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Research paper

Analysis of the life cycle concrete with the addition of polypropylene fibers

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Abstract: In accordance with the principles of sustainable construction, the results of Life Cycle Assessment (LCA) technique are useful inputs to the decision-making process when designing a building. This article presents such an analysis of a finished building product, which is a modified concrete mix. The calculations took into account the phases of the A1–A4 cycle, i.e. from the extraction of raw materials to the transport of the finished material to the construction site. Test results for concrete mixes and 28-day solid concrete are presented in tabular form. Based on all the test results obtained, it was found that the addition of waste polypropylene fibres has a positive effect on the key properties for the floor concrete. It has been found that proper processing of banding tapes or other polypropylene waste into macro-fibres can be a good example of proper waste management and can contribute to a significant reduction in residual waste. This additive is emission-free and sourced from recycling, making it an excellent alternative to commonly used dispersed reinforcement.

Keywords: Life Cycle Assessment method, modified concrete, recycling, sustainable construction

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1. Introduction

In recent years, addressing the threats of climate change and environmental degradation has become a key policy element in Europe and the rest of the world. As part of work against these issues, "The European Green Deal Action" action plan was created to transform the economies of the European Union countries into a modern, resource-efficient and sustainable. According to recent reports, the building ecosystem generated nearly 10% of the value-added and building materials industry in the EU is worth more than 800 billion euros. It is associated with the extraction and consumption of nearly 50% of raw materials each year, and construction waste accounts for more than 30% of all waste generated in the EU each year.

In previous year, the production of ready-mixed concrete in Europe reached the level of 250 million m^3, and only in Poland in 2021, 26.5 million m^3 of concrete was produced, what placing it in 4th place in the EU, behind France, Germany and Italy. In Poland works over the 1 100 concrete plants operate with a fleet of nearly 3 200 concrete mixers, what generate over 20 000 jobs. In national regulations ready-mixed concrete has gained the formal status of a construction product, and its producers have been obligatorily obliged to implement and operate the Factory Production Control (FPC) system, prepare a national declaration of performance and proper marking of the construction product with the construction mark. All these activities are aimed at controlling the quality of a product that effectively meets the basic requirements of a design for reliability, durability, safety and environmental impact throughout its life cycle.

Since the beginning of this year, the European Commission has been working on legal amendments aimed at the transition of member states to a circular economy, which include a proposal to amend the regulation on construction products no 305/2011 of 9 March 2011 establishing harmonized conditions for the marketing of construction products. According to the proposed changes, manufacturers will be required to provide environmental information about the life cycle of their products. In addition, they will have to fulfil a number of obligations, including comply with obligations regarding the use of a minimum content of recycled materials. The proposed changes are to gradually cover an increasing number of manufactured products, and in the future perhaps also ready-mixed concrete. The implementation of subsequent regulations and standardization is related to the idea of sustainable construction based on environmental issues and climate neutrality [1, 2].

The purpose of the study was to analysis of the structure made of concrete modified with the addition of polypropylene fibers on the environment, throughout its life, from the extraction of raw materials to its demolition with subsequent disposal or reuse. According to the above, the research included design concrete with the addition of polypropylene fibers, to determine the effect of polypropylene fibers on the properties of fresh concrete mix and hardened.

Responsibility for upward of 5% of anthropogenic greenhouse gas emissions is for the cement industry to bear as its main building material nowadays [3–6]. The largest source of carbon dioxide emissions (around 50%) is CO_2, which comes during lime formation in the limestone heating and decarbonizing process, including all phases, namely raw material preheating, calcination, clinker burning and clinker cooling [7–9]. As the cement production process is highly energy demanding, a large amount of fuel is burned irreversibly.

Fuel emissions account for 40% of total CO_2 from the cement manufacturing process. Therefore, both cement substitutes [10–13] and alternative sources of energy [14–17] that can be used in concrete and cement production are sought, as presented in the current research. Furthermore, the building sector is consuming huge amounts of energy, as existing buildings need electricity and heating and cooling systems [18–21]. In China only, energy use for buildings is responsible for 5% of global energy-related emissions [22]. Thus, it is necessary to seek environmentally friendly solutions able to reduce the negative impact on the environment by the building sector. In this study, new construction material is proposed as a partial solution that may contribute to reducing environmental damage caused by the construction industry, as it contains fibers derived from wastes.

A wide range of recycled fibers available on the market, e.g., steel, glass and polypropylene, can be used not only as distributed reinforcement [23, 24]. Most studies focus on achieving higher mechanical properties of hardened concrete, such as compressive strength, flexural strength and split tensile strength, as they are crucial for construction sustainability [25]. In the conducted research described in this article, concrete has been designed in four variants, which differ in the amount of the addition in the form of polypropylene fibers. The first variant W1 was modified with 2.22 kg/m^3, the second variant W2 contained the addition of 4.45 kg/m^3, and the third variant W3 – 6.66 kg/m^3. The last, fourth variant were reference samples that were not modified in any way and constituted a reference point for evaluating the results. Prior to the preparation of standardized samples, consistency tests were carried out using the cone drop method and air content in the concrete mix using a porosimeter. After 28 days, when the concrete gained full strength, volumetric densities, values of the modulus of elasticity, thermal properties were determined and strength tests were carried out during which the compressive strength, tensile strength in bending and tensile strength in splitting were determined.

This research explores physical characteristics of the polypropylene fibers. In addition, this study aims to review the literature that discusses the use of recycled polypropylene fibers in concrete as a partial or complete alternative to aggregates by focusing on the effect of this waste on the fresh and mechanical properties of concrete in order to demonstrate the possibilities of using recycled polypropylene fibers in concrete and to provide practical and brief guidance. Furthermore, it is establishing a foundation for future study on this material and describing research insights, existing gaps, and future research goals.

2. Description of the Life Cycle Assessment method on the practical example

In accordance with the principles of sustainable construction, the results of an LCA (Life Cycle Assessment) can be a useful input into the building planning decision-making process. The purpose of this approach is to assess the potential harm to the environment from the use of certain building materials, taking into account the full life cycle from raw material extraction to production, use, demolition and recycling options.

The LCA method has been standardized based on European rules and requirements in two main standards [26]:

– ISO 14040:2006/ 1:2020 "Environmental management – Life cycle assessment – Principles and framework".
– ISO 14044:2006/ 2:2020 "Environmental management – Life cycle assessment – Requirements and guidelines".

The ISO 14040 standard specifies the assumptions from which the life cycle assessment should consist, they are four main phases: definition of the goal and scope definition, inventory analysis, impact assessment and interpretation of the results. The standard specifies possible applications of the method in the development and improvement of the product, strategic planning, creating social policy or for marketing purposes. LCA method phases (Fig. 1):

1. Goal of the study and scope definition – The goal of an LCA study shall unambiguously state the intended application, the reasons for carrying out the study and the intended audience. In defining the scope of an LCA study, shall be clearly described research methodology, product functions and types of impact assessment.
2. Life cycle inventory analysis – Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. These inputs and outputs, may include the use of resources and releases to air, water and land associated with the system. The qualitative and quantitative data for inclusion in the inventory shall be collected for each unit process that is included within the system boundaries.
3. Life cycle impact assessment – The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis. In general, this process involves associating inventory data with specific environmental impacts and attempting to understand those impacts. The impact assessment phase include elements such as, classification and characterization of inventory data to impact categories.
4. Interpretation – Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are combined together, consistent with the defined goal and scope in order to reach conclusions and recommendations. The findings of this interpretation may take the form of conclusions and recommendations to decision-makers, consistent with the goal and scope of the study. The interpretation phase may involve the detecting high-risk elements, analysing the sensitive aspects and how that minimalized.

The time division of the product or building life cycle is described in EN 15804:2012 standard "Sustainability of construction works – Environmental product declarations" [27], which is related to the European standard EN 15643-1 "Sustainability of construction works – Sustainability assessment of buildings" [28]. Producers of building materials are required to perform LCA of the product in the scope of A1–A3 modules, i.e. raw material supply, transport, manufacturing and related processes (Fig. 2). The information provided relates mainly to the carbon footprint and the amount of energy used during production.

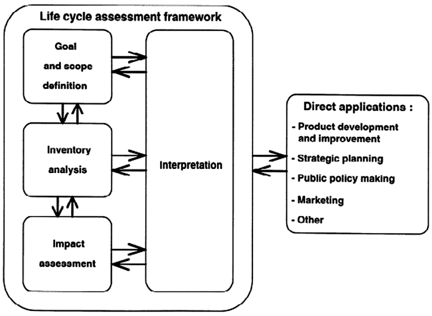

Fig. 1. Phases of an LCA [26]

Building Life Cycle Information "cradle to grave"														
Product Stage			Construction Process Stage		Use Stage					End Of Life Stage			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4
Raw material supply	Transport	Manufacturing	Transport	Construction-installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction demolition	Transport	Waste processing	Disposal
					B6 Operational energy use								
					B7 Operational water use								

Fig. 2. LCA “cradle to grave” stages [28]

2.1. Goal of the study and scope uses of concrete

The first focus of product life cycle analysis is to identify areas of use for design materials and to establish research methods to collect the necessary data. The subject of the analysis is concrete mixes for floors and subfloors. Strength tests are conducted to confirm the correct design of a compound that meets the requirements of such components and to determine the durability of the material.

Floor concrete should consist of low shrinkage concrete. Minimum concrete grade should be set to C20/25 for inner surfaces and C30/37 for outer surfaces. Selection of the appropriate grade aims to ensure the required watertight and frost resistance. Sufficiently low shrinkage guarantees reduction of undesirable cracks on properly laid concrete. When making concrete recipe, it is important to choosing the right cement. Recommended cement types are Portland CEM Group I (usually grade 32.5), especially during low temperature periods, and CEM Group III/A cements, which are more resistant to chemical attack.

Another important element of the mixture is the selection of the appropriate aggregate. In the case of floors concrete with the required high abrasion resistance, it is advantageous to use crushed rock, e.g. basalt. Sand should consist of gritty, hard particles free from dust, clay and animal, vegetable or other organic matter. It is also important that the fraction content up to 0.125 mm does not exceed 5% and that the sand point does not exceed 30–40%.

Too much fines will increase the water desires of the crumb pile, resulting in the addition of a large amount of fluidizing admixture to obtain the desired consistency.

Often, floor concretes are reinforced not with traditional wire mesh but with the addition of dispersed steel fibres. Due to the even distribution in the mass of concrete, the minimum amount of fibres used should be 20 kg/m^3, but their exact amount should be determined by the constructor. Increasingly, steel fibres are being replaced with polypropylene fibres that better reduce shrinkage cracks, which can be used in much smaller amounts. However, dispersed reinforcement compacts the concrete mass, so it will be required to add more fluidizing admixture [29, 30].

For the research in question, a mixture was designed that meets the requirements of the exposure classes:

XC3 – Corrosion induced by carbonation.

XD2 – Corrosion induced by chlorides.

XF3 – Freeze/Thaw attack.

XA2 – Chemical attack.

XM2 – Attrition.

The requirements resulting from the exposure classes define the maximum water-cement ratio (w/c) equal to 0.50, the minimum cement content of 320 kg/m^3, the minimum concrete class C30/37 and the aeration at least 4% [31].

Designing the composition of the concrete mix began with the adoption of initial assumptions resulting from exposure classes and requirements for concrete according to PN-EN 206:2013 for previously adopted conditions of use [31].

Table 1 shows the design assumptions for the concrete mix.

Table 1. Design assumptions for the concrete mix

1	2	3
Exposure class	XF3, XM2, XA2, XD2, XC3	–
Minimum strength class	C 30/37	–
Maximum W/C	0.50	–
Minimum cement content	320	[kg/m^3]
Minimum air content	≥ 5.5% or option without aeration for consistency V0 and W/C ≤ 0.40	[%]
Consistency class	dense plastic consistency	–
Strength class	C 30/37	–
Characteristic strength f_{ck}	37	[MPa]

Then, based on the sieve analysis for aggregate, sand 0–2 mm (Pp_1 = 98.34%) and basalt 2–8 mm (Pp_2 = 1.77%), a preliminary sand point was assumed Pp = 30% based on the minimum cement content (320 kg/m^3) and the approximate mortar content in 1m^3 of the mix equal to 500 dm^3/m^3 resulting from the type of construction and the use of aggregate up to 16 mm [32].

The next step was to determine the crumb pile of the aggregate mix and to prepare the grading curve (Fig. 3).

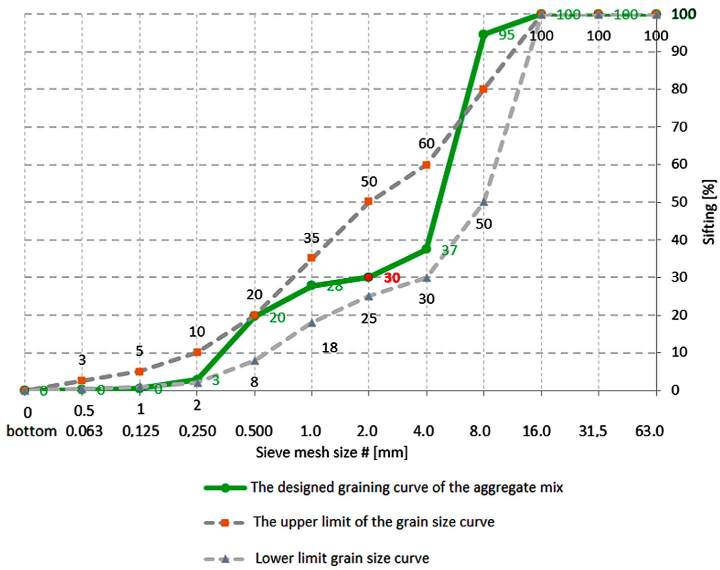

Fig. 3. Graining curve of the aggregate mixture – sand 0–2 and basalt 2–8

Table 2 shows the concrete mix recipe.

Table 2. Concrete mix recipe

Concrete Mix Recipe per m^3			
Aggregate ($K1 + K2$)	$K = 1000/[(W_k/(1 - W_c \times \omega)) \times (\omega/\rho_c + 1) + (1/\rho_k)] =$	2048	[kg/m^3]
Water	$W = [W_k/(1 - W_c \times \omega)] \cdot K =$	176	[kg/m^3]
Cement	$C = W \times \omega =$	367	[kg/m^3]
Fine aggregate (K1) Sand 0–2	$K1 = K \times (K1/K) =$	599	[kg/m^3]
Coarse aggregate (K2) Basalt 2–8	$K2 = K \times (K2/K) =$	1449	[kg/m^3]
Air volume		55	[dm^3]
Bulk density of concrete mix ρ	$\rho = C + K1 + K2 + W =$	2591	[kg/m^3]

The preparation of the mix began with the conversion of the amount of ingredients into 0.045 m^3, in order to improve the consistency of the mix, the designed recipe was enriched with the addition of Atlas DURUFLOW PE-531 fluidizing admixture (plasticizer) in the amount of 0.4% of the cement volume.

Concrete admixtures are defined in the PN-EN 9342 standard "Admixtures for concrete grout and mortar" [33] as a material added during the preparation of the concrete mix, in an amount not exceeding 5% of the mass of cement in the concrete, in order to modify the properties of the concrete mix or hardened concrete. Their use allows you to influence the amount of water in the mixture, the content of pores, speed up or slow down the setting time. An admixture that affects several properties of a mixture is called a complex admixture.

When making the concrete mix, as indicated above, a water-reducing and fluidizing admixture was used to produce Atlas DURUFLOW PE-531 prefabricated and ready-mix concrete. The manufacturer provides such admixture properties as:

- effective fluidization of the concrete mix while maintaining a low water-cement ratio,
- no agents retarding setting,
- increasing the early and final strength of concrete,
- improvement of the binder hydration level,
- facilitating the production of concrete with high water resistance and frost resistance,
- facilitating the pumping, spreading and compaction of the concrete mix,
- not affecting the corrosion of the reinforcement.

It is recommended to dose the admixture in the amount of 0.2–1.5% of the mass of cement in the mix.

Table 3 shows the working recipe.

Table 3. The working recipe

	1	2	3
	Material	a sample [kg]	1 m^3 [kg]
1	Basalt 2/8	65.220	1499.00
2	Sand 0/2	26.950	599.00
3	Cement CEM I 52.5 R	16.500	367.00
4	Water	7.920	176.00
5	Admixture 0.04%	0.066	1.47
6.1	Fibers 2.2 kg/m^3	0.100	2.20
6.2	Fibers 4.4 kg/m^3	0.200	4.40
6.3	Fibers 6.6 kg/m^3	0.300	6.60

All designed mixtures were based on Portland cement, which was CEM I 52.5R, in accordance with EN 197-1:2012 [34], and tap water. Chemical composition of cement and its physical and strength properties were determined according to EN 196-6:2019-01 [35] and PN EN 196-1:2016-07 [36].

2.2. Phase II: Life cycle inventory analysis

The inventory analysis consists of concrete components, i.e. Portland cement, a mixture of sand and basalt aggregates with a maximum grain size of 8 mm, water and the addition of polypropylene fibres made of banding tapes (Fig. 4). A reference mixture was prepared and modified 3 times by adding fibres at 2.2 kg/m^3, 4.4 kg/m^3 and 6.6 kg/m^3. The outputs of a concrete product is emission of carbon dioxides and aggregate which can be obtained from the recycling process.

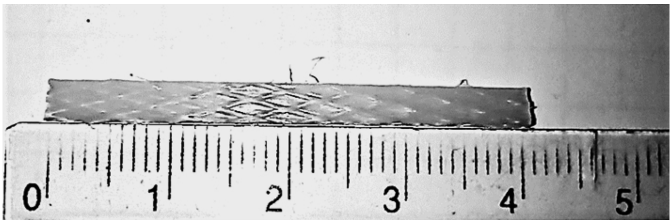

Fig. 4. Polypropylene recycled fiber

2.3. Phase III : Life cycle impact assessment

One of the elements of product analysis is the Life Cycle Impact Assessment (LCIA) on predefined categories and the determination of the degree of such impact. There are 3 most important divisions into categories:

– environmental impact, e.g. greenhouse effect, acidification, eutrophication,
– effects on human health, e.g. carcinogens,
– consumption of raw materials, e.g. consumption of energy and materials.

The choice of individual categories depends on the type of the tested product and the previously chosen test objective.

During the analyses, particular attention was paid to determining the impact of concrete production on negative environmental aspects, mainly related to the production of cement as the most emissive material. The high carbon dioxide (CO_2) emission of cement results from the chemical processes that take place during the production of the material. Portland cement consists mainly of calcium silicates obtained by calcining and sintering a mixture of calcium and aluminosilicates at high temperatures over 1450°C.

By sintering the clinker, calcium is broken down into calcium oxide and carbon dioxide, the emissions of which cannot be eliminated [37].

$$CaCO_3 = CaO + CO_2, \quad \Delta H = 163.7 \text{ kJ} \tag{2.1}$$

where: ΔH – the amount of heat energy consumed.

The development of technology and the use of a greater number of alternative energy sources may reduce the emissions resulting from the production process. Another method is to reduce the clinker content of the cement by replacing it with fly ash, blast furnace slag or lime flour. These additives are of waste origin, therefore the only source of their emission is their transport to the cement plant.

The measure of the emissivity during the entire life cycle of a product is its carbon footprint, a concept defined in the ISO 14067 standard [38] as the sum of greenhouse gases emitted and absorbed by a product expressed in CO_2e equivalent. The carbon footprint therefore includes not only CO_2 emissions, but also other gases such as N_2O (nitrogen oxide) or CH_4 (methane). The main source of greenhouse gas emissions is the combustion of fossil fuels to produce the energy necessary for production processes. For example, the emission from coal combustion is > 1.0 kg CO_2 e/kWh, therefore it is more environmentally friendly to use alternative fuels. The transport of raw materials and finished products is also a noteworthy factor, because the consumption of a 1 l of gasoline emits an average of about 2.3 kg of CO_2.

The paper determined the carbon footprint based on statistical data and a calculator created by the consulting company Circular ecology [39], taking into account the number of specific components of concrete, the assumed potential emissivity of cement, the type of concrete produced and the average accepted route of transport of the finished mixture to the construction site equal to 50 km. The obtained results show an emissivity of 1 m^3 of the designed concrete at the level of 452 kg CO_2e, of which almost 90% is emissions related to the used in a mixture with cement (Figs. 5 and 6). The data are comparable to numerous literary studies [40].

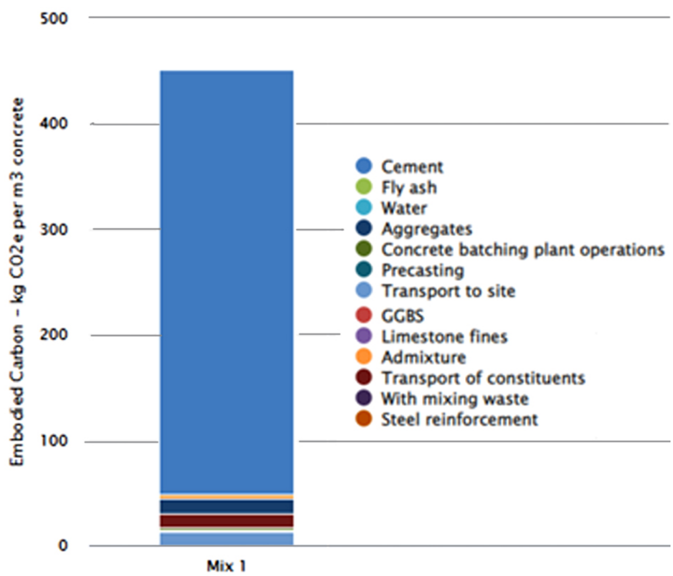

Fig. 5. Embodied carbon of concrete

Concrete calculations - Embodied Carbon Contribution - kg CO2e / m3 concrete

	Mix 1	Mix 1
Material	**Mix 1**	**Mix 1**
Cement	403.4	89.2%
GGBS	0.0	0.0%
Fly ash	0.0	0.0%
Limestone fines	0.0	0.0%
Water	0.1	0.0%
Admixture	4.0	0.9%
Aggregates	15.3	3.4%
Transport of constituents	12.9	2.9%
Concrete batching plant operations	1.9	0.4%
With mixing waste	2.18	0.5%
Precasting	0.0	0.0%
Steel reinforcement	0.0	0.0%
Transport to site	12.5	2.8%
RESULTS - kg CO2e / m3 concrete	**452**	
RESULTS - kg CO2e / kg concrete	**0.174**	

Fig. 6. Summary of the carbon footprint of concrete

2.4. Phase IV: Interpretation

Taking into account all the obtained results, the addition of polypropylene fibres of waste origin has a positive effect on the key properties for the floor be-tone. Proper conversion of banding tapes or other PP waste into macrofibres can be an excellent example of proper waste management and contribute to a significant reduction in residual waste. This additive is emission-free, recycled and can be an excellent alternative to the commonly used distributed reinforcement.

3. Results

The aim of the research was to analyse the life cycle of concrete with a waste additive in the form of polypropylene fibres as a finished construction product. The test cycle consists of tests of the mixture and 28-day-hardened concrete, on the basis of which the product life cycle was analysed, and the results obtained were designed to verify the effect of additives on the durability of the material throughout its life cycle [41]. The results of strength tests of concrete samples [42–45] are presented below (Figs. 7– 14) and Table 4.

(a) (b)

Fig. 7. Failure after compressive strength test for reference sample (a) and modified 6.6 kg/m^3 fiber sample (b)

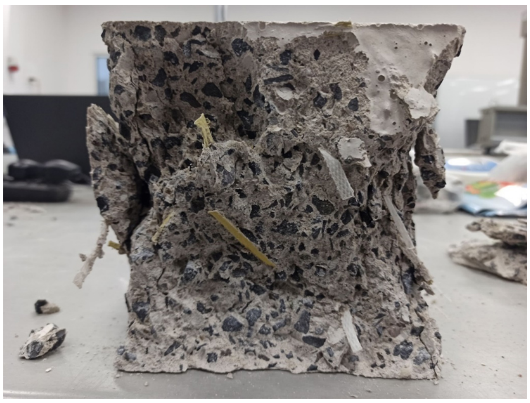

Fig. 8. Complete failure of a sample containing 4.4 kg/m^3 fibers after compressive strength test

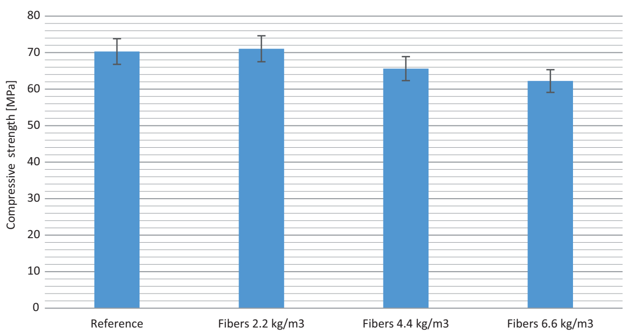

Fig. 9. Compressive strength of concrete depending on polypropylene fibre content

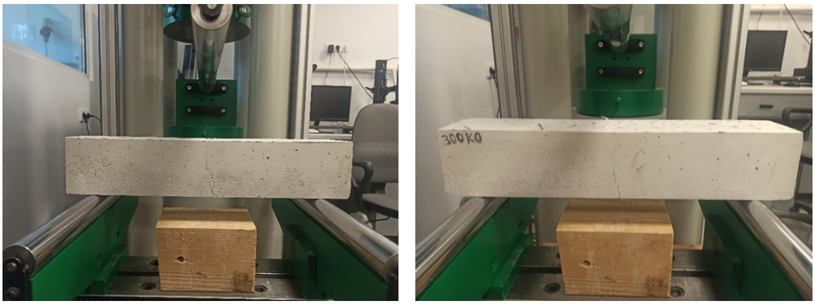

Fig. 10. Failure of a beam made of 2.2 kg/m^3 modified concrete and 6.6 kg/m^3 of fibers after tensile and compression tests

Fig. 11. Comparison of cracks formed on the beam after the flexural tensile strength test

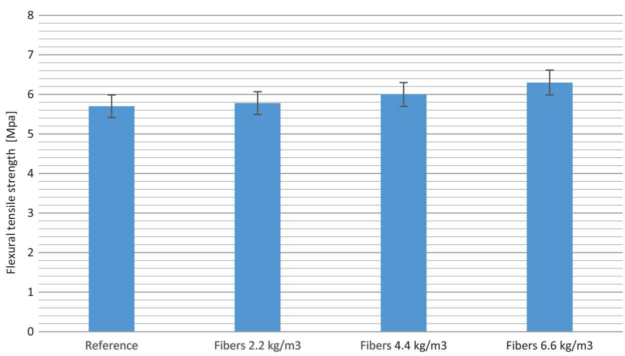

Fig. 12. Flexural tensile strength of concrete depending on the content of polypropylene fibers

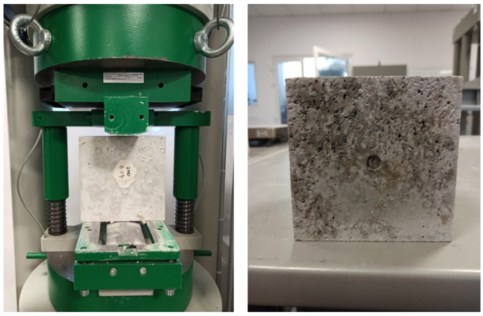

Fig. 13. A sample of 4.4 kg/m^3 fibers before and after failure in the splitting tensile strength test

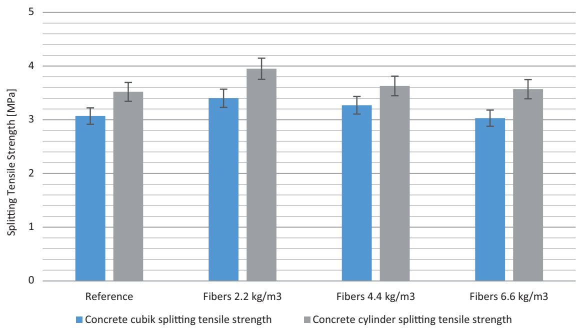

Fig. 14. Tensile strength of concrete at splitting depending on the content of polypropylene fibers

Table 4. Summary of test results of samples depending on the content of polypropylene fibers

Type	Destructive Force F [kN]	Breaking stress f_{ci} [MPa]	Average compressive strength f_{cm} [MPa]	Deviation standard [MPa]	Measurement uncertainty [MPa]	Measurement uncertainty [MPa]
Reference	1533.6	68.2	70.30	1.84	5.59	64.71–75.89
	1612.1	71.6				
	1600.7	71.1				
Fibers 2.2 kg/m^3	1628.4	72.4	71.07	1.53	4.65	66.42–75.72
	1605.4	71.4				
	1562.1	69.4				
Fibers 4.4 kg/m^3	1490.9	66.3	65.63	0.95	2.88	62.75–68.51
	1523	67.7				
	1481.9	65.9				
Fibers 6.6 kg/m^3	1414.4	62.9	62.23	1.33	4.05	58.18–66.28
	1366.1	60.7				
	1418.8	63.1				

4. Discussion

Concrete design began with determining the goals and scope of material use. It was assumed that it will be the floor concrete used for external and internal surface exposed to a high risk of abrasion and work in a wet environment and subjected to low temperatures. In order to meet these exposition requirements, the recipe of the concrete mixture was based on crushed aggregate with low abrasion – basalt, sand and high-strength cement CEM I class 52.5 R. To limit shrinkage cracks that are not recommended for screed concrete, additives in the form of polypropylene fibres are used in amounts of 2.2 kg/m^3, 4.4 kg/m^3 and 6.6 kg/m^3. Despite the addition plasticizer of 0.4% volume of cement, the consistency of the mixture was measured as S1 [44], with a maximum cone slump of 29 mm for the reference mixture. For the modified mixture with the largest amount of fibre, the cone fall reduced to 18 mm. For better workability, the blend should be more liquid. According to the requirements of frost-resistant concrete, measurements using a porosimeter showed a porosity of approximately 5% per modification [45].

An important element in the assessment of the life cycle of the material is its durability, in the study this feature was interpreted on the basis of concrete strength tests after 28 days of maturation. The highest compressive strength was recorded for the modified samples, 2.2 kg/m^3 of fibres, this value was over 71 MPa (C55/67), but the addition of more fibres caused the strength to drop to 65 and 62 MPa.

The gradual increase in strength along with the addition of more fibres was observed in the tensile strength tests. In this study, the reference samples showed a strength of 5.7 MPa, and a modification of 6.6 kg/m^3 of fibres was 6.30 MPa. In addition, the samples containing the fibres showed reduced scratching in the tensile zone and a more dense structure. In the split tensile strength test, the addition of fibres improved the properties of the concrete. Analysing the obtained results, the addition of fibres has a positive effect on improving the durability of concrete.

Below, the current state of knowledge regarding concretes with polypropylene fibers and the amount of polypropylene fibers used in concrete is reviewed [46–51].

The compressive strength of a fiber is highly dependent on the amount used. Figure 15 shows the effect on the compressive strength of different mix designs depending on the fiber percentage.

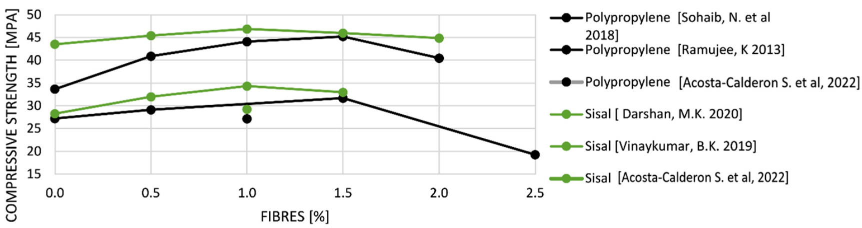

Fig. 15. Impact in the compression strength of different mix designs according to the fiber percentages [46–51]

The addition of natural sisal and polypropylene fibres improved the tensile strength depending on the amount of fibres (Fig. 16).

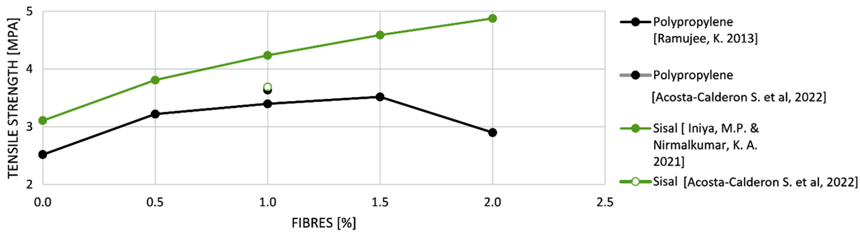

Fig. 16. Impact in the tensile strength of different mix designs according to the fiber percentages [46–51]

When assessing the life cycle of concrete, the key factor is to assess the environmental impact of the concrete produced. Taking into account the data provided by the producers of the materials used in the mixture and the statistical data, the emissivity of the designed concrete was determined at the level of 452 kg CO_2e/m^3. The calculations took into account the phases of the A1–A4 cycle, i.e. from the extraction of raw materials to the transport of the finished material to the construction site.

The research currently conducted by many researchers on the Life Cycle Analysis of concrete with admixtures in the form of waste materials confirms their wide application [52–54]. Badino V. et al. [52] states that the critical point in the analysis of recycled materials is the energy content of secondary materials; this case study of the use of LCA in the automotive industry is a good example of assessing the importance of this tipping point and triggering a discussion on the energy value of scrap.

Ahmad Z., et al. [55] in the research showed that fibrous materials have a better impact on the mechanical efficiency of e-waste concrete. The incorporation of 0.5% dosage of PPF, as by volume fraction, in concrete, resulted in an increment in flexural strength and splitting tensile strength (STS) values of about 42% and 78%, respectively. However, the permeability-based durability parameters (sorptivity coefficient, chloride penetration, and porosity) are inversely influenced by an enhanced dosage of PPF.

Moreover the LCA results in the research of Yin S, et. al. [56] show that industrial recycled PP fibre offers important environmental benefits over virgin PP fibre. Specifically, the industrial recycled PP fibre can save 50% of CO_2 equivalent, 65% of PO_4 equivalent, 29% of water and 78% of oil equivalent, compared to the virgin PP fibre.

Interpreting the obtained results, it can be stated that the fibres have a positive influence on the durability and other parameters of concrete throughout its life cycle. This additive can be an excellent form of a good waste management environment [57, 58].

5. Summary and directions for further actions

In further research, the authors will focus on testing the durability of the resulting composite and, above all, documenting that it is suitable for construction use by meeting environmental standards, including frost resistance, algae growth resistance, resistance to

UV radiation, thermal shock. Thanks to such information, the authors will fully confirm the suitability of this type of composites for general construction applications. Based on the available literature and required standards, these studies are long-term and require a number of samples to be compared with results obtained by other researchers in the discipline [59, 60].

The improvements to consider regarding the methodology in the future are:
- confirmation of the origin of the polypropylene fibers,
- considering adding more polypropylene fibers in favor of a weaker type of cement, e.g. metallurgical, to reduce the CO_2 footprint
- the possibility of using chemical additives to modify the physical properties of composites, e.g. increasing the strength between cement and polypropylene fibers aggregate or accelerating or slowing down the hydration reaction.

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Analiza cyklu życia betonu z dodatkiem odpadowym w postaci włókien polipropylenowych

Słowa kluczowe: cykl życia, metoda LCA, beton zmodyfikowany, recykling, budownictwo zrównoważone

Streszczenie:

Zgodnie z zasadami rozwoju zrównoważonego budownictwa przy projektowaniu obiektów budowlanych, użytecznymi danymi wejściowymi do podjęcia procesów decyzyjnych są wyniki analizy cyklu życia LCA. W artykule dokonano takiej analizy na gotowym wyrobie budowlanym, jakim jest zmodyfikowana mieszanka betonowa. W obliczeniach uwzględniono fazy cyklu A1–A4, czyli od wydobycia surowców do transportu gotowego materiału na plac budowy. W formie tabelarycznej przedstawiono wyniki badań dla mieszanki betonowej oraz dojrzałego betonu. Na podstawie wszystkich otrzymanych wyników badań stwierdzono, iż dodatek włókien polipropylenowych pochodzenia odpadowego pozytywnie wpływa na właściwości kluczowe dla betonu posadzkowego. Zauważono, iż odpowiednie przerobienie taśm bandujacych lub innych odpadów polipropylenowych na makrowłókna może stanowić doskonały przykład prawidłowej gospodarki odpadami i przyczynić się do znacznego ograniczenia zalegających śmieci, dodatek ten jest nieemisyjny, pochodzący z recyklingu i może stanowić doskonałą alternatywę dla powszechnie używanego zbrojenia rozproszonego.

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