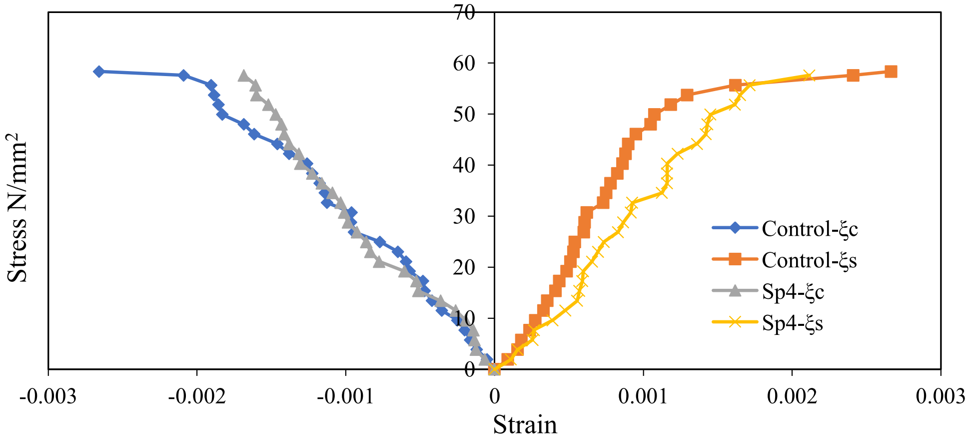

Fig. 18. Stress-strain behaviour of control and Sp4 beam.

4.7. Ductility, stiffness, and energy absorption capacity of Bakelite concrete beams

Concrete beams' ductility, stiffness, and energy absorption are all significant mechanical characteristics that affect how the beams respond to loads. Table 2 presents the results of initial first crack load (P_i), ultimate load (P_u), deflection at first crack (Δx), deflection at final crack (Δy), initial stiffness (S_i), final stiffness (S_f), ductility index (D.I = Δy/Δx) The ratio of the midspan deflection at the first crack load to the ultimate mid-span deflection of control and specimen concrete beams is known as the ductility index. The ductility index is crucial in determining a material's mechanical attributes and whether it is suitable for structural applications. Table 3 demonstrates that the ductility index of the Bakelite specimen beam is lower than that of the control concrete beam. The amount of discarded Bakelite utilized in the combination and the relatively low ductility of Bakelite affect the ductility index of the resulting concrete. The observed low tensile strength of the employed Bakelite plastic waste, 50 MPa, may affect the overall ductility of the concrete mixture. This is not a significant issue for some applications, such as for some precast concrete elements, where higher ductility is not required.

Table 3
Ductility and stiffness results of Bakelite concrete beams.

Specimen	P_i (kN)	P_u (kN)	Δx (mm)	Δy (mm)	D.I	S_i (kN/mm)	S_f (kN/mm)	Reduction in stiffness (%)
Control	10	61	1.34	23.77	17.70	7.44	2.56	65.55
Sp1	8	41	3.04	24.27	7.98	2.63	1.68	35.80
Sp2	16	53	2.39	21.71	9.08	6.69	2.44	63.54
Sp3	12	57	2.95	20.59	6.96	4.05	2.76	31.78
Sp4	14	60	2.03	18.56	9.13	6.88	3.23	53.07
Sp5	10	44	4.27	18.30	4.28	2.34	2.40	-2.70

The resistance of a material to deformation under load is referred to as stiffness. Stiffness in concrete beams is commonly calculated as the load-deflection curve's slope up to the yield point. Table 3 lists the stiffness values for the control, Sp1, Sp2, Sp3, Sp4, and Sp5 specimens at ultimate and first crack loads. Table 3 shows that control and Sp4 specimens have similar stiffness values and are stiffer than the others up to the first fracture load. This demonstrates how the concrete becomes stiffer when waste plastic is added. A beam with high stiffness can hold weights without experiencing excessive deflection (see Fig. 19), which is significant for applications where stability and deformation control are essential, like bridges and tall buildings.

The energy absorption ratio is the energy absorbed at the first crack to the energy absorbed until the ultimate load. Therefore, the area under the load-deflection curves up to the ultimate load divided by the area under the load-deflection curve up to the first crack load will give an energy absorption value. Figs. 20 and 21 gives data on the energy absorption and energy absorption ratio of both control and Bakelite Specimens, respectively. Bakelite beams shows lower energy absorption than the control specimen. This can be due to the cracking and fragmentation of the coarse Bakelite waste reduce energy absorption ratio. However, initial energy absorption of the Bakelite beams reflects higher values than the control specimen.

Overall, Bakelite can still be a good alternative for some applications even though it may have a lower energy absorption ratio than control concrete. However, to further enhance its performance and longevity, careful consideration of the specific needs and characteristics of the Bakelite content is required.

4.8. Crack pattern and failure modes

Fig. 22 displays the specimens' crack patterns. Two-point loading tests were performed on every beam. During testing, we took note of the load at which the fracture appeared, the place where the crack began, and the maximum load at which the specimen failed. Upon flexure failure, all the beams failed. The first crack appeared in the middle of the beam, running from bottom to middle. Major fractures have developed in the flexural area and have spread in the direction of the point loads. Also, as shown in Fig. 22, the reinforcement effect of the tested beams with Bakelite waste has a considerable impact on the cracking profile at the service and ultimate loading phases. The tested beams exhibit the typical pattern of flexural crack propagation. Cracks begin at the tension face's pure flexure zone and move gradually towards the compressive face, where the concrete crushing occurs. According to Fig. 22, the crack spacing is related to the amount of Bakelite waste present. In comparison to Bakelite specimens, the control specimen has wider cracks. This may be linked to the yielding of the steel bars, which led to an increase in concrete tension and further cracking. It is renowned for having a high degree of hardness, strength, and chemical and heat resistance. In addition, Bakelite, with strong cross-linking bonds between the polymer chains during a process known as polymerization, forms a stiff and long-lasting substance [56,57].

4.9. Benefits of Bakelite waste

The higher tensile strength of Bakelite waste is the main technical advantage of employing it in concrete composites [30,51]. Moreover, the Bakelite waste included in the concrete enhanced the cement composites' stiffness. The formulation for generating Bakelite waste composites is difficult, and the qualities of the composites rely on the manufacturing method and mix composition. Also, there is an opportunity to add Bakelite strips as fibres during the mixing stage of concrete. However, additional research is recommended to determine the suitability of Bakelite fibres by conducting relevant lab tests. Waste from the manufacture of Bakelite is a

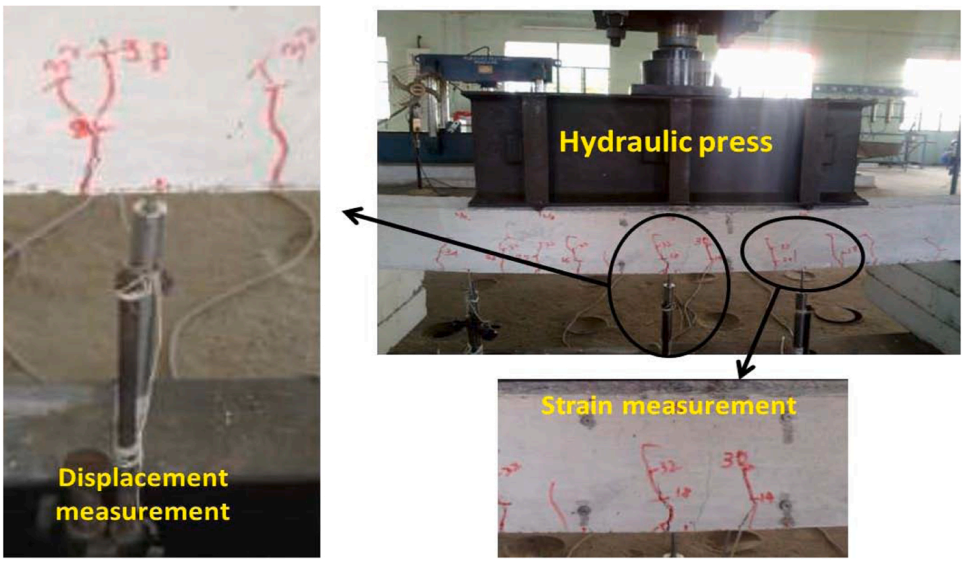

Fig. 19. Flexural failure of beams strain measurements.

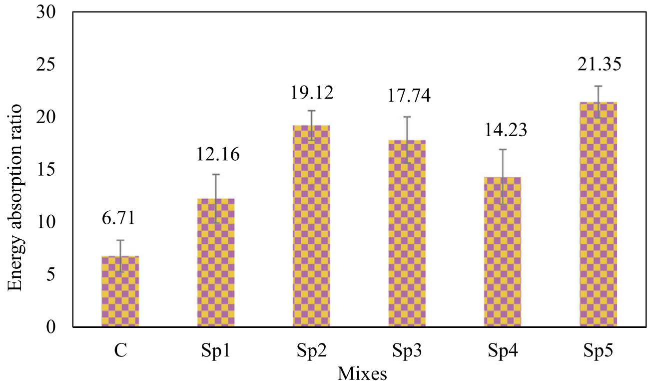

Fig. 20. Initial energy absorption of Bakelite concrete beams.

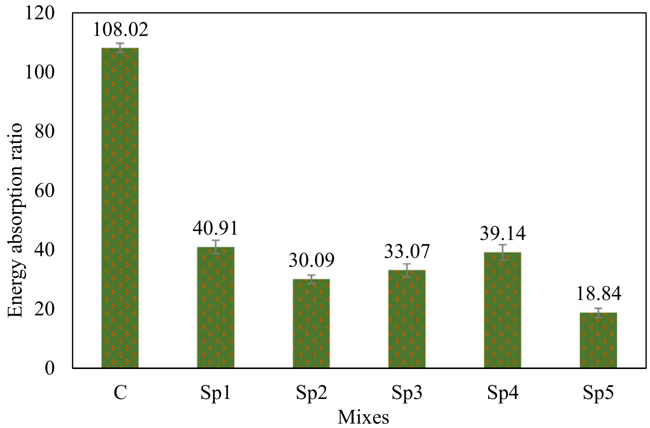

Fig. 21. Energy absorption ratio of Bakelite concrete beams.

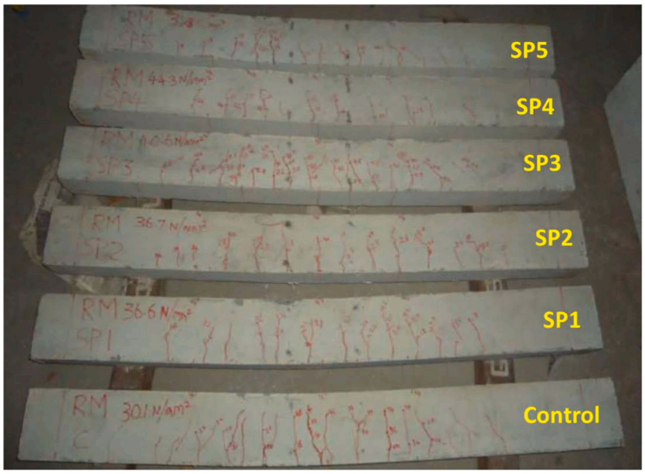

Fig. 22. View of crack and failure patterns of the tested concrete specimens.

harmless material; mixing and producing concrete with it had no unfavourable effects. Waste from Bakelite production is used in concrete, reducing waste management, transportation, storage, and landfill tax costs. Concrete can use less river sand, energy-intensive granite aggregates, and manufactured sand by substituting Bakelite waste for those materials. As long-term exposure in landfills may result in microplastics, treating Bakelite waste is difficult in practically all nations. Recycling Bakelite waste can contribute to more sustainable waste management.

5. Conclusions

The use of Bakelite waste in concrete presents a viable solution to address the environmental issues associated with its disposal. This study revealed that the addition of Bakelite waste to concrete led to a decrease in its compressive and split tensile strength. However, adding 6 % Bakelite waste to the concrete mixture resulted in an increase in both compressive and split tensile strength.

Furthermore, the inclusion of Bakelite waste prevented the specimens from suddenly breaking, thereby ensuring that the two halves of the specimen remained joined. Although the ultimate load of all reinforced concrete beams containing Bakelite waste decreased, the ultimate load of a concrete beam containing 8 % Bakelite waste was similar to that of the control beam, measuring 60 kN.

The ductility index of the resulting concrete was affected by the relatively low ductility of Bakelite. Nonetheless, this may not be a significant issue for certain applications, such as precast concrete elements where higher ductility is not necessary. When used in structural applications, concrete with an 8 % addition of Bakelite waste displayed similar strength to control concrete beams. Hence, Bakelite waste aggregates can be used as a partial replacement for coarse aggregate in concrete mixtures, especially in situations where higher ductility is not essential.

The use of Bakelite waste in concrete provides an innovative and sustainable solution to the scarcity of natural aggregates. Further research can be carried out to optimize the proportion of Bakelite waste in concrete and assess its durability in various environmental conditions.

Funding

The author thanks Vicerrectoria de Investigacion y Desarrollo (VRID) y Direccion de Investigacion y Creacion Artistica DICA, Proyecto presentado al Concurso VRID-Iniciación 2022, VRID N°2022000449-INI, Universidad de Concepción, Concepción, Chile.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors gratefully acknowledge the Alagappa Chettiar Government College of Engineering and Technology for performing the experimental works. Facultad de Salud y Ciencias Sociales, Universidad de las Américas, Providencia, Santiago 7500975, Chile. Centro Nacional de Excelencia para la Industria de la Madera (ANID BASAL FB210015 CENAMAD), Pontificia Universidad Católica de Chile, Vicuña Mackenna 7860, Santiago, Chile.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

References

[1] B. Cohen, Urbanization in developing countries: current trends, future projections, and key challenges for sustainability, Technol. Soc. 28 (1–2) (2006) 63–80.
[2] U.S. Agrawal, S.P. Wanjari, D.N. Naresh, Characteristic study of geopolymer fly ash sand as a replacement to natural river sand, Constr. Build. Mater. 150 (2017) 681–688.
[3] G.F. Huseien, A.R.M. Sam, K.W. Shah, A.M.A. Budiea, J. Mirza, Utilizing spend garnets as sand replacement in alkali-activated mortars containing fly ash and GBFS, Constr. Build. Mater. 225 (2019) 132–145.
[4] A.T. Gebremariam, A. Vahidi, F. Di Maio, J. Moreno-Juez, I. Vegas-Ramiro, A. Łagosz, P. Rem, Comprehensive study on the most sustainable concrete design made of recycled concrete, glass and mineral wool from C&D wastes, Constr. Build. Mater. 273 (2021), 121697.

[5] M.S. Bidabadi, M. Akbari, O. Panahi, Optimum mix design of recycled concrete based on the fresh and hardened properties of concrete, J. Build. Eng. 32 (2020), 101483.
[6] A. Alsalman, L.N. Assi, R.S. Kareem, K. Carter, P. Ziehl, Energy and CO_2 emission assessments of alkali-activated concrete and Ordinary Portland Cement concrete: a comparative analysis of different grades of concrete, Clean. Environ. Syst. 3 (2021), 100047.
[7] C.K. Varnava, C.S. Patrickios, Polymer networks one hundred years after the macromolecular hypothesis: a tutorial review, Polymer 215 (2021), 123322.
[8] P.M. Mahapatra, S. Kumar, P. Mishra, A.K. Panda, Effect of different thermoplastics on the thermal degradation behavior, kinetics, and thermodynamics of discarded bakelite, Environ. Sci. Pollut. Res. (2023) 1–13.
[9] S.K. Saha, S.K. Suman, Characterization of bakelite-modified bitumen, Innov. Infrastruct. Solut. 2 (2017) 1–6.
[10] B. Klun, U. Rozman, M. Ogrizek, G. Kalčíková, The first plastic produced, but the latest studied in microplastics research: the assessment of leaching, ecotoxicity and bioadhesion of Bakelite microplastics, Environ. Pollut. 307 (2022), 119454.
[11] R. Dhunna, R. Khanna, I. Mansuri, V. Sahajwalla, Recycling waste bakelite as an alternative carbon resource for ironmaking applications, ISIJ Int. 54 (3) (2014) 613–619.
[12] D. Crespy, M. Bozonnet, M. Meier, 100 Years of Bakelite, the material of a 1000 Uses, Angew. Chem. Int. Ed. 47 (18) (2008) 3322–3328.
[13] L. Canopoli, B. Fidalgo, F. Coulon, S.T. Wagland, Physico-chemical properties of excavated plastic from landfill mining and current recycling routes, Waste Manag. 76 (2018) 55–67.
[14] M.G. Davidson, R.A. Furlong, M.C. McManus, Developments in the life cycle assessment of chemical recycling of plastic waste–a review, J. Clean. Prod. 293 (2021), 126163.
[15] A.I. Al-Hadithi, N.N. Hilal, The possibility of enhancing some properties of self-compacting concrete by adding waste plastic fibers, J. Build. Eng. 8 (2016) 20–28.
[16] X. Li, T.C. Ling, K.H. Mo, Functions and impacts of plastic/rubber wastes as eco-friendly aggregate in concrete–A review, Constr. Build. Mater. 240 (2020), 117869.
[17] R. Alyousef, W. Ahmad, A. Ahmad, F. Aslam, P. Joyklad, H. Alabduljabbar, Potential use of recycled plastic and rubber aggregate in cementitious materials for sustainable construction: a review, J. Clean. Prod. 329 (2021), 129736.
[18] K.M. Mane, P.A. Nadgouda, A.M. Joshi, An experimental study on properties of concrete produced with M-sand and E-sand, Mater. Today.: Proc. 38 (2021) 2590–2595.
[19] I. Capasso, S. Lirer, A. Flora, C. Ferone, R. Cioffi, D. Caputo, B. Liguori, Reuse of mining waste as aggregates in fly ash-based geopolymers, J. Clean. Prod. 220 (2019) 65–73.
[20] A. Mohammadinia, Y.C. Wong, A. Arulrajah, S. Horpibulsuk, Strength evaluation of utilizing recycled plastic waste and recycled crushed glass in concrete footpaths, Constr. Build. Mater. 197 (2019) 489–496.
[21] L.F. Cabeza, L. Boquera, M. Chàfer, D. Vérez, Embodied energy and embodied carbon of structural building materials: worldwide progress and barriers through literature map analysis, Energy Build. 231 (2021), 110612.
[22] M. Manjunatha, S. Preethi, H.G. Mounika, K.N. Niveditha, Life cycle assessment (LCA) of concrete prepared with sustainable cement-based materials, Mater. Today.: Proc. 47 (2021) 3637–3644.
[23] S. Da, P. Le Billon, Sand mining: stopping the grind of unregulated supply chains, Extr. Ind. Soc. (2022), 101070.
[24] A.K. Ram, P. Rawat, S. Mohanty, Strength performance of soil-fly ash-MSW fine layered system under different controlled loading conditions: a comparative study, Constr. Build. Mater. 369 (2023), 130524.
[25] M.S. Imbabi, C. Carrigan, S. McKenna, Trends and developments in green cement and concrete technology, Int. J. Sustain. Built Environ. 1 (2) (2012) 194–216.
[26] S.P. Makhija, S.P. Dubey, Optimally sized hybrid energy system for auxiliaries of a cement manufacturing unit with diesel fuel price sensitivity analysis, Int. J. Ambient Energy 38 (3) (2017) 267–272.
[27] A. Akhtar, A.K. Sarmah, Construction and demolition waste generation and properties of recycled aggregate concrete: a global perspective, J. Clean. Prod. 186 (2018) 262–281.
[28] R. Fediuk, High-strength fibrous concrete of Russian Far East natural materials. Mater. Sci. Eng. Conf. Ser., AA, Far Eastern State University, Russia, 2016, p. 12020, https://doi.org/10.1088/1757-899X/116/1/012020.
[29] M. Vandana, S.E. John, K. Maya, S. Sunny, D. Padmalal, Environmental impact assessment (EIA) of hard rock quarrying in a tropical river basin—study from the SW India, Environ. Monit. Assess. 192 (2020) 1–18.
[30] A. Surendranath, P.V. Ramana, Valorization of bakelite plastic waste aimed at auxiliary comprehensive concrete, Constr. Build. Mater. 325 (2022), 126851.
[31] P.V. Ramana, Temperature effect and microstructural enactment on recycled fiber concrete, Mater. Today.: Proc. 66 (2022) 2626–2635.
[32] K. Salim, A. Houssam, A. Belaid, H. Brahim, Reinforcement of building plaster by waste plastic and glass, Procedia Struct. Integr. 17 (2019) 170–176.
[33] M. Kopić, T. Milović, B. Matić, S. Jovanović, M. Marinković, Optimum fluid content in pavement cold in-place recycling containing waste materials, Sustainability 14 (24) (2022) 16691.
[34] M.Y. Khalid, A. Al Rashid, Z.U. Arif, W. Ahmed, H. Arshad, A.A. Zaidi, Natural fiber reinforced composites: Sustainable materials for emerging applications, Results Eng. 11 (2021), 100263.
[35] V.C. Li, Large volume, high-performance applications of fibers in civil engineering, J. Appl. Polym. Sci. 83 (3) (2002) 660–686.
[36] M. Amran, R. Fediuk, G. Murali, N. Vatin, M. Karelina, T. Ozbakkaloglu, R.S. Krishna, A.S. Kumar, D.S. Kumar, J. Mishra, Rice husk ash-based concrete composites: a critical review of their properties and applications, Crystals 11 (2021) 1–33, https://doi.org/10.3390/cryst11020168.
[37] W. Ahmed, S. Gul, M. Awais, Z.U. Hassan, S. Jabeen, M. Farooq, A review: novel nanohybrids of epoxy/polyamide with carbon nanotube/nano-diamond, Polym. -Plast. Technol. Mater. 60 (6) (2021) 579–600.
[38] R.S. Fediuk, Y.G. Yevdokimova, A.K. Smoliakov, N.Y. Stoyushko, V.S. Lesovik, Use of geonics scientific positions for designing of building composites for protective (fortification) structures, IOP Conf. Ser. Mater. Sci. Eng. 221 (2017) 12011, https://doi.org/10.1088/1757-899X/221/1/012011.
[39] B.A. Manjunath, Partial replacement of E-plastic waste as coarse-aggregate in concrete, Procedia Environ. Sci. 35 (2016) 731–739.
[40] F. Ahmad, M.I. Qureshi, Z. Ahmad, Influence of nano graphite platelets on the behavior of concrete with E-waste plastic coarse aggregates, Constr. Build. Mater. 316 (2022), 125980.
[41] S. Ullah, M.I. Qureshi, P. Joyklad, S. Suparp, Q. Hussain, K. Chaiyasarn, E. Yooprasertchai, Effect of partial replacement of E-waste as a fine aggregate on compressive behavior of concrete specimens having different geometry with and without CFRP confinement, J. Build. Eng. 50 (2022), 104151.
[42] K. Ali, P. Saingam, M.I. Qureshi, S. Saleem, A. Nawaz, T. Mehmood, S. Suparp, Influence of recycled plastic incorporation as coarse aggregates on concrete properties, Sustainability 15 (7) (2023) 5937.
[43] S. Rezvan, M.J. Moradi, H. Dabiri, K. Daneshvar, M. Karakouzian, V. Farhangi, Application of machine learning to predict the mechanical characteristics of concrete containing recycled plastic-based materials, Appl. Sci. 13 (4) (2023) 2033.
[44] N. Prasad, G. Murali, N. Vatin, Modified falling mass impact test performance on functionally graded two stages aggregate fibrous concrete, Materials 14 (19) (2021) 5833.
[45] R. Siddique, J. Khatib, I. Kaur, Use of recycled plastic in concrete: a review, Waste Manag. 28 (10) (2008) 1835–1852.
[46] X. He, W. Li, Y. Su, Z. Zheng, J. Fu, J. Zeng, J. Yang, Recycling of plastic waste concrete to prepare an effective additive for early strength and late permeability improvement of cement paste, Constr. Build. Mater. 347 (2022), 128581.
[47] A.M. Zeyad, I.Y. Hakeem, M. Amin, B.A. Tayeh, I.S. Agwa, Effect of aggregate and fibre types on ultra-high-performance concrete designed for radiation shielding, J. Build. Eng. 58 (2022), 104960.
[48] I.M. Maafa, A. Abutaleb, N. Zouli, A.M. Zeyad, A. Yousef, M.M. Ahmed, Effect of agricultural biomass wastes on thermal insulation and self-cleaning of fired bricks, J. Mater. Res. Technol. 24 (2023) 4060–4073.
[49] M. M. Al-Tayeb, A. M. Zeyad, O. Dawoud, B.A. Tayeh, Experimental and numerical investigations of the influence of partial replacement of coarse aggregates by plastic waste on the impact load, Int. J. Sustain. Eng. 14 (4) (2021) 735–742.

[50] A.A. Ghanim, F.U. Rahman, W. Adil, A.M. Zeyad, H.M. Magbool, Experimental investigation of industrial wastes in concrete: mechanical and microstructural evaluation of pumice powder and Fly Ash in concrete, Case Stud. Constr. Mater. 18 (2023), e01999.
[51] N. Usahanunth, S. Tuprakay, W. Kongsong, S.R. Tuprakay, Study of mechanical properties and recommendations for the application of waste Bakelite aggregate concrete, Case Stud. Constr. Mater. 8 (2018) 299–314.
[52] P.V. Ramana, Temperature effect and microstructural enactment on recycled fiber concrete, Mater. Today.: Proc. 66 (2022) 2626–2635.
[53] R.R. Bhopi, M. Sinha, An Experimental Study of concrete by Partial Replacement of Fine Aggregate with Bakelite Waste (June), in: IOP Conference Series: Earth and Environmental Science, Vol. 1032, IOP Publishing, 2022, 012040 (June).
[54] P. Ganesh, A.R. Murthy, Tensile behaviour and durability aspects of sustainable ultra-high performance concrete incorporated with GGBS as cementitious material, Constr. Build. Mater. 197 (2019) 667–680.
[55] D.K. Sudarshan, A.K. Vyas, Impact of fire on mechanical properties of concrete containing marble waste, J. King Saud. Univ. -Eng. Sci. 31 (1) (2019) 42–51.
[56] O. Awogbemi, D.V. Von Kallon, Achieving affordable and clean energy through conversion of waste plastic to liquid fuel, J. Energy Inst. (2022), 101154.
[57] L. Rybakiewicz, D. Sokolowsk, Tests of thermal insulation properties of bakelite and glass-epoxy composite (April), in: Journal of Physics: Conference Series, Vol. 1507, IOP Publishing, 2020, 062013 (April).
[58] L. Prasittisopin, P. Termkhajornkit, Y.H. Kim, Review of concrete with expanded polystyrene (EPS): Performance and environmental aspects, J. Clean. Prod. (2022), 132919.
[59] Y.W. Choi, D.J. Moon, J.S. Chung, S.K. Cho, Effects of waste PET bottles aggregate on the properties of concrete, Cem. Concr. Res. 35 (4) (2005) 776–781.
[60] N. Dulsang, P. Kasemsiri, P. Posi, S. Hiziroglu, P. Chindaprasirt, Characterization of an environment friendly lightweight concrete containing ethyl vinyl acetate waste, Mater. Des. 96 (2016) 350–356.