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Eco Trends in Civil Engineering

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Abstract

Civil engineering is a human activity, a scientific and technical discipline that includes the design, organization and execution of all civil engineering and construction works. Some of the common construction products are roads, bridges, railways, tunnels, ports, drainage and water supply systems, dams, residential and public buildings, sports halls, etc. The construction of new buildings reduces the amount of green or arable land needed by the population. Also, the demolition of existing buildings creates waste that needs to be properly disposed. The problem of waste disposal is very pronounced nowadays, so it is necessary to look for new ways of using existing as well as newly created waste. One of the available ways of using waste is its incorporation into materials used in the construction of buildings. The above can be observed through the concept of circular economy, which is the opposite of linear economy. Circular economy says that products should be kept as long as possible in their life cycle, i.e. that no waste is created. Such resources should be reused in other products. The paper will present some of the materials that can be reused in construction, as well as application of certain products that improve certain properties of construction products. Some examples are reuse of glass fiber reinforced plastic in concrete, utilizing biosilica to enhance the compressive strength of cement mortar, boosting concrete strength with sewage sludge fly ash, adding rubber into the concrete mix and polyethylene terephthalate (PET) waste in concrete mixture. Eco trends must be applied in all phases: from design to construction and to removal of various objects. Eco trends in civil engineering are aimed at protecting the environment by reducing the amount of unusable waste material and saving on construction material prices.

Keywords

circular economy, civil engineering, eco trends, recycling, waste materials

1. INTRODUCTION

Construction sector is one of the largest and most dynamic sectors in Europe, currently accounting for 25% [1] of the total industrial production in Europe. Since the construction industry requires a large amount of raw materials, this makes it unsustainable. The fact behind the benefits of using recycled materials in construction is that if people mismanage and overuse natural resources — as they do now — these will eventually run out, so replacing natural resources with waste recycled products is the first step towards a circular economy and sustainable construction. Recycling materials contribute to reduction of waste, resource conservation, greenhouse gas emission reduction, and increased energy efficiency. Increased profitability and cost savings are two further benefits of employing recycled materials in the construction sector [2]. Utilizing recycled materials may prove to be more cost-effective compared to virgin materials, particularly when obtained from nearby sources and incurring reduced transportation expenses. Additionally, they have the potential to decrease the necessity for costly charges associated with waste management, such as disposal fees and taxes. Recycled materials have the potential to foster new markets and open up new opportunities for companies and workers in the recycling industry. This, in turn, can contribute to the growth of local economy and generate additional income. On the other hand, recycled materials may have different properties and characteristics than the original materials, such as strength, durability, quality and compatibility, so it is important to conduct extensive laboratory research. In this context, this paper reviews the use of biosilica, glass fiber reinforced plastic, sludge fly ash, rubber and PET waste in concrete mix. A review of these five studies shows that the use of recycled materials has positive effects on the mechanical properties of concrete, indicating that their application is the basis for future innovation development.

2. CIRCULAR ECONOMY IN THE CONSTRUCTION INDUSTRY

Construction sector has been a sustainable sector since ancient times. The materials and building techniques used in the past were effective, creating ecologically designed structures while utilizing environmentally friendly materials that had a high potential for reuse and recyclability [3].

Sustainable circular economy represents a new economic model where the focus shifts from the narrow growth of gross domestic product to a multidimensional progress – broadly strengthening the quality of the environment, human well-being, and economic prosperity for current and future generations. The circular economy is a business model with the potential to generate competitiveness of an economic entity in combination with innovation and sustainability. In order to implement this model, the traditional approach to the market, customers, and natural resources must change [4].

The construction industry has always had a significant impact on every national economy, evident from its contribution to the gross domestic product (GDP) structure and employment of a large workforce [5].

The transition from linear to circular economy is inevitable as linear production is associated with mass production and consumption of raw materials, without concern for the potential limitations of the availability of these resources [6]. Circular economy can make positive contribution to sustainability. It must be fully integrated with the sustainable development of an economic entity, expanding its scope from closed-loop recycling and short-term economic gain to a transformed economy that organizes resource access for maintaining or enhancing social welfare and environmental quality [4]. The concept of circular economy is shown on figure 1.

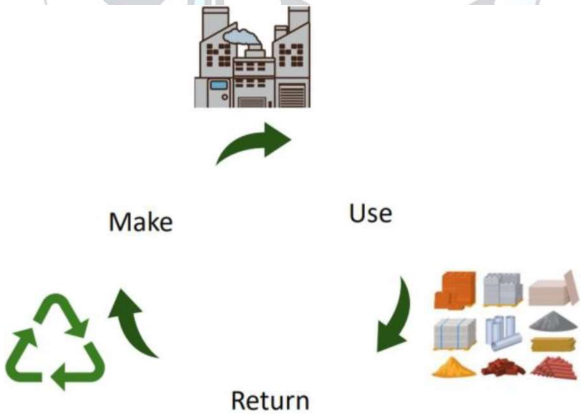

Figure 1. Concept of circular economy [7]

3. USE OF RECYCLED MATERIALS IN CONTRUCTION

3.1. Utilizing Biosilica to Enhance the Compressive Strength of Cement Mortar

Recent developments in the industrial sector involve the use of microsilica, a byproduct of metallurgical operations used to create metallic silicon, ferrosilicon, silumin, and other silicon alloys. Additionally, biosilica obtained by thermochemical processes from natural sources, like rice husk ash, is of considerable interest [8], [9]. The possibility that biosilica, a kind of silica that is naturally produced by diatoms, might improve the mechanical properties of cement-based materials is being studied. Due to the fact that it comes from a sustainable source and is biodegradable, biosilica has several advantages over traditional silica additions. In the building materials field, the use of biosilica in cement mortar is becoming increasingly important. Because of its special characteristics, which include a wide surface area, small particle dimensions, and pozzolanic activity, it is a desirable addition for cement-based products to improve their mechanical performance.

The efficacy of an addition in cement mortar is determined not only by its intrinsic qualities, but also by the technique of inclusion into the mortar mixture. To produce a homogeneous dispersion of additives, maintain sufficient contact with the cement matrix, and influence the performance of composites, mixing processes are essential. Therefore, it is necessary to comprehend how mixing methods impact this material to maximize its efficacy and realize its full potential when using biosilica in cement mortar [9]. Biosilica synthesis from rice husk is shown on figure 2.

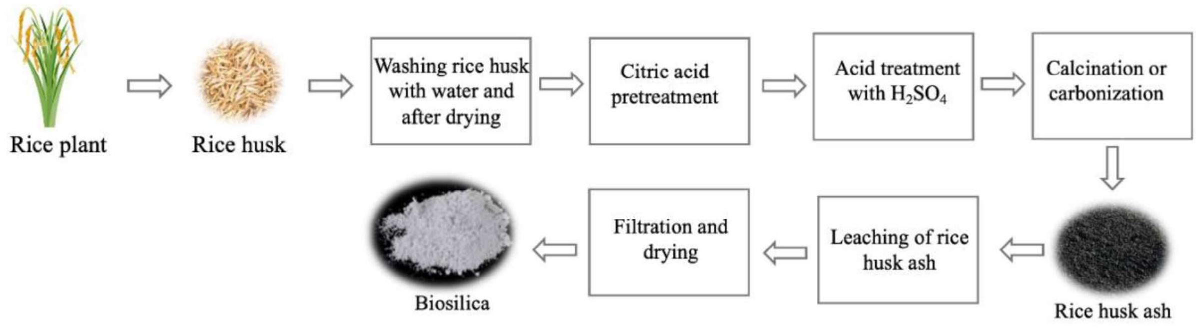

Figure 2. Schematic of biosilica synthesis from rice husk [10]

Research shows that integrating a significant quantity of biosilica can fill cracks, potentially boosting compressive strength and minimizing water absorption. Biosilica particles are capable of bearing compressive loads, contributing to enhanced strength. Owing to their minute dimensions, these particles can occupy empty spaces within the cement, resulting in heightened density. The presence of biosilica renders the pores rigid, aiding in preserving the structural integrity [9], [11].

3.2. Boosting Concrete Strength with Sewage Sludge Fly Ash

According to European regulations, sewage sludge fly ash (SSFA) waste generated by the combustion of municipal waste sludge in a fluidized bed should not end up in landfills, but must be subjected to different treatment methods. Considering the large quantities being produced, it is necessary to explore new approaches to managing this waste. Storage of SSFA has negative environmental consequences, including water pollution, changes in soil pH and adverse effects on flora and fauna [12], [13], [14].

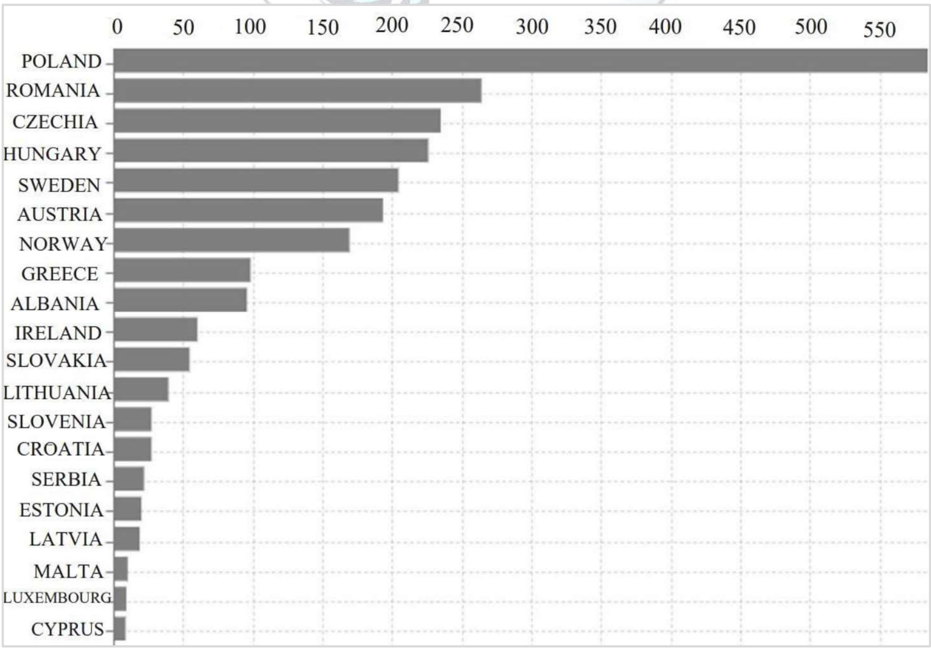

Figure 3. Sewage sludge production and disposal for 2021 [1]

Figure 3 shows sewage sludge production and disposal for countries in Europe for 2021. Quantities are expressed in thousands of tons. There is no data for Bulgaria, Germany, Spain, France, Netherlands, Portugal, Finland, Switzerland and United Kingdom.

Adding SSFA to cement and concrete brings a number of financial and environmental benefits. This reduces the amount of waste sludge in landfills, optimizes the costs and quality of construction materials, and reduces total disposal costs, including those specific to landfills. It also reduces the need for primary raw materials and promotes the sustainable development of the economy through the conversion of waste sludge into useful products. In addition, energy savings and the reduction in emissions of harmful substances such as NOx, CO_2 and other pollutants are achieved [15].

Considering the results of the experiments, it was observed that the compressive strength of concrete increases when SSFA is added, considering this fact, SSFA can be successfully used as an admixture in concrete. Furthermore, there are no legal guidelines related to the requirements of the physical and chemical properties of SSFA, as well as the possibility of its use in concrete production. By tailoring it to the unique requirements of the construction industry, we can successfully decrease SSFA [16]. By adapting it to the unique requirements of the construction industry, we can successfully reduce SSFA which is a starting point for further research.

3.3. Reuse of Glass Fibre Reinforced Plastic in Concrete

Glass fibre reinforced plastic, or GFRP, is becoming increasingly popular in several sectors. It is used, for instance, in the automotive, aerospace, building, marine, and renewable energy sectors [17]. A substantial quantity of glass fibre reinforced plastic waste is expected to decrease in the coming years due to the growth in production and use of the product on the basis of GFRP [18].

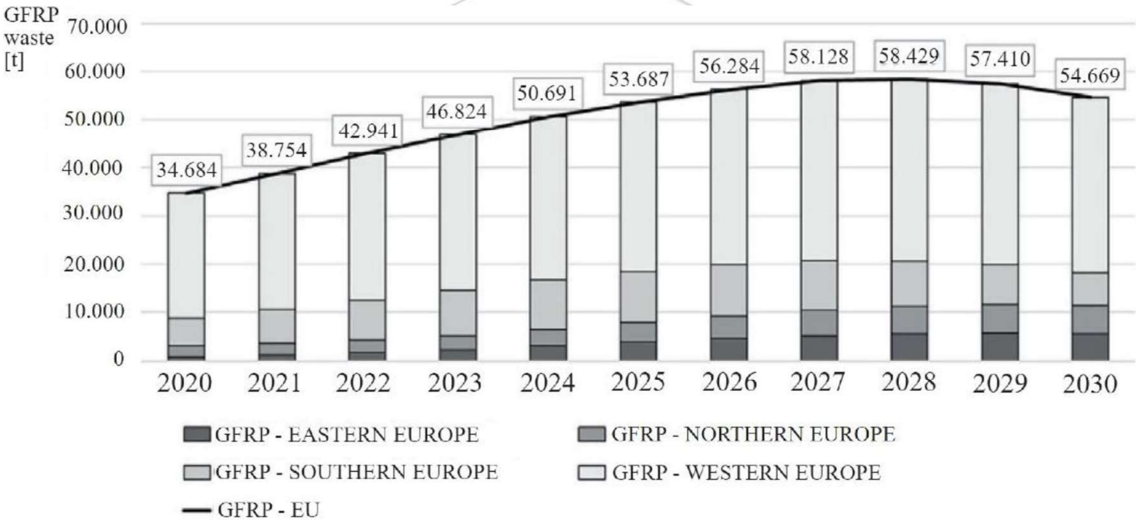

Figure 4. Amount of GFRP waste per region [19]

Figure 4 shows the amount of GFRP waste that appears in Europe. Data for Eastern, Northern, Southern and Western Europe from 2020 to 2030 are displayed. The black line across the graph represents the total waste from GFRP in the EU. The Y-axis represents the "Amount of GFRP waste per region" and ranges from 0 to 70,000. The X-axis represents the years from 2020 to 2030. Western Europe has the most GFRP waste in 2024, and Northern Europe the least. Western Europe has approximately 55,000 tons of waste and Northern Europe has approximately 20,000 tons of waste [19].

Sorting, trimming, pulverizing, and sifting are just some of the steps in the mechanical recycling process that are used to reduce the amount of GFRP waste [2], [20]. In the production of concrete, the use of mechanically recycled glass fibre reinforced plastic (rGFRP) appears to be a viable choice. This tactic not only lessens the quantity of materials that must be disposed of in landfills, but it also maintains and occasionally even enhances the concrete's quality [21].

Currently, three methods may integrate rGFRP from mechanical recycling in concrete. One method entails transforming GFRP waste into fine granules that can be used as fine aggregate in concrete mix. Another method entails cutting the GFRP waste into larger pieces, which are suitable for replacing the coarse aggregate in the concrete mix. In addition, GFRP waste that is turned into fine fibres by mechanical processing can be used in the production of reinforcing bars. Fibres further improve the mechanical properties of reinforcing bars. These three methods for incorporating rGFRP into concrete have potential advantages as they can greatly improve the mechanical properties of concrete.

Research [22], [23], [24] showed that adding GFRP to concrete has increased the flexural strength, toughness of concrete, durability of concrete, control of cracking due to drying and reduction of moisture in the concrete mixture.

GFRP holds the potential to improve the properties of concrete mixture, but its application in concrete has not received enough research yet. Evaluating the long-term effects of using GFRP waste on the durability of concrete is also crucial. Further research into the possibilities of waste glass fiber reinforced polymer in concrete is becoming more pertinent due to the growing need for sustainable materials in the building industry.

3.4. PET Waste in Concrete Mixture

Significant environmental problems have arisen as a result of the massive amounts of stable waste made by polyethylene terephthalate (PET). Though they trail behind in terms of recycling and reuse, they nonetheless represent a sizable amount of all plastic waste. Recent research has investigated the viability of using recycled PET solid wastes as short fibres in cementitious composites [25].

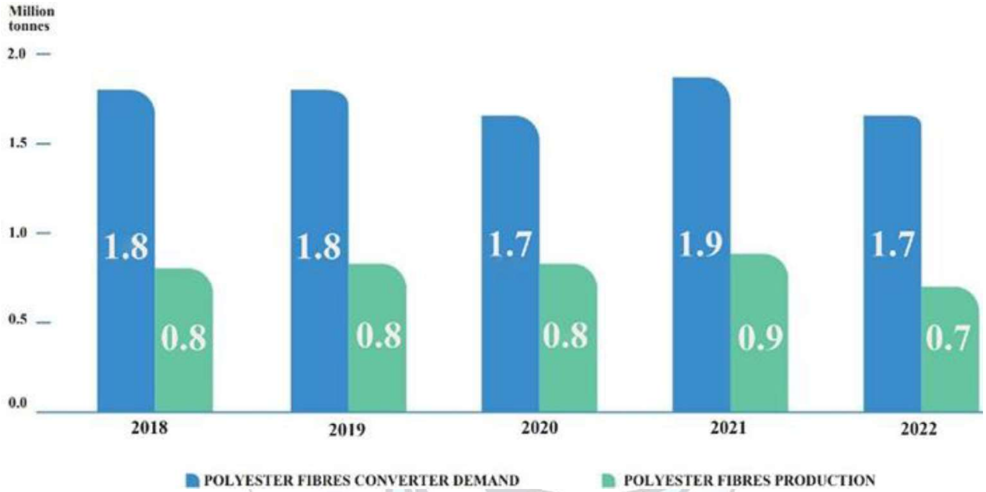

Figure 5. Polyester fibres production and converter demand evolution between 2018 and 2022 for EU [26]

Figure 5 shows the comparison of polyester fibre demand (blue bars) and production (green bars) from 2018 to 2022. The highest demand was recorded in 2021 and amounted to 1.9 million tons, while the lowest production was in 2022 and amounted to 700,000 tons. In 2022, the demand decreased due to unfavorable economic conditions, rising prices, and recessionary issues. Fibre production process is shown on figure 6. Also, table 1 shows the summary of test results on the mechanical properties of concrete modified with PET fibres.

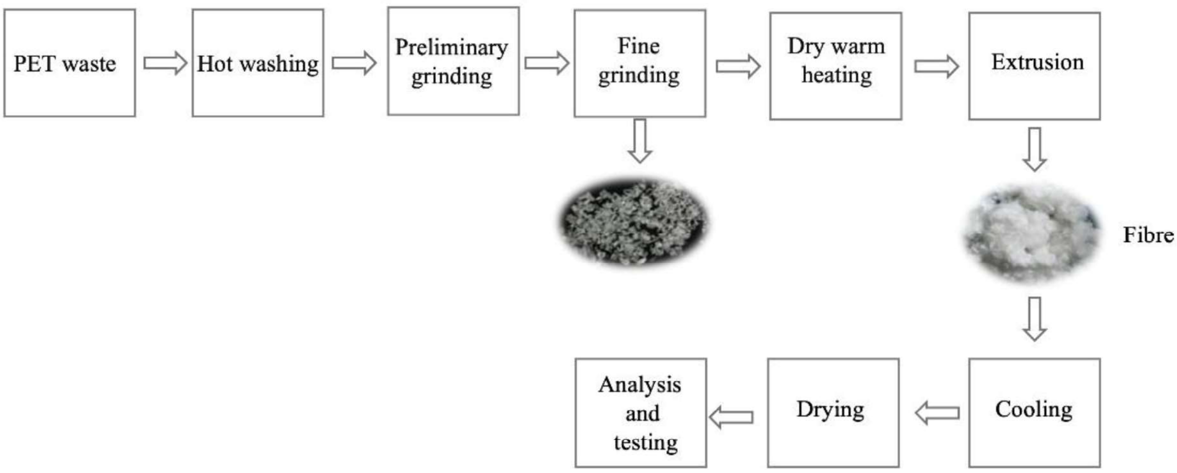

Figure 6. Fibre production process [27]

Table 1. Test results on the mechanical properties of concrete modified with PET fibres

Mechanical properties	Test results	References
Compressive strength	With a higher proportion of fibres, the compressive strength decreases	[27]
Flexural strength	Increases as the percentage of fibres in concrete increases	[28]
Split tensile strength	Fiber can enhance the tensile splitting strength of concrete	[29]
Shear strength	At 1 % volume percent of plastic fibres, the shear strength of concrete increases, and it decreases as the volume fraction of fibres increases thereafter	[27]
Modulus of elasticity	With a higher proportion of fibres, the modulus of elasticity decreases	[30]
Bulk density	With a higher proportion of fibres, the modulus of elasticity decreases	[31]
Energy consumption	Increases as the percentage of fibres in concrete increases	[32]

Apart from the fact that plastic is very useful for any form of industry, it also creates a big problem for the environment due to its slow decomposition. Considering the large quantities of PET waste, its use in concrete in the form of fibres provides an alternative to the disposal of large quantities of PET waste. Adding PET fibres to concrete improves flexural strength, split tensile strength, energy consumption and shear strength (depending on fibre concentration), while it has a negative impact on compressive strength and bulk density. For further research, it is necessary to examine how different concentrations, lengths, thicknesses, shapes, textures and surface treatments of PET fibres affect the mechanical properties of concrete under different loads and environmental conditions.

3.5. Adding Rubber into the Concrete Mix

European countries face the problem of rehabilitation of a large amount of polymer waste that has no practical application. Rubber floor mats for cars belong to the group of polymer waste. Polymeric waste is a big problem because there is currently no effective method for disposing this type of waste. Some European Union countries charge an environmental fee for the disposal of rubber car floor mats, and the first country to introduce an environmental fee for this type of waste is Poland. Due to the mentioned problem, the option of adding polymer waste to concrete as a substitute for aggregate is being considered more and more [33]. Shredding process of rubber floor mats for cars is shown on figure 7.

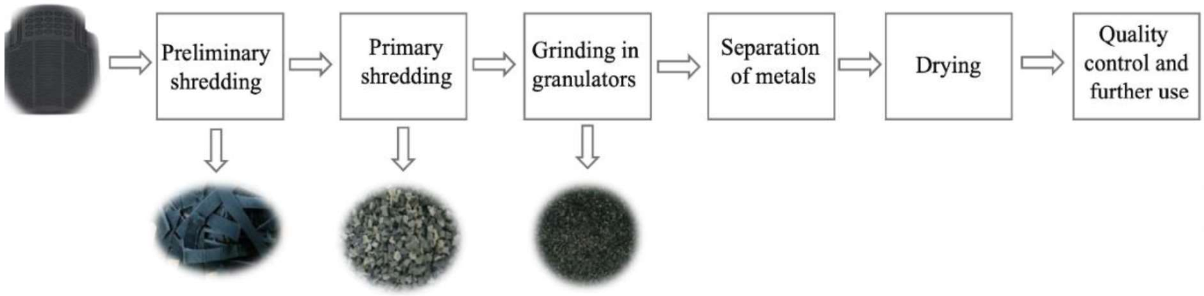

Figure 7. Shredding process of rubber floor mats for cars [34]

Table 2. Advantages and disadvantages of adding rubber as an aggregate to the concrete mixture [35], [36], [37]

Advantages	Disadvantages
increases shrinkage	increases the penetration of chloride ions
increases electrical resistance	reduces workability
increases the ductility and deformation capacity of concrete	reduces the fire resistance
increases thermal insulation	reduces resistance to carbonation
improves impact load behaviour and impact load behaviour	reduces density
increases the wear resistance of concrete	reduces mechanical strength
increases sound absorption	

Rubber has many benefits over natural aggregates in mortars and concrete, including lower matrix density, greater flexibility, durability, better resistance to impact loads, better freeze-thaw resistance, better thermal and acoustic insulation, increased deformation capacity, and better energy absorption capabilities. However, using shredded rubber in place of natural aggregates in mortar or concrete formulations may have some disadvantages. A few examples are reduced workability, increased drying shrinkage, higher water absorption, and improved chloride ion penetration. To sum up, crumb rubber is a great material to use for creating lightweight mortars and concrete. Two interesting applications for it are as a shock absorber in road construction and as a shock-wave dampener in construction.

4. CONCLUSION

Sustainable construction and responsibility towards the environment requires the use of eco-friendly materials, waste reduction and the application of net zero building. The future of construction in the framework of sustainable development is reflected in the application of advanced construction technologies and sustainable designs. This implies the use of various environmentally acceptable materials. All this points to the necessity of adopting the principles of the circular economy in construction. Circular economy implies circular flows of materials, reuse of waste and resources, which ultimately results in an increase in ecological efficiency.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

REFERENCES

[1]. Eurostat, EC Data Browser, Sewage sludge production and disposal, 2024, [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/env_ww_spd/default/bar?lang=en&category=env.env_wat.env_nwat. (Accessed: 04.05.2024.)

[2]. A. E. Krauklis, C. W. Karl, A. I. Gagani, and J. K. Jørgensen, "Composite Material Recycling Technology—State-of-the-Art and Sustainable Development for the 2020s," *Journal of Composites Science*, vol. 5, no. 1, p. 28, 2021, doi: 10.3390/jcs5010028

[3]. P. Núñez-Cacho, J. Górecki, V. Molina, and F. A. Corpas-Iglesias, "New Measures of Circular Economy Thinking In Construction Companies," *Journal of EU Research in Business*, vol. 2018, pp. 1–16, Apr. 2018, doi: 10.5171/2018.909360

[4]. K. Vićentijević, "Održivost i cirkularna ekonomija", in *Zbornik radova MES*, vol. 1, no. 9, Oct. 2023, doi: 10.7251/BLCZR0623287V

[5]. L. Lovrenčić Butković and M. Mihaljević, "Poznavanje koncepta kružne ekonomije u građevinskom sektoru", *Ekonomska misao i praksa*, vol. 30, no. 2, pp. 587–608, Dec. 2021, doi: 10.17818/EMIP/2021/2.14.

[6]. M. Geissdoerfer, P. Savaget, N. M. P. Bocken, and E. J. Hultink, "The Circular Economy – A new sustainability paradigm?," *Journal of Cleaner Production*, vol. 143, pp. 757–768, Feb. 2017, doi: 10.1016/j.jclepro.2016.12.048.
[7]. C. K. Purchase *et al.*, "Circular Economy of Construction and Demolition Waste: A Literature Review on Lessons, Challenges, and Benefits," *Materials*, vol. 15, no. 1, p. 76, Dec. 2021, doi: 10.3390/ma15010076.
[8]. J. Li, W. Zhang, C. Li, and P. J. M. Monteiro, "Green concrete containing diatomaceous earth and limestone: Workability, mechanical properties, and life-cycle assessment," *Journal of Cleaner Production*, vol. 223, pp. 662–679, Jun. 2019, doi: 10.1016/j.jclepro.2019.03.077.
[9]. N. G. Muradyan *et al.*, "The Use of Biosilica to Increase the Compressive Strength of Cement Mortar: The Effect of the Mixing Method," *Materials*, vol. 16, no. 16, p. 5516, Aug. 2023, doi: 10.3390/ma16165516.
[10]. S. Nawaz, F. Jamil, P. Akhter, M. Hussain, H. Jang, and Y.-K. Park, "Valorization of lignocellulosic rice husk producing biosilica and biofuels—a review," *Journal of Physics: Energy*, vol. 5, no. 1, p. 012003, 2023, doi: 10.1088/2515-7655/aca5b4.
[11]. L. P. Singh, S. R. Karade, S. K. Bhattacharyya, M. M. Yousuf, and S. Ahalawat, "Beneficial role of nanosilica in cement based materials – A review," *Construction and Building Materials*, vol. 47, pp. 1069–1077, Oct. 2013, doi: 10.1016/j.conbuildmat.2013.05.052.
[12]. T. Umar, M. Yousaf, M. Akbar, N. Abbas, Z. Hussain, and W. S. Ansari, "An Experimental Study on Non-Destructive Evaluation of the Mechanical Characteristics of a Sustainable Concrete Incorporating Industrial Waste," *Materials*, vol. 15, no. 20, p. 7346, 2022, doi: 10.3390/ma15207346.
[13]. Z. Hussain *et al.*, "Effect of fiber dosage on water permeability using a newly designed apparatus and crack monitoring of steel fiber–reinforced concrete under direct tensile loading," *Structural Health Monitoring*, vol. 21, no. 5, pp. 2083–2096, Sep. 2022, doi: 10.1177/14759217211052855.
[14]. S. Ahmed, A. Hussain, Z. Hussain, Z. Pu, K. A. Ostrowski, and R. Walczak, "Effect of Carbon Black and Hybrid Steel-Polypropylene Fiber on the Mechanical and Self-Sensing Characteristics of Concrete Considering Different Coarse Aggregates' Sizes," *Materials*, vol. 14, no. 23, p. 7455, Dec. 2021, doi: 10.3390/ma14237455.
[15]. O. Ginés, J. M. Chimenos, A. Vizcarro, J. Formosa, and J. R. Rosell, "Combined use of MSWI bottom ash and fly ash as aggregate in concrete formulation: Environmental and mechanical considerations," *Journal of Hazardous Materials*, vol. 169, no. 1–3, pp. 643–650, Sep. 2009, doi: 10.1016/j.jhazmat.2009.03.141.
[16]. T. Kalak, P. Szypura, R. Cierpiszewski, and M. Ulewicz, "Modification of Concrete Composition Doped by Sewage Sludge Fly Ash and Its Effect on Compressive Strength," *Materials*, vol. 16, no. 11, p. 4043, May 2023, doi: 10.3390/ma16114043.
[17]. C. B. Farinha, J. de Brito, and R. Veiga, "Assessment of glass fibre reinforced polymer waste reuse as filler in mortars," *Journal of Cleaner Production*, vol. 210, pp. 1579–1594, 2019, doi: 10.1016/j.jclepro.2018.11.080.
[18]. F. Tittarelli and S. P. Shah, "Effect of low dosages of waste GRP dust on fresh and hardened properties of mortars: Part 1," *Construction and Buildings Materials*, vol. 47, pp. 1532–1538, 2013, doi: 10.1016/j.conbuildmat.2013.06.043.
[19]. V. Sommer, J. Stockschläder, and G. Walther, "Estimation of glass and carbon fiber reinforced plastic waste from end-of-life rotor blades of wind power plants within the European Union," *Waste Management*, vol. 115, pp. 83–94, Sep. 2020, doi: 10.1016/j.wasman.2020.06.043.
[20]. A. C. Meira Castro *et al.*, "Sustainable waste recycling solution for the glass fibre reinforced polymer composite materials industry," *Construction and Building Materials*, vol. 45, pp. 87–94, 2013, doi: 10.1016/j.conbuildmat.2013.03.092.
[21]. N. Sebaibi, M. Benzerzour, N. E. Abriak, and C. Binetruy, "Mechanical properties of concrete-reinforced fibres and powders with crushed thermoset composites: The influence of fibre/matrix interaction," *Constr Build Mater*, vol. 29, pp. 332–338, 2012, doi: 10.1016/j.conbuildmat.2011.10.026.
[22]. B. Fu, K. C. Liu, J. F. Chen, and J. G. Teng, "Concrete reinforced with macro fibres recycled from waste GFRP," *Construction and Building Materials*, vol. 310, p. 125063, Dec. 2021, doi: 10.1016/j.conbuildmat.2021.125063.
[23]. A. Yazdanbakhsh, L. C. Bank, and C. Chen, "Use of recycled FRP reinforcing bar in concrete as coarse aggregate and its impact on the mechanical properties of concrete," *Construction and Building Materials*, vol. 121, pp. 278–284, Sep. 2016, doi: 10.1016/j.conbuildmat.2016.05.165.
[24]. M. Mastali, Z. Abdollahnejad, A. Dalvand, A. Sattarifard, and M. Illikainen, "Comparative effects of using recycled CFRP and GFRP fibers on fresh- and hardened-state properties of self-compacting concretes: a review," in *New Materials in Civil Engineering*, Elsevier, 2020, pp. 643–655. doi: 10.1016/B978-0-12-818961-0.00019-3.
[25]. J. Yu *et al.*, "Tensile performance of sustainable Strain-Hardening Cementitious Composites with hybrid PVA and recycled PET fibers," *Cement and Concrete Research*, vol. 107, pp. 110–123, May 2018, doi: 10.1016/j.cemconres.2018.02.013.

[26]. Pet Market in Europe: State of Play, Independent Commodity Intelligence Services, 2024, [Online]. Available: https://www.unesda.eu/wp-content/uploads/2024/03/PET-Market-in-Europe-State-of-Play.pdf. (Accessed: 25.05.2024.)
[27]. R. N. Nibudey, P. B. Nagarnaik, D. K. Parbat, and A. M. Pande, “A model for compressive strength of PET fiber reinforced concrete,” *American Journal of Engineering Research*, vol. 02, no. 12, pp. 367–372, 2013.
[28]. R. Kandasamy and R. Murugesan, “Fiber Reinforced Self Compacting Concrete Using Domestic Waste Plastics as Fibres,” *Journal of Engineering and Applied Sciences*, vol. 7, no. 6, pp. 405–410, Jun. 2012, doi: 10.3923/jeasci.2012.405.410.
[29]. D. Foti, “Preliminary analysis of concrete reinforced with waste bottles PET fibers,” *Construction and Building Materials*, vol. 25, no. 4, pp. 1906–1915, Apr. 2011, doi: 10.1016/j.conbuildmat.2010.11.066.
[30]. J. M. Irwan, R. M. Asyraf, N. Othman, K. H. Koh, M. M. K. Annas, and S. K. Faisal, “The Mechanical Properties of PET Fiber Reinforced Concrete from Recycled Bottle Wastes,” *Advanced Materials Research*, vol. 795, pp. 347–351, Sep. 2013, doi: 10.4028/www.scientific.net/AMR.795.347.
[31]. Sampada Chavan and Pooja Rao, “Utilization of Waste PET Bottle Fibers in Concrete as an Innovation in Building Materials,” *International Journal of Engineering Research*, vol. 5, pp. 304–307, 2016.
[32]. M. da Silva Magalhães and M. Soares Viana Fernandes, “Bending Behaviour of Recycled PET Fiber Reinforced Cement-Based CompositeBending Behaviour of Recycled PET Fiber Reinforced Cement-Based Composite,” *International Journal of Engineering and Technology*, vol. 7, no. 4, pp. 282–285, Aug. 2015, doi: 10.7763/IJET.2015.V7.805.
[33]. A. Pietrzak and M. Ulewicz, “Influence of Post-Consumer Waste Thermoplastic Elastomers Obtained from Used Car Floor Mats on Concrete Properties,” *Materials*, vol. 16, no. 6, p. 2231, Mar. 2023, doi: 10.3390/ma16062231.
[34]. A. Pietrzak and M. Ulewicz, “Influence of Post-Consumer Waste Thermoplastic Elastomers Obtained from Used Car Floor Mats on Concrete Properties,” *Materials*, vol. 16, no. 6, p. 2231, Mar. 2023, doi: 10.3390/ma16062231.
[35]. N. M. Al-Akhras and M. M. Smadi, “Properties of tire rubber ash mortar,” *Cement and Concrete Composites*, vol. 26, no. 7, pp. 821–826, Oct. 2004, doi: 10.1016/j.cemconcomp.2004.01.004.
[36]. A. O. Atahan and A. Ö. Yücel, “Crumb rubber in concrete: Static and dynamic evaluation,” *Construction and Building Materials*, vol. 36, pp. 617–622, Nov. 2012, doi: 10.1016/j.conbuildmat.2012.04.068.
[37]. A. Benazzouk, O. Douzane, T. Langlet, K. Mezreb, J. M. Roucoult, and M. Quéneudec, “Physico-mechanical properties and water absorption of cement composite containing shredded rubber wastes,” *Cement and Concrete Composites*, vol. 29, no. 10, pp. 732–740, Nov. 2007, doi: 10.1016/j.cemconcomp.2007.07.001.