Budownictwo i Architektura 23(2) 2024, 87-97

DOI: 10.35784/bud-arch.5701
Received: 19.12.2023; Revised: 25.02.2024;
Accepted: 12.04.2024; Available online: 15.06.2024

Orginal Article

Utilisation of waste glass from solar thermal collectors for the production of polymer concrete

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Abstract: The article discusses the use of waste tempered glass from damaged or decommissioned thermal solar collectors to produce polymer concretes. The waste underwent mechanical recycling to obtain powders of alternative grain sizes: below 2.0 mm and below 0.5 mm. To produce the polymer concrete, ground glass waste served as the fine fraction, and sandstone gravel as the coarse fraction. An epoxy resin acted as the binder for the resulting composite. The research conducted has demonstrated that glass waste from solar collectors can be successfully utilised as a fine fraction in polymer concrete technologies. It was observed that there are no significant differences between the grains at 0.5 mm and 2.0 mm, and both fractions yield the desired results. The resulting polymer concretes are characterised by high mechanical strength, significantly surpassing the properties of typical cement concretes. The compressive strength is at 110.7 MPa, and the flexural strength is at 41.2 MPa. The proposed recycling method allows for the effective management of waste that is difficult to reuse on an industrial scale.

Keywords: polymer concretes, waste, recycling, epoxy-based composites, solar thermal collectors

1. Introduction

Photovoltaic panels and solar collectors are increasing in popularity due to significant environmental benefits. However, the rising use of such solar systems presents a new challenge: recycling after damage or decommissioning. Despite the many similarities between photovoltaic systems and solar thermal collectors, their recycling processes differ fundamentally due to variations in material composition, manufacturing processes, and continuous technological development. Some components of solar collectors are easily recyclable, but the problematic tempered glass on the collector surface is typically landfilled [1–2].

A solar collector is used to convert solar energy into the thermal energy of a fluid, such as water. It comprises several components: a frame, solar glass, a solar absorber, copper tubes, and an insulation layer. A schematic of the construction of a solar collector is shown in Fig. 1.

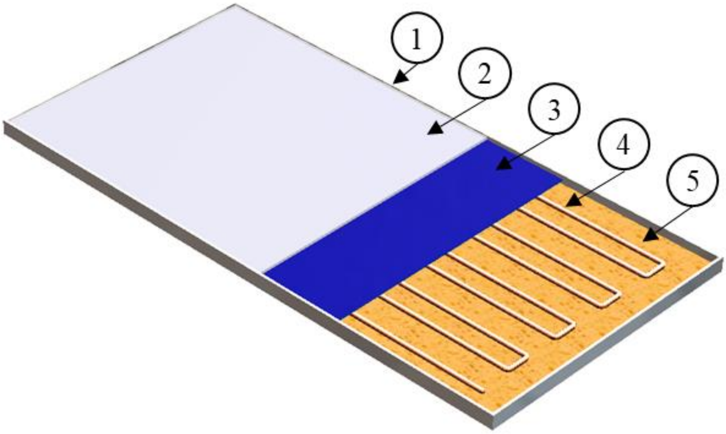


Fig. 1. Construction of a thermal solar collector (1 – frame, 2 – solar glass, 3 – solar radiation absorber, 4 – copper pipes, 5 – insulating layer)

The role of the frame in a solar collector is to stabilize the shape of the collector and to protect against the ingress of impurities. The glass panel is positioned at the top of the solar collector. Typically, a single glass layer or multilayer glass bonded by an adhesive is used. The glass exhibits high transmittance of short-wave radiation while blocking long-wave radiation. Glasses with reduced iron content are typically used due to their near-zero long-wave transmittance and high short-wave transmittance. Anti-reflective coatings are applied to the surface of the glass. A solar absorber is a component designed to absorb as much thermal energy as possible. It usually has a black surface to increase the absorption of solar energy. It absorbs short-wave radiation while allowing long-wave radiation through. Copper tubing is used for fluid flow and must exhibit high thermal conductivity. The insulation layer is located at the base of the collector and serves to minimize the heat loss of the solar collector [1–5].

Traditional cement concretes, geopolymer concretes, or polymer concretes allow for the extensive use of waste materials, which often consist of waste that is difficult to reuse and poses a significant environmental problem. Waste materials can replace both aggregates and binders – cement [6] or polymer [7]. The use of waste in concrete production may be beneficial due to minimizing the amount of waste in landfills and limited consumption of natural raw materials (sand, gravel, cement, etc.). Numerous scientific publications describe the use of glass waste [8–11], polymer materials [12–14], rubber [15–17], sanitary ceramics [18], bricks [19], concrete [20–21], or agricultural and organic waste [22–23] in concrete production. Waste materials added to concrete should demonstrate no negative environmental impact or should be efficiently encapsulated within the concrete mass. It is important to conduct intensive aging tests that demonstrate the durability of the material and its tendency to release substances (including hazardous substances) into the environment [24–26].

Polymer concretes are a relatively new group of construction materials compared to traditional cement-based concretes. The development of polymers in the 20th century and the popularization of synthetic polymer resins led to the modification of traditional solutions. Polymer concretes, which replace the cement binder with resins, exhibit a set of favourable properties, often significantly better than those of traditional concrete. Bedi et al., in a review article [27], described polymer concretes as having superior mechanical properties, such as tensile strength and compressive strength. A large part of the research incorporates waste and local aggregates. They noted that epoxy polymer concretes have more favourable properties than polyester polymer concretes and concluded that the addition of fibers to the polymer concrete structure improves strength. Nodehi M., in another review article on polymer concretes [28], identified three basic types: polymer-impregnated, polymer-coated, polymer-modified, and ordinary polymer concretes, which use polymer resin instead of ordinary Portland cement (OPC). The authors also highlighted their higher mechanical properties and significantly better chemical and corrosion resistance compared to traditional cement concrete.

The topic of recycling thermal solar collectors has rarely been described in the literature due to the limited issues related to the management of these wastes. The average usage time of collectors is estimated at several decades, so the current problem with recycling is minimal, but interest is expected to increase in the future as the number of waste solar collectors grows following their end of use. Ardente et al., in their publication [29], discussed the effectiveness of using thermal solar collectors, addressing problems and challenges related to the production and supply of energy and raw materials, production processes, assembly, maintenance, disposal, and transport. They estimate the average product lifetime at 15 years. The novelty of recycling solar glass from thermal solar collectors has motivated further research in this area.

Waste photovoltaic panels and waste thermal solar collectors pose challenges to the current and future environmental situation. One component that constitutes difficult waste is tempered solar glass, which includes additional layers on the surface such as solar radiation-absorbing layers, self-cleaning coatings, and others. Using waste from thermal solar collectors in concrete significantly reduces the volume of this waste in landfills. This article presents an initial study on the mechanical recycling of solar glass and its subsequent use in polymer concretes as a fine aggregate fraction. The research considered the impact of grain size after grinding on the final mechanical properties and investigated the presence of potentially hazardous substances in the grist that could be released into the environment during use. The research has demonstrated that mechanical recycling of glass from thermal solar collectors is feasible and enables the production of polymer concretes with favourable properties. The resulting epoxy polymer concretes, with a 70% volume addition of ground solar glass and 30% resin content, are characterized by high compressive strength (approximately 100–110 MPa) and high flexural strength (approximately 35–40 MPa).

2. Materials and methods

Glass waste from a thermal solar collector was used to produce polymer concrete in the research. The glass was untreated. Solar glass typically has a multi-layered structure, with external anti-reflective coatings characterized by high solar light transmittance (>95%) while minimizing reflectivity. Anti-reflective coatings are produced on an industrial scale using acid etching or sol-gel technologies, including roller-coating or dip-coating. The inner layer of solar glass consists of one or two layers of glass bonded by an adhesive layer. Typical solar glass is tempered glass, composed of silicon dioxide (SiO_2) and calcium oxide (CaO), and is characterized by a reduced iron oxide content. The construction diagram of typical solar glass used for the production of thermal solar collectors is shown in Fig. 2.

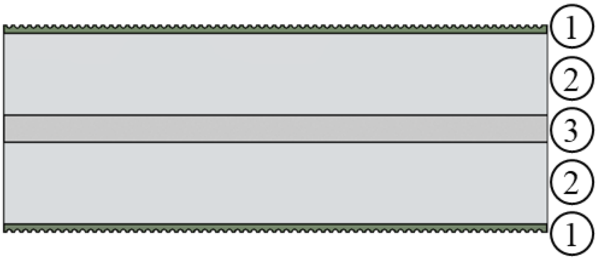


Fig. 2. Scheme of solar collector glass: 1 – anti-reflective coating, 2 – tempered glass, 3 – adhesive layer

Solar glass waste was milled without additional cleaning using a Retsch SK300 cross-beater mill at a rotational speed of 3000 rpm. Milling was carried out using 0.5 mm and 2.0 mm separating sieves. The morphology and chemical composition of the obtained powders were characterized using a Hitachi S-3400N scanning electron microscope with a Thermo Noran X-ray spectrometer (EDS). The test was performed in low vacuum mode without applying additional conductive coatings. The particle size distribution (PSD) was described using the laser diffraction technique with a Mastersizer 3000 particle size analyzer. Ground solar glass was considered as a minor fraction in the production of polymer concretes. For the coarse fraction (gravel), the particle size distribution was determined by sieve analysis using a Multiserw LPzE-2e mechanical shaker.

The dry aggregates were mixed with Havel LH 288 epoxy resin and H505 Hardener (Havel Composites, Czech Republic) in a weight ratio of 100:27, following the designations contained in Table 1. The tests maintained a constant resin volume of 30%. The amount of resin is related to the size of the powders and their surface area, the larger the grains, the smaller the required resin volume. For the materials tested, a resin volume above 30% would constitute an excess, while a volume below 30% would result in the formation of porous polymer concrete. Adding the resin at 30% by volume ensures the tightness of the concrete and accurate reproduction of the shape and dimensions of the moulds. The composition was then homogenised and poured into silicone moulds. Samples were prepared in five series for mechanical testing. For each series, three samples were produced to determine the flexural strength and another three to measure the compressive strength. The sample preparation scheme is shown in Fig. 3. Three-point bending tests and compressive tests were performed on samples measuring 40 x 40 x 160 mm, in accordance with the PN EN 196-1 standard, using the INSTRON 4469 testing machine (tensile strength) and the MTS-810 testing machine (compressive strength).

Table 1. List of samples

Sample	Fine fraction		Coarse fraction	Binder
	solar glass waste < 0.5 mm [vol%]	solar glass waste < 2.0 mm [vol%]	gravel [vol%]	epoxy resin [vol%]
PC_1	-	-	70 %	30 %
PC_2	70 %	-	-	
PC_3	-	70 %	-	
PC_4	35 %	-	35 %	
PC_5	-	35 %	35 %	

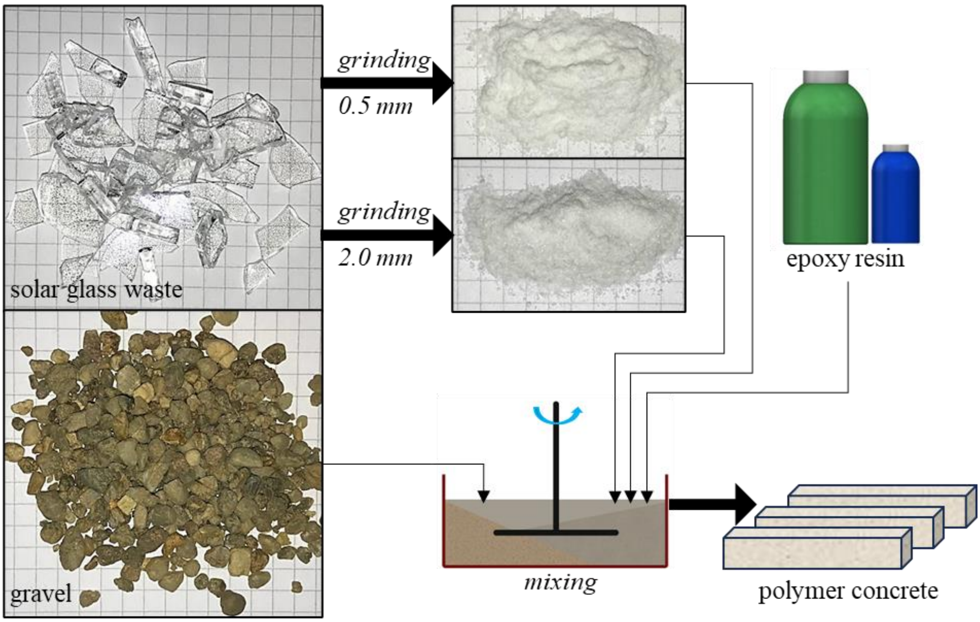


Fig. 3. Scheme of producing polymer concrete samples

3. Results and discussion

Figure 4 presents the results of the particle size distribution (PSD) for solar glass waste and gravel. Solar glass after grinding through 0.5 mm sieves has an average particle size (Dv(90) parameter) of approximately 466 μm, while after grinding through 2.0 mm sieves, the average particle size is approximately 624 μm. During the grinding process in a cross-beater mill, glass particles quickly fragment into powder. Grinding collector glass waste after separation through the smaller (0.5 mm) sieves requires approximately 30% more time than grinding the same mass of waste using 2.0 mm sieves. For economic reasons, it is more advantageous to carry out the grinding process using larger separation sieves. Gravel, which is a coarse fraction used in polymer concrete, consists of over 50% of the 2-4 mm fraction and about 35% of the 4-6 mm fraction. Particles larger than 6 mm constitute less than 10% of the weight.

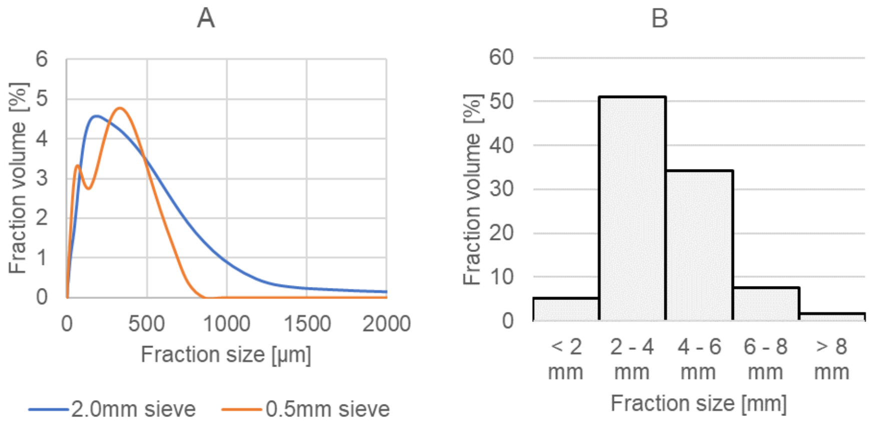
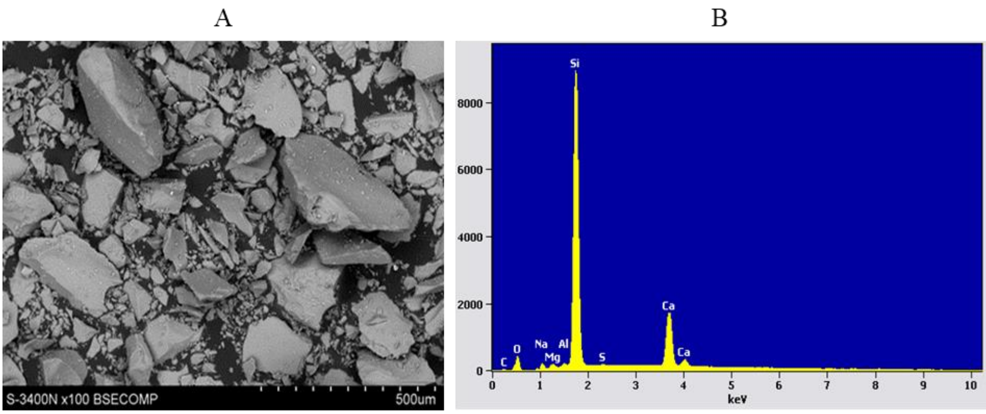


Fig. 4. Grain size distribution (PSD) A) ground solar glass waste, B) gravel

After the grinding process, solar glass waste was inspected using scanning electron microscopy, and its chemical composition (elemental mapping) was assessed, as shown in Fig. 5. The glass particles vary in size from very fine particles below 5 µm to those approximately 500 µm in size. The surface of the glass particles exhibits features typical of brittle materials. No contaminants or materials other than glass were detected in the SEM images. The chemical analysis showed that the solar glass is composed mainly of silicon dioxide (SiO_2) and calcium oxide (CaO). Small amounts of sodium, magnesium, and aluminum, present in the form of oxides, were also detected.



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Element	Weight %	Weight % Error	Atom %	Atom % Error
O	47.1	---	63.1	± 1.5
Na	1.1	± 0.0	1.0	± 0.0
Mg	0.8	± 0.0	0.7	± 0.0
Al	0.2	± 0.0	0.1	± 0.0
Si	34.4	± 0.2	26.3	± 0.1
S	0.3	± 0.0	0.2	± 0.0
Ca	16.1	± 0.2	8.6	± 0.1
Total	100.0		100.0	

Fig. 5. Solar glass waste particles after grinding A) SEM image, B, C) chemical composition analysis

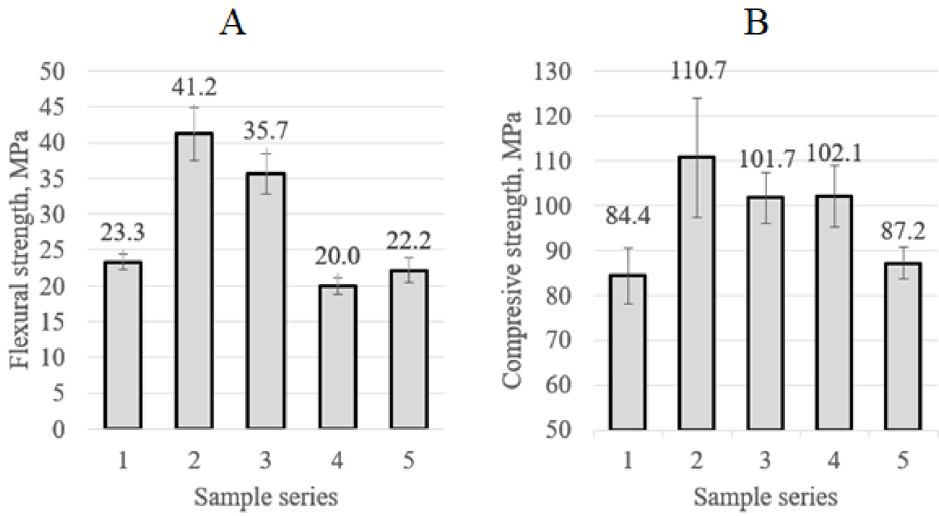

Fig. 6. Mechanical test results of the prepared specimens A) flexural strength test, B) compressive strength test

Based on Fig. 6A, it was observed that Series 2 and 3 achieved the highest flexural strengths of 41.2 MPa and 35.7 MPa, respectively. Series 1, 4, and 5 produced similar results relative to each other (23.3 MPa, 20.0 MPa, and 22.2 MPa respectively), which is almost half the bending strength of Series 2 and 3. Figure 6B indicates that the highest compressive strength was achieved by Series 2 at 110.7 MPa. Lower compressive strengths were recorded for Series 3 and 4, achieving 101.7 MPa and 102.1 MPa, respectively. The lowest compressive strengths were noted in Series 1 (84.4 MPa) and Series 5 (87.2 MPa), approximately 30 MPa lower than Series 2. Figure 7 illustrates the relationship between the compressive strength and the flexural strength of the tested series of polymer concretes. The most favourable results were observed in Series 2 and 3, which did not include the addition of gravel. The series with added gravel showed a similar pattern, where the gravel negatively impacted the correlated values.

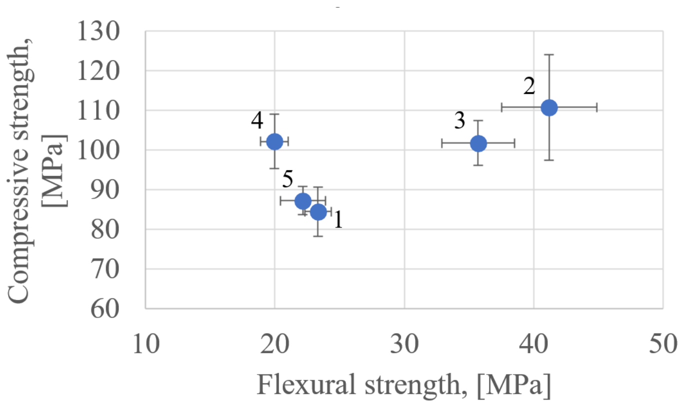

Fig. 7. Graph of the compressive strength - flexural strength relationship

The fracture of sample series 1 (Fig. 8) indicates a strong interfacial bond in the resulting polymer concrete between the filler (gravel) and the matrix (epoxy resin). On the plane of the fracture, it is evident that the fracture did not progress at the resin-gravel interface, but directly through the gravel aggregates, as indicated by the visible multiple destroyed gravel grains.

Fig. 8. Cross-section of a polymer concrete sample at the fracture area

Comparing the results of the flexural and compressive strength tests, the highest strength was achieved by Series 2 and 3, in which the glass from solar thermal collectors served solely as the filler. Among these series, samples containing smaller filler grains displayed superior strength properties. This suggests that using filler in the form of tempered glass with smaller grain sizes increases the contact area of the fillers with the resin matrix, thereby enhancing the integrity and strength of the material. Similar conclusions were reached in the publication by Y. Li et al. [30], although the mechanical strength of the material obtained by their team is approximately 50% lower than that achieved in this study. The compressive strength of the polymer concrete produced with tempered glass is about 25 MPa higher than that of the steel-fibre-reinforced HSC concrete tested by A. A. Shah et al. [31]. Additionally, when comparing the strength of the produced polymer concrete with the HSC concrete produced by T. Drzymała et al. [32], the polymer concrete with collector glass shows a 13.5 MPa higher compressive strength and an almost 35 MPa higher flexural strength.

4. Conclusions

The following conclusions were drawn from the research:

- Milling tempered glass from solar collectors using a cross-beater mill poses no problems. The use of a 0.5 mm mesh separation sieve resulted in a material with an average grain size of approximately 466 µm; with a 2.0 mm mesh separation sieve, the average particle size was 624 µm. For economic reasons, the use of sieves with larger mesh sizes is more justified.

- The workability of mixtures containing ground solar glass is slightly worse than those containing only a coarse fraction of aggregate (gravel), due to the size of the particles used.
- Chemical analysis has shown that tempered glass from solar thermal collectors consists mainly of silicon dioxide (SiO_2), calcium oxide (CaO), and smaller amounts of oxides of sodium (Na_2O), magnesium (MgO), and aluminium (Al_2O_3), and does not contain hazardous compounds.
- Analysis of the crack in the material shows that the interphase connection (between the aggregate and the binder) is satisfactory, and the crack propagates through the aggregates.
- In terms of flexural and compressive strength properties, the most optimal samples are Series 2 and 3, where the filler was solely glass, with different grain sizes. Series 2 specimens with a smaller grain size filler showed higher strength values, indicating that the smaller the grain size of this type of filler, the higher the strength of the material.
- The production of polymer concrete is an effective method of mechanically recycling tempered glass from solar thermal collectors. Moreover, the strength values of such material are higher than those of traditional concrete or, in some cases, reinforced concrete.

Funding

The study was partially financed by the Silesian University of Technology, Faculty of Materials Engineering, within the Statutory Research Projects BK-220/RM3/2023 and BK/RM3/2024.

References

[1] Soteris Kalogirou A., "Solar thermal collectors and applications", *Progress in Energy and Combustion Science*, vol. 30, (2004), pp. 231-295. https://doi.org/10.1016/j.pecs.2004.02.001

[2] Battisti R., Corrado A., "Environmental assessment of solar thermal collectors with integrated water storage", *Journal of Cleaner Production*, vol. 13, (2005), pp. 1295-1300. https://doi.org/10.1016/j.jclepro.2005.05.007

[3] Lamnatou C., Notton G., Chemisana D., Cristofari C., "Life cycle analysis of a building-integrated solar thermal collector, based on embodied energy and embodied carbon methodologies", *Energy and Buildings*, vol. 84, (2014), pp. 378-387. https://doi.org/10.1016/j.enbuild.2014.08.011

[4] Tian Y., Zhao C.Y., "A review of solar collectors and thermal energy storage in solar thermal applications", *Applied Energy*, vol. 104, (2013), pp. 538-553. https://doi.org/10.1016/j.apenergy.2012.11.051

[5] Lamnatou Chr., Motte F., Notton G., Chemisana D., Cristofari C., "Cumulative energy demand and global warming potential of a building-integrated solar thermal system with/without phase change material", *Journal of Environmental Management*, vol. 212, (2018), pp. 301-310. https://doi.org/10.1016/j.jenvman.2018.01.027

[6] Tavakoli D., Hashempour M., Heidari A., "Use of waste materials in concrete: A review", *Pertanika J. Sci. Technol*, vol. 26(2), (2018), pp. 2499-522.

[7] Barbuta M., Rujanu M., Nicuta A., "Characterization of polymer concrete with different wastes additions", *Procedia Technology*, vol. 22, (2016), pp. 407-412. https://doi.org/10.1016/j.protcy.2016.01.069

[8] Shi C., Zheng K., "A review on the use of waste glasses in the production of cement and concrete", *Resources, Conservation and Recycling*, vol. 52(2), (2007), pp. 234-247. https://doi.org/10.1016/j.resconrec.2007.01.013

[9] Jani Y., Hogland W., "Waste glass in the production of cement and concrete–A review", *Journal of Environmental Chemical Engineering*, vol. 2(3), (2014), pp. 1767-1775. https://doi.org/10.1016/j.jece.2014.03.016

[10] Shayan A., Xu A., "Value-added utilisation of waste glass in concrete", *Cement and Concrete Research*, vol. 34(1), (2004), pp. 81-89. https://doi.org/10.1016/S0008-8846(03)00251-5

[11] Shao Y., Lefort T., Moras S., Rodriguez D., "Studies on concrete containing ground waste glass", *Cement and Concrete Research*, vol. 30(1), (2000), pp. 91-100. https://doi.org/10.1016/S0008-8846(99)00213-6

[12] Dawood A. O., Hayder A. K., Falih R. S., "Physical and mechanical properties of concrete containing PET wastes as a partial replacement for fine aggregates", *Case Studies in Construction Materials*, vol. 14, (2021), e00482. https://doi.org/10.1016/j.cscm.2020.e00482

[13] Zehil G. P., Assaad J. J., "Feasibility of concrete mixtures containing cross-linked polyethylene waste materials", *Construction and Building Materials*, vol. 226, (2019), pp. 1-10. https://doi.org/10.1016/j.conbuildmat.2019.07.285

[14] Islam M. J., Shahjalal M., Haque N. M. A., "Mechanical and durability properties of concrete with recycled polypropylene waste plastic as a partial replacement of coarse aggregate", J*ournal of Building Engineering*, vol. 54, (2022), 104597. https://doi.org/10.1016/j.jobe.2022.104597

[15] Li Z., Li F., Li J.S., "Properties of concrete incorporating rubber tyre particles", *Magazine of Concrete Research*, vol. 50(4), (1998), pp. 297-304. https://doi.org/10.1680/macr.1998.50.4.297

[16] Strukar K., Šipoš T. K., Miličević I., Bušić R., "Potential use of rubber as aggregate in structural reinforced concrete element–A review", *Engineering Structures*, vol. 188, (2019), pp. 452-468. https://doi.org/10.1016/j.engstruct.2019.03.031

[17] Siddika A., Al Mamun M. A., Alyousef R., Amran Y. M., Aslani F., Alabduljabbar H., "Properties and utilizations of waste tire rubber in concrete: A review", *Construction and Building Materials*, vol. 224, (2019), pp. 711-731. https://doi.org/10.1016/j.conbuildmat.2019.07.108

[18] Medina C., De Rojas M. S., Frías M., "Reuse of sanitary ceramic wastes as coarse aggregate in eco-efficient concretes", *Cement and Concrete Composites*, vol. 34(1), (2012), pp. 48-54. https://doi.org/10.1016/j.cemconcomp.2011.08.015

[19] Debieb F., Kenai S., "The use of coarse and fine crushed bricks as aggregate in concrete", *Construction and Building Materials*, vol. 22(5), (2008), pp. 886-893. https://doi.org/10.1016/j.conbuildmat.2006.12.013

[20] Topcu I. B., "Physical and mechanical properties of concretes produced with waste concrete", Cement *and Concrete Research*, vol. 27(12), (1997), pp. 1817-1823. https://doi.org/10.1016/S0008-8846(97)00190-7

[21] Topcu I. B., Şengel S., "Properties of concretes produced with waste concrete aggregate", Cement *and Concrete Research*, vol. 34(8), (2004), pp. 1307-1312. https://doi.org/10.1016/j.cemconres.2003.12.019

[22] Shafigh P., Mahmud H. B., Jumaat M. Z., Zargar M., "Agricultural wastes as aggregate in concrete mixtures–A review", C*onstruction and Building Materials* 2014, vol. 53, (2014), pp. 110-117. https://doi.org/10.1016/j.conbuildmat.2013.11.074

[23] Mannan M. A., Ganapathy C., "Concrete from an agricultural waste-oil palm shell (OPS)", *Building and Environment*, vol. 39(4), (2004), pp. 441-448. https://doi.org/10.1016/j.buildenv.2003.10.007

[24] Kusuma G. H., Budidarmawan J., Susilowati A., "Impact of concrete quality on sustainability", *Procedia Engineering* 2015, vol. 125, (2015), pp. 754-759. https://doi.org/10.1016/j.proeng.2015.11.122

[25] Bandow N., Gartiser S., Ilvonen O., Schoknecht U., "Evaluation of the impact of construction products on the environment by leaching of possibly hazardous substances", *Environmental Sciences Europe*, vol. 30(1), (2018), pp. 1-12. https://doi.org/10.1186/s12302-018-0144-2

[26] Togerö Å., "Leaching of hazardous substances from additives and admixtures in concrete", *Environmental Engineering Science*, vol. 23(1), (2006), pp. 102-117. https://doi.org/10.1089/ees.2006.23.102

[27] Bedi R., Chandra R., Singh S. P.. "Mechanical properties of polymer concrete", *Journal of Composites*, vol. 13, (2013), 1-12. https://doi.org/10.1155/2013/948745

[28] Nodehi M., "Epoxy, polyester and vinyl ester based polymer concrete: a review", *Innovative Infrastructure Solutions*, 7(1), (2022), 64. https://doi.org/10.1007/s41062-021-00661-3

[29] Ardente F., Beccali G., Cellura M., Brano V. L., "Life cycle assessment of a solar thermal collector", *Renewable Energy*, 30(7), (2005), 1031-1054. https://doi.org/10.1016/j.renene.2004.09.009

[30] Li Y., Zhang J., Cao Y., Hu Q., Guo X., "Design and evaluation of light-transmitting concrete (LTC) using waste tempered glass: A novel concrete for future photovoltaic road", *Construction and Building Materials* 2021, vol. 280, (2021), 122551. https://doi.org/10.1016/j.conbuildmat.2021.122551

[31] Shah A. A., Ribakov Y., "Recent trends in steel fibered high-strength concrete", *Materials & Design*, vol. 32(8-9), (2011), pp. 4122-4151. https://doi.org/10.1016/j.matdes.2011.03.030

[32] Drzymała T., Jackiewicz-Rek W., Gałaj J., Šukys R., "Assessment of mechanical properties of high strength concrete (HSC) after exposure to high temperature", *Journal of Civil Engineering and Management*, vol. 24(2), (2018), pp. 138-144. https://doi.org/10.3846/jcem.2018.457