Structures 57 (2023) 104966

Contents lists available at ScienceDirect

Structures

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

Flexural characterization of a novel recycled-based polymer blend for structural applications☆

Nicholas Fantuzzi [b,*], Aditya Vidwans [a], Antoine Dib [b], Patrizia Trovalusci [a], Jacopo Agnelli [c], Aldo Pierattini [d]

[a] Sapienza University of Rome, Via Gramsci 53, Rome, 00197, Italy
[b] University of Bologna, Viale del Risorgimento 2, Bologna, 40136, Italy
[c] Carbon Dream Srl, Via F. Melotti 16, Barberino Tavarnelle, 50028, Italy
[d] Roofy Srl, Via Bramante, 8/1, Barberino Tavarnelle, 50028, Italy

ARTICLE INFO

Keywords:
Sustainable structures
Recycled plastics
Mechanical properties
Life Cycle Assessment

ABSTRACT

The use of recycled plastic in construction fields, among others, is becoming a turning point for resolving significant related problems such as resource management, sustainability and plastic waste generation. Hence, in the context of sustainability, the "Three R's": reduce, reuse and recycle, are getting more attention day after day. There has been a huge surge in the recycling and reuse of plastic composites due to their eco-friendliness, lightweight, life cycle superiority and low cost. However, because of a lack of knowledge of their performance and behavior, their application is still limited in the real world. The aim of this research is to understand the behavior of recycled plastic and derive its material properties which can be used in the design of structural and non-structural elements. In the present study, three stiffened plates are manufactured from 80% of recycled plastic (around 50% of recycled Polypropylene rPP, and around 50% of High Density Polyethylene PEHD with a little part of Low Density Polyethylene PELD) and 20% of virgin polypropylene PP Copolymer. Three-point bending test is performed on the three specimens. In the experimental campaign, the behavior of these stiffened plates under pure bending loads has been studied. After that, the material properties are extracted from the data collected during the experiment using Ramberg–Osgood equation. Then, once implemented in finite element models, it was observed that the simulated material shows similar behavior to the one registered during the experiment. As a conclusion, the derived material properties show reliability and they can be used to study a design of a structural or non-structural component including recycled plastic.

1. Introduction

Despite its recent beginning in the early 20th century, plastic material became pervasive in daily activities and widely used in every aspect of the human-being life. Its use is becoming so evident that its production surpasses the production of most other man-made products, except for the cement and steel in the construction industry [1]. This fast success of plastic returns to many advantages such as flexibility, versatility, robustness and affordable prices, even though its production and plastic waste incineration are causing an emission of approximately 400 million tons of carbon dioxide per year. Unfortunately, its huge detrimental impacts on the ecosystem and environmental footprint did not overshadow its appeal that is increasing day after day [2]. As per a report by the United Nations, plastic production will double in the next 20 years which will result in 12 billion tons of plastic waste by the year 2050. Therefore, as per the UN, more focus should be given to waste reduction, resource efficiency, long-term circular approach and to the implementation of concepts of recycle, refurbish, refuse, re-manufacture, repair and reuse [3].

In parallel, the increment of urbanization rate at a global scale has driven the building activity to flourish much more than it was previously thought [4] which leads to a higher demand, extraction and consumption of raw materials. Speaking by the numbers, construction activities consume the majority of raw materials out of all industrial sectors: this consumption is around 32% of the world's resources and around 40% of raw materials extracted from the earth, including 12% of water, 40% of energy and approximately 25% of virgin wood [5].

☆ The results of this research have been partially presented at the 2nd International Conference on Computations for Science and Engineering, 30 August–2 September 2022, Rimini Riviera, Italy.

* Corresponding author.
E-mail addresses: nicholas.fantuzzi@unibo.it (N. Fantuzzi), aditya.vidwans@uniroma1.it (A. Vidwans), antoine.dib2@unibo.it (A. Dib), patrizia.trovalusci@uniroma1.it (P. Trovalusci), jacopo.agnelli@tiscali.it (J. Agnelli).

https://doi.org/10.1016/j.istruc.2023.104966
Received 13 March 2023; Received in revised form 21 June 2023; Accepted 26 July 2023
Available online 23 August 2023

Non-randomly, increased construction and demolition activities also generate a surge in waste materials [6] with all the damage that cause to the environment.

Combining the two problems mentioned above and driven by economic necessities and environmental risks, and encouraged by social awareness, national laws and international institutions [3,7], industries all around the world are shifting their focus from non-sustainable materials toward natural and sustainable materials [8,9] and are creating circular resource flows known as the circular economy [10,11] which aim to keep resources/materials in the loop for a longer period through reusing, repairing and recycling before their disposal [12,13]. Such process showed to be efficient in two directions: to reduce the extraction of raw materials and to reduce the generation of waste [14].

Regardless of the difference between countries in applying the circular economy and the gaps between the aims set to achieve sustainability versus the actual actions [15,16], efforts in the academic field are expended toward the finding of innovative solutions. For instance, one branch that appeared in the field of reducing plastic waste is to insert new natural fibres [17] in a plastic mixture, which are designed to be quickly biodegradable, replace the use of good amount of synthetic petrochemical products and lead up to high performance new aesthetic materials in terms of mechanical properties [18]. Some of the researchers studied the life cycle assessment of such composites [19] and their economic impact [20], others [21,22] evaluated their mechanical properties. The concept of resilience is used in multiple scientific contexts, being understood according to several different perspectives and it is essential in civil engineering for a novel and more sustainable way of building constructions [23].

Another concept that is trying to open road in the market of the construction industry, is the use of plastic and recycled plastics in structural and non-structural elements. The bubble deck is a striking example of the light weight, low cost and eco-friendly use of plastic in construction [24]. Another large scale application of plastic waste in civil engineering is in road construction [25]. In the academic environment, many studies showed that the use of recycled plastic aggregates in the construction industry is gaining wide spread attention [26]. In Poland for example, [27] analyzed the possibility of the application of PET foam manufactured by recycling plastic packaging in civil engineering applications like composite sandwich panels. Other researchers worked on the optimization of similar panels with PET foams and aluminum skins subjected to impact loads [28]. [29] studied the possibility of using plastic bottles in concrete blocks. However, few are the researchers that studied the performance of structural elements made of plastic waste or including plastic waste in their compositions like [30] who paved a way to fabricate composite T-beam with HSC in the flange and PWAC in the web or [31] who verified that coarse aggregate can be replaced by PET wastes in reinforced concrete beams.

In light of what it was mentioned, it can be noticed that the use of green composites and recycled plastics is taking more place in the civil engineering world, but few are the researches related to the characterization of the mechanical behavior of elements incorporating plastic waste. The aim of this research is to extend what it is done regarding this topic. More explicitly, the scoop is to study the properties of three plastics specimens prepared from 80% recycled plastics derived from industrial and urban waste, and 20% of virgin plastic. The mechanical behavior and parameters of the specimens in the form of stiffened plates were studied through a 3-point bending test. Afterwards, in order to verify the behavior of the specimen through Finite Element models, the Ramberg–Osgood equation has been applied to extract the unknown material properties of the new mixture. Finally, a comparative study has been done between the experimental results and the numerical results of FE models.

2. Experimental analysis

The experimental campaign consisted of testing three stiffened rectangular specimens made of plastics under bending loads. In what concerning the material, the three specimens are manufactured with 80% of recycled plastic (around 50% of recycled polypropylene rPP and around 50% of High Density polyethylene HDPE with a small quantity of low density polyethylene LDPE) and 20% of virgin PP Copolymer with high impact which is tougher than polypropylene Homopolymer [32]. Regarding the geometrical features, the overall dimensions of these plates are: length 145 mm, depth 35 mm and width 2.4 mm. The specimens in Fig. 1 reveal that the tested strips are cut out from a bigger plate. These plates are stiffened by longitudinal and transversal stiffeners with depth of 4.5 mm for each, and thickness of 2.2 mm and 1.5 mm respectively. The plates are stiffened with one stiffener in the longitudinal direction and five stiffeners along the transverse direction.

It should be observed in Fig. 1 that specimen 3 is missing. During the experiment, and due to a manufacturing error, specimen 3 was damaged. For this reason, specimen 3 was not considered, instead, specimen 4 was. In the next parts of the paper, the value and results will refer to specimen 1, specimen 2 and specimen 4.

The tests of the specimens were carried out in the laboratory of the faculty of Civil Engineering at the Sapienza University of Rome, Italy. Bending tests were carried out using machine testing 'Zwick Roell'. Each stiffened plate was supported at its both ends in order to simulate a simply supported beam. The displacement-controlled bending test was performed in a way that the controlled displacement was applied at the center of the beam in very small increments, from 0.010 mm to 0.014 mm, and the corresponding force was measured. A total displacement of 20 mm is applied at the center of each specimen. The resulting force–displacement history was recorded. The testing setup is shown in Fig. 2.

Thus, the force–displacement graphs corresponding to each specimen are obtained as shown in Fig. 3.

From Fig. 3a, it can be observed that specimens 1 and 2 show linear behavior up to a displacement of around 4 mm. But after this point, the graph is non-linear and the material shows a non-linear behavior.

As for specimen 4, it can be observed that when displacement is 2.6466 mm, there is a sudden drop in the force. This is return to the fact that during the experiment, there was a little movement in the apparatus where the corresponding force was applied. Hence, at that instance, there is a sudden drop in the force. If this small error is ignored, then it can be visualized that this specimen shows also similar behavior as the other ones, or in another words, it will show a linear behavior up to a certain point and nonlinear behavior afterwards.

When a maximum displacement of 4 mm is applied at the center, the corresponding force is 20.05 N for specimen 1; for specimen 2 it is 16.4 N and it is 11.77 N for specimen 4. When a maximum displacement of 20 mm is applied at the center, the corresponding force is 53.59 N for specimen 1; for specimen 2 it is 41.85 N and it is 41.27 N for specimen 4.

With reference to the theory of a simple supported beam, the experimental results have been analyzed and elaborated in order to obtain a stress–strain curve that can express easily the material behavior of each corresponding specimen. From Classical beam theory, it is possible to write, $\delta_c = FL^3/48EI$, $\epsilon_c = 12Z\delta_c/L^2$, $\sigma_c = M_c/W$, where δ_c = Deflection at the center, F = Concentrated load applied at the center, L = Beam span, E = Modulus of elasticity, I = Moment of inertia, ϵ_c = Strain at the center, Z = Distance between the neutral axis and outermost fibre of the beam, σ_c = Stress at the center (MPa), M_c = Moment at the center (N-mm) and W = Section Modulus (mm^3). Applying these relationships, the obtained strain–stress graphs are plotted in Fig. 3b) from which the basic properties such as yield stress and modulus of elasticity can be extracted and their values have been considered as 12 MPa and 800 MPa, respectively.

Fig. 1. Tested stiffened plates: a) Specimen 1; b) Specimen 2; c) Specimen 4.

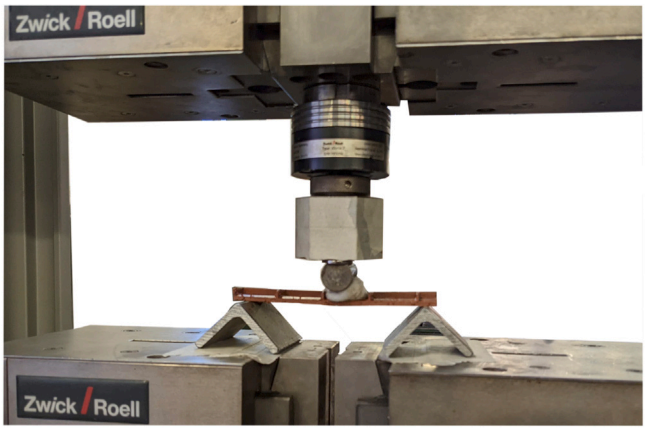

Fig. 2. Experimental setup photographed during the test.

3. Numerical verification

To understand the material behavior, a finite element analysis was performed. Since this mixture of plastics can be considered a new material from material properties stand point, the Ramberg–Osgood equation is used. The material properties and parameters obtained from the Ramberg–Osgood equation are used then to simulate the material in a finite element model.

As it can be seen in Fig. 3b), the stress–strain relationship of the studied material is non-linear. To create this relationship with mathematical formulation, it is vital to determine various material properties such as modulus of elasticity, yield strength, cyclic-strength coefficient and cyclic strain-hardening exponent. This can be completed taking advantage of the Ramberg–Osgood equation [33] which is defined as follows,

$$\epsilon = \sigma/E + (\sigma/k)^{1/n} \tag{1}$$

where k = Cyclic-strength coefficient and n = Cyclic strain-hardening exponent. In Eq. (1), the first term is related to the elastic strain whereas the second term is related to the plastic strain. From the experiment, it is possible to calculate both total strain and elastic strain which can be used to calculate the plastic strain. To determine the plastic components k and n, the following process can be followed,

$$\epsilon_p = \epsilon - \sigma/E = (\sigma/k)^{1/n}, \tag{2}$$

where ϵ_p is the plastic strain. Taking the logarithm of ϵ_p and rearranging the equation gives,

$$\log(\sigma) = n(\log(\epsilon_p)) + \log(k) \tag{3}$$

Eq. (3) can be graphically presented in Fig. 4 where the values of n and k can be extracted by linear interpolation as: n = 0.3442 and $\log(k)$ = 4.5236, hence k = 92.1711 MPa. Here, values for specimen 2 are derived, the same can be done for specimen 1 and specimen 4.

The values obtained from the experiments can be used as starting input for the FE analysis. It can be observed from Fig. 4 that the equation from which the value of k and n are extracted is the equation for the linear trend-line which does not perfectly describe the relation (i.e. the solid blue curve) between stress and plastic strain. Therefore, these extracted values may not be directly used in the analysis as the material properties but as a starting point. With these extracted values, it is expected to have from the FEM results slightly deviated respecting to the experimental ones. If this is the case, these values may be modified step by step and applied in new FEM analysis, at each step, until the values of the FEM results reach the results acquired from the experiment. In this study, these extracted values result in similar behavior in FEM as in the experiment, hence the modification was not required. The values of k and n for all the specimens are derived and arranged in Table 1.

Applying Eq. (1) and values from Table 1, the stress–strain relation are plotted as shown in Fig. 5. This stress–strain relation is used as input for the finite element analysis. In this FE model, shell elements are used to create the stiffened plate. Discrete rigid elements are used to model the supports. The displacement-controlled analysis is done by applying the load in small increments and measuring the resulting reaction force at the support. The FE models, with boundary condition and applied load, are shown in Fig. 6.

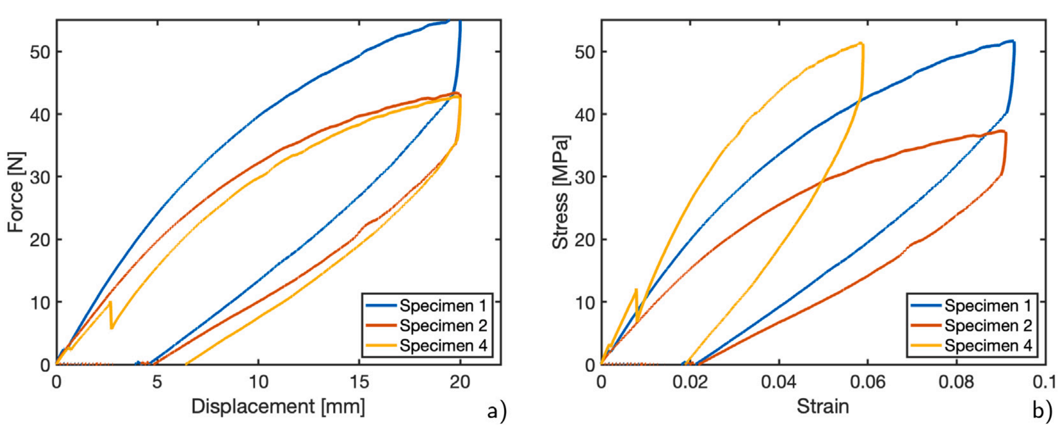

Fig. 3. Three tested specimens: a) experimental force–displacement curves. b) post-processed stress–strain curves.

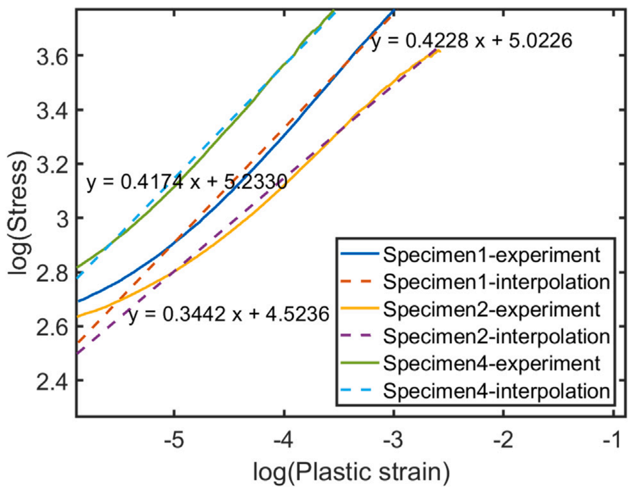

Fig. 4. log(Stress)-log(Plastic strain) Relation.

Table 1
Derived material properties for each specimen using the Ramberg–Osgood law.

	Specimen 1	Specimen 2	Specimen 4
σ_y (MPa)	12	12	12
E (MPa)	800	800	800
n	0.4228	0.3442	0.4147
k (MPa)	151.8088	92.1711	187.3624

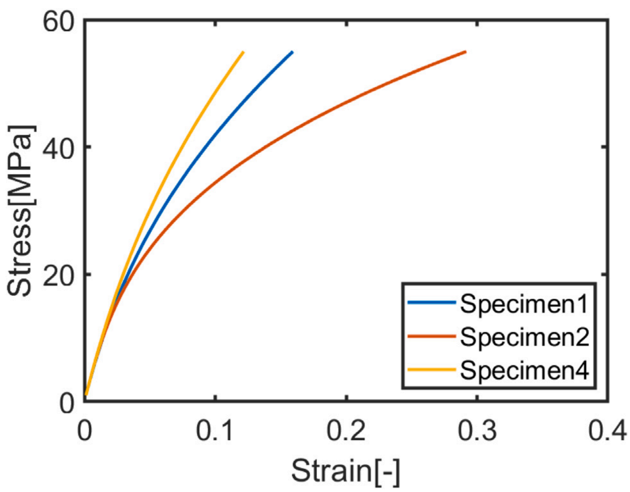

Fig. 5. Stress–Strain relation derived from the material properties.

4. Comparison and discussion

Graphical comparison between numerical and experimental results are displayed in Fig. 7. According to the FEM results the maximum principle stress generated in the base plate is around −17 MPa, whereas in the longitudinal stiffener is −48 MPa. The maximum Von Mises stress generated in the base plate is 12 MPa and in the longitudinal stiffener is 40 MPa.

From Fig. 7, it can be observed that for the specimen 1, when the stress is 42.04 MPa, the corresponding strain is 0.042. In what concerns specimen 2, when the stress is 34.54 MPa, the corresponding strain is 0.058 and for specimen 4, the stress is 47.07 MPa when the strain is 0.036. When the stress is around 13 MPa, the specimens 1, 2 and 4 register a value of strain equal to 0.0031, 0.0036 and 0.0017 respectively.

Table 2
Stress and strain comparison between experimental and numerical results.

	$\varepsilon_p = 0.036$			$\sigma = 18$ MPa		
	Experiment (MPa)	Numerical (MPa)	Δ (%)	Experiment (–)	Numerical (–)	Δ (%)
Specimen 1	37.825	39.316	3.9	0.00648	0.00626	3.39
Specimen 2	29.857	29.268	1.9	0.00940	0.00891	5.21
Specimen 4	47.518	46.994	1.1	0.00365	0.00364	0.27

The main aim of this study was to derive accurately the material properties of stiffened plates made from 80% of recycled plastic and 20% of virgin PP to be used in any possible future application in research and/or industry.

To verify the derived material properties, the results obtained from the bending experiments are compared with the FEM results. The FEM results are comparable to the experimental results and it was noticed that the same material behavior is observed. Therefore, it can be concluded that the derived material parameters are acceptable and correct.

The comparison of the stress–strain curve obtained from the FE model and experimentally of specimens 1, 2 and 4 are shown respectively in Fig. 7.

The stress corresponding to the plastic strain $\varepsilon_p = 0.036$ is measured for each specimen. Results from the experiments and FEM are arranged in Table 2 and compared. The variation and its percentage between both results are calculated taking into account the results obtained from the experiments as the reference values.

Similarly, the plastic strain corresponding to the $\sigma = 18$ MPa is extracted for each specimen. The results obtained from the experiments and FEM are arranged in Table 2 and compared. The variation and its percentage between both results are calculated where the experimental results have been considered as the reference numbers.

From Fig. 7 it can be observed that experimental and FEM results are similar with small deviation. Both graphs from the experiment and FEM overlap with each other with a very small deviation. From Table 2 it can be observed that difference between experiment and FEM results is less than 5%. Therefore, it can be concluded that the material properties obtained from the Ramberg–Osgood equation are reliable because of the similarity of behavior shown to that of the experimental specimens. As a result, these modified properties can be used in the modeling of any design or any future application including similar materials by considering an average value of the carried out parameters.

5. Conclusion

In this study, the material behavior of three stiffened plates manufactured from 80% of mixture of recycled plastic and 20% of virgin PP has been studied. More precisely, to understand the behavior under pure bending loads, three-point bending test has been performed on each of them. Material properties are extracted from data collected from the experiment results through Ramberg–Osgood equation. These derived material properties are verified by FE Analysis. It can be observed that the mechanical behavior of the studied material obtained from the experimental campaign is comparable to the results of the FEM. Therefore, it can be concluded that the Ramberg–Osgood equation can be successfully used to extract the material properties of the unknown material. The present material properties can be used for simulating material in FEM for further applications.

CRediT authorship contribution statement

Nicholas Fantuzzi: Data curation, Methodology, Writing – original draft, Project administration, Funding acquisition, Software, Investigation, Methodology. **Aditya Vidwans:** Data curation, Methodology,

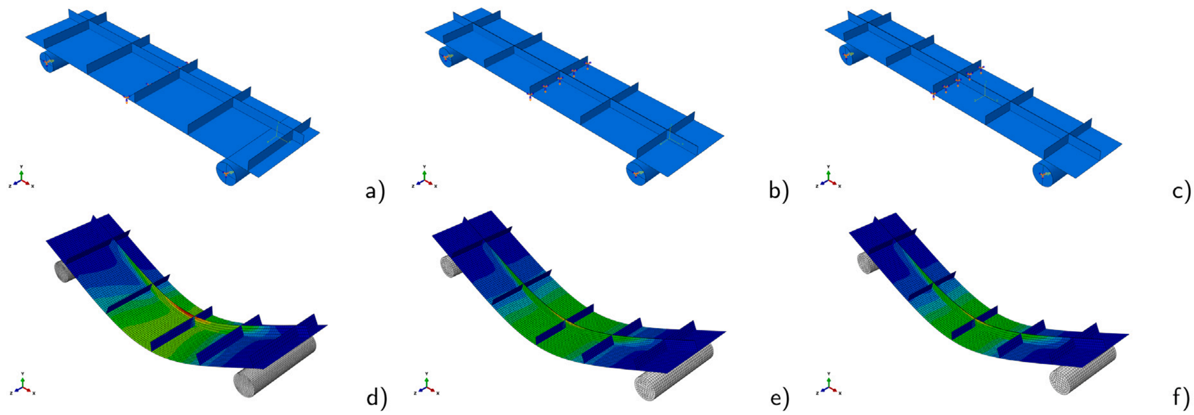

Fig. 6. Finite element model and von Mises stress field: a),d) Specimen 1; b),e) Specimen 2; c),f) Specimen 4.

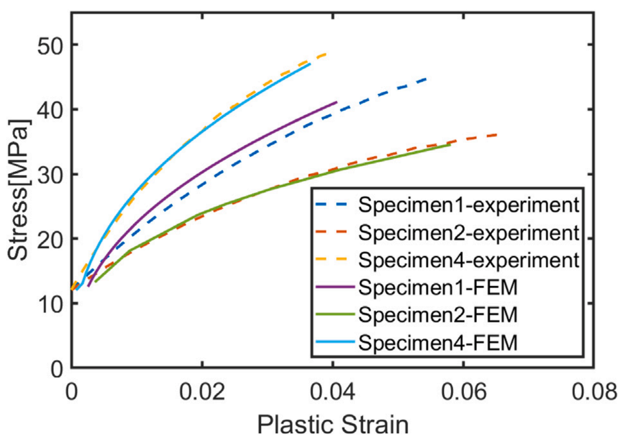

Fig. 7. Stress-plastic strain plot comparison between experiments and FEA.

Writing – original draft, Writing – review & editing, Formal analysis, Software, Experimentation, Validation. **Antoine Dib:** Writing – original draft, Writing – review & editing, Data curation. **Patrizia Trovalusci:** Visualization, Supervision, Project Administration, Funding acquisition, Software. **Jacopo Agnelli:** Conceptualization of this study, Methodology, Visualization. **Aldo Pierattini:** Resources.

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.

Acknowledgments

The study was supported by the Department of Structural and Geotechnical Engineering of the Sapienza University of Rome, Italy. Thanks to Dr Biagio Carboni and Sawan Kumar Guruva for helping while conducting laboratory tests. This work has been supported by "Alma Idea 2022" Linea di Intervento B, Italy (CUP: J33C22001420001) and by the financial support of the Italian Ministry of Industry Incentives (MISE) for R&D law 30/12/2020, n. 178. This study is supported by: Italian Ministry of University and Research PRIN 2017, project No. 2017HFPCUP. Aditya Vidwans, PON Ph.D. 2017, thanks the Ministero dell'Università e della Ricerca (MUR) and Sapienza.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.istruc.2023.104966.

References

[1] Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. Sci Adv 2017;7(3):119–26. http://dx.doi.org/10.1016/j.spc.2020.11.001.

[2] Aubin S, Beaugrand J, Berteloot M, Boutrou R, Buche P, Gontard N, et al. Plastics in a circular economy: Mitigating the ambiguity of widely-used terms from stakeholders consultation. Environ Sci Policy 2022;134(1):119–26.

[3] United Nations Environment Programme GAoCE, Efficiency R. Circular economy and climate change. 2022-07, UN Environment Document Repository, United Nations.

[4] Nazifa TH, Yuniarto A, Shanawaz Uddin A, Salmiati S, Shahid S. An empirical study of construction and demolition waste generation and implication of recycling. Waste Manag 2019;95:10–21. http://dx.doi.org/10.1016/j.wasman.2019.05.049, URL: https://www.sciencedirect.com/science/article/pii/S0956053X19303575.

[5] Yeheyis M, Hewage K, Alam MS, Eskicioglu C, Sadiq R. An overview of construction and demolition waste management in Canada: A lifecycle analysis approach to sustainability. Clean Technol Environ Policy 2012;15. http://dx.doi.org/10.1007/s10098-012-0481-6.

[6] Tang Z, Li W, Tam VW, Xue C. Advanced progress in recycling municipal and construction solid wastes for manufacturing sustainable construction materials. Resour Conserv Recycl: X 2020;6. http://dx.doi.org/10.1016/j.rcrx.2020.100036, URL: https://www.sciencedirect.com/science/article/pii/S2590289X20300074.

[7] Mazur-Wierzbicka E. Towards circular economy—A comparative analysis of the countries of the European union. Resources 2021;10(5):49. http://dx.doi.org/10.3390/resources10050049, URL: http://dx.doi.org/10.3390/resources10050049.

[8] Shamsuyeva M, Endres H-J. Plastics in the context of the circular economy and sustainable plastics recycling: Comprehensive review on research development, standardization and market. Compos C: Open Access 2021;6. http://dx.doi.org/10.1016/j.jcomc.2021.100168.

[9] Mathijsen D. The renaissance of flax fibers. Reinforced Plast 2018;62(3):138–47. http://dx.doi.org/10.1016/j.repl.2017.11.020, URL: https://www.sciencedirect.com/science/article/pii/S0034361717306082.

[10] Balador Z, Gjerde M, Isaacs N. Influential factors on using reclaimed and recycled building materials. Sustain Energy Build 2019.

[11] Rodríguez-Antón JM, Rubio-Andrada L, Celemín-Pedroche MS, Ruíz-Peñalver SM. From the circular economy to the sustainable development goals in the European union: An empirical comparison. Int Environ Agreements: Politics Law Econ 2022;22(1):67–95.

[12] Caldera S, Desha C, Dawes L. Transforming manufacturing to be 'good for planet and people', through enabling lean and green thinking in small and medium-sized enterprises. Sustain Earth 2019;2:4. http://dx.doi.org/10.1186/s42055-019-0011-z.

[13] Bocken N, Pauw I, Bakker C, van der Grinten B. Product design and business model strategies for a circular economy. J Ind Prod Eng 2016;1015.

[14] Singh R, Singh N, Fabbrocino F, Fraternali F, Ahuja I. Waste management by recycling of polymers with reinforcement of metal powder. Composites B 2016;105:23–9. http://dx.doi.org/10.1016/j.compositesb.2016.08.029, URL: https://www.sciencedirect.com/science/article/pii/S1359836816314500.

[15] Mazur-Wierzbicka E. Circular economy: Advancement of European union countries. Environ Sci Europe 2021;33:1–15.

[16] Calisto Friant M, Vermeulen WJ, Salomone R. Analysing European union circular economy policies: words versus actions. Sustain Prod Consumpt 2021;27:337–53. http://dx.doi.org/10.1016/j.spc.2020.11.001, URL: https://www.sciencedirect.com/science/article/pii/S2352550920313750.

[17] Sathishkumar T, Navaneethakrishnan P, Subramaniam S, Rajasekar R, Rajini N. Characterization of natural fiber and composites - A review. J Reinf Plast Compos 2013;32:1457–76. http://dx.doi.org/10.1177/0731684413495322.

[18] Fantuzzi N, Bacciocchi M, Benedetti D, Agnelli J. The use of sustainable composites for the manufacturing of electric cars. Compos C: Open Access 2021;4. http://dx.doi.org/10.1016/j.jcomc.2020.100096.

[19] Operato L, Vitiello L, Aprea P, Ambrogi V, de Luna MS, Filippone G. Life cycle assessment of poly (lactic acid)-based green composites filled with pine needles or kenaf fibers. J Clean Prod 2023;135901.

[20] Gurunathan T, Mohanty S, Nayak SK. A review of the recent developments in biocomposites based on natural fibres and their application perspectives. Composites A 2015;77:1–25. http://dx.doi.org/10.1016/j.compositesa.2015.06.007, URL: https://www.sciencedirect.com/science/article/pii/S1359835X15002067.

[21] Takagi H, Ochi S. Mechanical properties and biodegradation behavior of high-strength. WIT Trans Built Environ 2004;76.

[22] Dittenber DB, GangaRao HV. Critical review of recent publications on use of natural composites in infrastructure. Composites A 2012;43(8):1419–29. http://dx.doi.org/10.1016/j.compositesa.2011.11.019, URL: https://www.sciencedirect.com/science/article/pii/S1359835X11003903.

[23] Bozza A, Asprone D, Fabbrocino F. Urban resilience: A civil engineering perspective. Sustainability 2017;9(1). URL: https://www.mdpi.com/2071-1050/9/1/103.

[24] Konuri S, Lakshmi VT. Experimental studies for comparing conventional concrete with bubble deck concrete. Mater Today: Proc 2022. http://dx.doi.org/10.1016/j.matpr.2022.10.198.

[25] Sasidharan M, Torbaghan ME, Burrow M. Using waste plastics in road construction. K4D Helpdesk Report, Brighton, UK: Institute of Development Studies; 2019.

[26] Gu L, Ozbakkaloglu T. Use of recycled plastics in concrete: A critical review. Waste Manag 2016;51:19–42. http://dx.doi.org/10.1016/j.wasman.2016.03.005.

[27] Pyrzowski Ł, Miśkiewicz M. Application of foam made of post-consumer pet materials for the construction of footbridges. Int Multidiscip Sci GeoConf: SGEM 2017;17:9–16.

[28] Ribeiro SLMF, Tonatto ML, Hallak TP, Remillat CD, Scarpa F. Multi-objective optimisation of aluminium skins and recycled/perforated PET foams sandwich panels subjected to impact loads. Structures 2022;43:1750–65. http://dx.doi.org/10.1016/j.istruc.2022.07.071.

[29] Safinia S, Alkalbani A. Use of recycled plastic water bottles in concrete blocks. Procedia Eng 2016;164:214–21.

[30] Faqe Rahim AA, Mohammed AA, Al-Kamaki YS. Flexural behavior of composite T-beam made of plastic waste aggregate concrete web and high-strength concrete flange. Structures 2023;47:2138–47. http://dx.doi.org/10.1016/j.istruc.2022.11.096.

[31] Fakhruddin, Irmawaty R, Djamaluddin R. Flexural behavior of monolith and hybrid concrete beams produced through the partial replacement of coarse aggregate with PET waste. Structures 2022;43:1134–44. http://dx.doi.org/10.1016/j.istruc.2022.07.015.

[32] Tan LJ, Zhu W, Sagar K, Zhou K. Comparative study on the selective laser sintering of polypropylene homopolymer and copolymer: Processability, crystallization kinetics, crystal phases and mechanical properties. Addit Manuf 2021;37. http://dx.doi.org/10.1016/j.addma.2020.101610.

[33] Mostaghel N, Byrd RA. Inversion of Ramberg–Osgood equation and description of hysteresis loops. Int J Non-Linear Mech 2002;37(8):1319–35. http://dx.doi.org/10.1016/S0020-7462(02)00025-2, URL: https://www.sciencedirect.com/science/article/pii/S0020746202000252.