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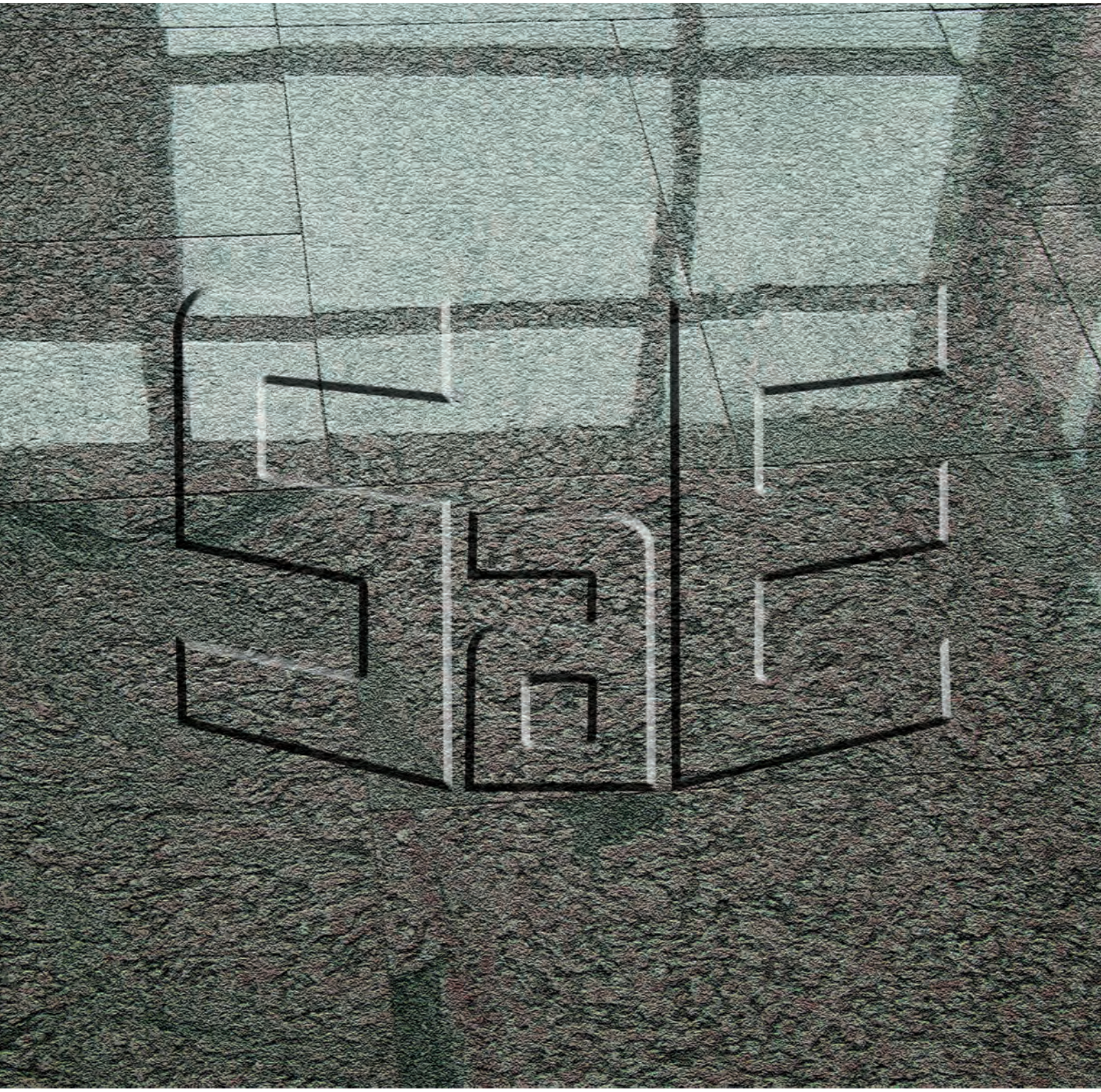

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SELECTED PROPERTIES OF POLYMER-MODIFIED BITUMENS

WYBRANE WŁAŚCIWOŚCI ASFALTÓW MODYFIKOWANYCH POLIMERAMI

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Abstract

The article presents an analysis of research results on bitumens modified with waste polymers polypropylene (PP) and polyethylene terephthalate (PET). The bitumens were modified under conditions consistent with the Plackett-Burman experimental design by appropriately selecting the mixing process variables. The results of basic tests are presented. The microstructure of bitumens modified with waste polymers was compared with two commercially available bitumens modified with styrene-butadiene-styrene (SBS) copolymer. The analysis of test results revealed certain similarities between laboratory-prepared bitumens and PmB 45/80-55. Modification of road bitumens 20/30 and 70/100 resulted in improvement particularly in the softening point temperature range. Furthermore, modification of certain binder parameters without changing its consistency proved possible. The possibility of polymer particle coagulation at higher homogenizer rotational speeds was also demonstrated.

Keywords: modified bitumen, waste polymer, Plackett-Burman experimental design, bitumen microstructure

Streszczenie

W artykule przedstawiono analizę rezultatów badań asfaltów modyfikowanych odpadowymi polimerami polypropylene (PP) i polyethylene therepthalate (PET). Asfalty zmodyfikowano w warunkach zgodnych z planem eksperymentu Placketta-Burmana, dobierając odpowiednio zmienne procesu mieszania. Przedstawiono wyniki badań podstawowych, takich jak temperatura mięknienia, penetracja, temperatura łamliwości wg Fraassa. Porównano mikrostrukturę asfaltów modyfikowanych odpadowymi polimerami z dwoma asfaltami dostępnymi komercyjnie modyfikowanymi kopolimerem styren-butadien-styren (SBS). Analiza wyników badań ukazała pewne podobieństwa pomiędzy asfaltami przygotowanymi w laboratorium a asfaltem PmB 45/80-55. Modyfikacja asfaltów drogowych 20/30 i 70/100 przyniosła poprawę szczególnie w zakresie temperatury mięknienia. Ponadto możliwa okazała się modyfikacja niektórych parametrów lepiszcza bez zmiany jego konsystencji. Wykazano również możliwość koagulacji cząstek polimeru przy wyższych prędkościach obrotowych homogenizatora.

Słowa kluczowe: asfalt modyfikowany, polimery odpadowe, plan eksperymentu Placketta-Burmana, mikrostruktura asfaltu

1. INTRODUCTION

Polymer-modified bitumens are a commonly used material for road pavement construction. Bitumens modified with SBS elastomer are typically utilized for this purpose. This copolymer allows for obtaining bitumen with very good mechanical properties, which translates into higher fatigue life of mineral-asphalt mixtures compared to traditional road bitumens. Development of work on polymer-modified bitumens (PmB) has led to obtaining binders in which the limits of SBS polymer content have been exceeded, after which the polymer becomes the continuous phase. The properties of bitumen in which so-called phase inversion has occurred depend to a greater extent on

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the properties of the polymer used for modification than on the bitumen [1]. Nevertheless, due to lower availability and higher production costs, these bitumens are used less frequently than PmB with a continuous bitumen matrix.

The properties of bitumens can be modified by agents such as synthetic waxes or styrene-butadiene-styrene copolymer, which have been known in the road industry for many years [2-3]. However, this does not imply stagnation in the field of bitumen modification, and research is ongoing worldwide to improve their properties using various modifiers. Some of these are thermoplastic polymers originally used for entirely different applications, such as the production of plastic bags [4-5]. The results of studies on new binder modifiers are often promising, although certain problems can also be observed. One such issue is the low stability of modified bitumens, which results in phase segregation between the polymer and bitumen [6]. This situation leads to a heterogeneous mixture that cannot be successfully used for the production of mineral-asphalt mixtures. Furthermore, there is a need to use waste and renewable materials in the industry [7]. This situation has led to research focusing on the use of bio-modifiers derived from wood pellets, straw, or vegetable oils [8]. Regardless of the modifier used, the ultimate goal of the research is to improve the properties of mineral-asphalt mixtures.

Research on modifying the properties of mineral-asphalt mixtures using plastics has so far been carried out by two methods [9]. The first of these is the so-called wet process. It involves modifying the binder with a polymer and then adding the polymer-modified bitumen to the aggregate. The second method is referred to as the dry method. In this method, plastics are added directly to the mixture without prior contact with the bitumen. Research has also been conducted in which the aggregate is coated with polymer. The plastic coating formed in this way increases the aggregate's resistance to crushing [10] and also reduces the aggregate's water absorption [11]. Studies have also indicated the possibility of using mixtures of various polymer materials [12], such as rubber waste from used car tires and recycled polyethylene terephthalate, for the construction of inexpensive and environmentally friendly roads [13].

The benefits of modifying mineral-asphalt mixtures with polymers are evident in both the dry and wet methods [4-6], [14-15]. The wet method applied in this study allows for determining the properties of the binder after modification and enables the entire added polymer to react in contact with the bitumen, which can be difficult to achieve with the dry method. Furthermore, the wet method allows for a preliminary assessment of the mineral-asphalt mixture's character based on the properties of the binder itself. This significantly reduces the amount of material used to select the optimal solution.

2. MATERIALS

2.1. Road Bitumens and Polymer-Modified Binders (PmB)

Waste polymers were used to modify road bitumens 70/100 and 20/30. The first is a soft bitumen primarily used for the production of bitumen emulsions and cold deep recycling. It can also be used as a binder for the wearing course of road pavements with low traffic intensity in SMA mixtures and bitumen concrete. The second is an bitumen with low penetration and high softening temperature. Due to its high sensitivity to low-temperature cracking, it is used for base and binder layers made of bitumen concrete with a high stiffness modulus. Preferred applications are roads with medium and high traffic volumes.

Polymer-modified bitumens (PmB) can also be used for the production of mineral-asphalt mixtures. They exhibit favorable properties at both low and high service temperatures. For the studies, two bitumens used in surface layers, PmB 45/80-55 and 45/80-65, were selected to compare their properties with bitumens modified with polymer waste materials. They are used on roads regardless of traffic load.

2.2. Waste polymers

Modification of the properties of road bitumens was carried out using two polymers derived from recycling. The first is polyethylene terephthalate (PET), primarily used for beverage packaging production. The second is polypropylene (PP), commonly used for the production of toys and food packaging. Both belong to the group of plastomers with a crystalline structure. An important fact is the relatively high softening temperature of PET compared to PP (approximately 100°C difference).

3. METHODS

3.1. Modification of bitumen with waste polymers

The research was based on the use of two reference bitumens, 20/30 and 70/100, and binders formed from their modification. Recycled waste polymers such as PET and PP were used to modify road bitumens, and selected basic and rheological properties of the resulting binders were then measured.

Laboratory-modified bitumens were produced by dispersing polyethylene terephthalate and polypropylene polymer particles in the matrix of 20/30 and 70/100 road bitumens. Using various values of variable factors affecting the homogenization process, initially eight bitumens modified with plastics used for many years in the production of, among others, food packaging and toys were obtained. Bitumen modification was carried out under conditions specified in Table 1 regarding polymer content, temperature, mixing speed and time, type of polymer, and type of base bitumen. The resulting bitumens were subjected to testing, and the obtained results allowed comparison of the properties of bitumens modified with recycled polymers. The experimental plan variables were selected using the Plackett-Burman elimination design.

Table 1. Plackett-Burman experiment design

Case	Independent variable						
	Mixing speed rpm/min^{-1}	Mixing temperature °C	Mixing time min.	Waste polymer content %	Bitumen type –	Waste polymer type –	Waste polymer granulation –
1	120	160	30	5	70/100	PP	<5.6
2	9500	160	30	2	20/30	PP	>5.6
3	120	180	30	2	70/100	PET	>5.6
4	9500	180	30	5	20/30	PET	<5.6
5	120	160	180	5	20/30	PET	>5.6
6	9500	160	180	2	70/100	PET	<5.6
7	120	180	180	2	20/30	PP	<5.6
8	9500	180	180	5	70/100	PP	>5.6

3.2. Basic properties of bitumens

The prepared bitumens were subjected to tests demonstrating their basic properties. The first of these was the softening point test determined by the ring-and-ball method according to the EN 1427 standard [16]. Two metal rings filled with bitumen are placed in a heated vessel containing water or glycerin with controlled, constant temperature increase and are loaded with steel balls. As the temperature rises, the weight of the balls causes deformation of the bitumen. The temperature at which the sample deformation reaches 25 ±0.4 mm is defined as the softening point.

The second test used to determine the basic properties of the binders is the penetration test conducted in accordance with EN 1426 [17]. The result is expressed as the penetration depth of a standardized needle vertically penetrating the bitumen sample at a temperature of 25°C, with the unit being 0.1 mm. The needle load is 100 g, and the loading time is 5 seconds. Bitumens with higher penetration values are classified as "soft," in contrast to binders considered "hard," which have lower penetration. Bitumen penetration is one of the factors enabling the classification of road bitumens according to the applicable European standard nomenclature. The penetration range, along with the minimum declared softening temperature, forms the basis for the designation of modified bitumens.

The next test was the measurement of Fraass cracking temperature performed according to EN 12593 [18]. A thin layer of bitumen placed on a bending metal plate undergoes deformation of a constant value at progressively lower temperatures. The temperature at which the force required to bend the plate with the sample decreases signifies the breaking of the continuity of the applied bitumen layer, i.e., a crack induced by low temperature and constant, standardized deformation. The test result expressed in degrees Celsius provides valuable information about the behavior of bitumen at low temperatures.

3.3. Analysis of the microstructure

The microstructure analysis of modified bitumens was carried out using a Carl Zeiss Axio Scope.A1 epi-fluorescence microscope at 100x magnification. Microstructure observation was performed on a fresh fracture of the sample by analyzing the image in reflected light. The image recorded according to EN 13632 [19] allowed determination of the structure of modified bitumens based on phase continuity (continuous polymer phase, bitumen phase, or continuity of both phases), phase homogeneity (homogeneous, heterogeneous), polymer particle size (small, medium, large), and shape of dispersed particles (round, elongated, other).

4. TEST RESULTS

4.1. Basic properties

The results of the basic properties tests of modified bitumens are presented in Table 2. They included the determination of penetration values, softening temperature, and Fraass cracking temperature. The nomenclature of polymer-modified bitumens was adopted according to Table 1, which defines modification parameters conducted according to the Plackett-Burman experimental design. Furthermore, the obtained values were compared with those for road bitumens before modification. Table 2 also includes data for two bitumens labeled as PMB. Polymer-modified bitumens PMB 45/80-55 and PMB 45/80-65 are commercially available bitumens based on modification technology using the SBS block copolymer (styrene-butadiene-styrene). These binders were developed to reduce the destructive effect of factors acting during the service life on bitumen pavements. The application of SBS elastomer in these bitumens enabled an improvement in the mechanical properties of mineral-asphalt mixtures compared to traditional road bitumens.

The conducted tests revealed the influence of waste polymers on the basic properties of road bitumens. Combinations of the experimental design numbers 1, 3, 6, and 8 containing 70/100 road bitumen demonstrated higher softening point values compared to the base bitumen from which they were derived. Among the modified bitumens, based on 20/30 bitumen, in two cases (combinations 2 and 7), significantly higher softening point values were also obtained. Combinations 4 and 5, despite the relatively high plastomer content (5%), exhibited softening point temperatures similar to the base bitumen, which may suggest lower compatibility between 20/30 bitumen and PET plastomer. It should be noted that some modified bitumens (2, 7, 8) had a higher softening point temperature than the commercially available polymer-modified bitumen PMB 45/80-55, while bitumen no. 8 showed a higher softening point even compared to PMB 45/80-65. Such an effect can be considered beneficial in terms of resistance to permanent deformation under high service temperatures of mineral-asphalt mixtures. Furthermore, modification of bitumen with waste polymers shows a significant influence on the softening temperature of the bitumen.

Modification of road bitumens with waste polymers can cause a significant change in the consistency of the base binders. The change in consistency is more noticeable in bitumens characterized by higher penetration. Table 2 shows that with appropriate selection of dependent variables, it is possible to achieve a consistency of polymer-modified bitumen close to that of 20/30 bitumen, regardless of the type of bitumen used for the modification. It can also be observed that in certain cases (combinations 2 and 7) no significant change in penetration compared to the base bitumen was found. Analysis of these cases suggests that it is possible to increase the softening temperature of bitumen by modification with waste polymers without significant change in bitumen consistency.

Table 2. Results of property designation for modified bitumen

Case	Independent variable							Dependent variable		
	A rpm/min^{-1}	B °C	C min	D %	E –	F –	G –	$T_{R\&B}$ °C	Penetration 0.1 mm	Breaking point temperature °C
1	120	160	30	5	70/100	PP	<5.6	46.2 ±0.6	72.6 ±1.2	-12.8 ±3.4
2	9500	160	30	2	20/30	PP	>5.6	65.9 ±3.4	24.1 ±1.3	-9.3 ±1.2
3	120	180	30	2	70/100	PET	>5.6	45.1 ±1.2	86.7 ±2.6	-16.2 ±1.9
4	9500	180	30	5	20/30	PET	<5.6	63.2 ±0.2	22.5 ±1.2	-8.5 ±2.0
5	120	160	180	5	20/30	PET	>5.6	63.4 ±0.5	28.2 ±1.2	-10.8 ±1.0
6	9500	160	180	2	70/100	PET	<5.6	46.5 ±0.3	76.6 ±3.5	-14.0 ±2.1
7	120	180	180	2	20/30	PP	<5.6	67.2 ±0.4	21.3 ±2.5	-8.0 ±1.8
8	9500	180	180	5	70/100	PP	>5.6	75.3 ±11.5	21.7 ±3.8	-12.0 ±1.2
20/30	–	–	–	–	–	–	–	61.3 ±1.2	27.4 ±2.1	-10.4 ±2.2
70/100	–	–	–	–	–	–	–	44.7 ±0.7	91.5 ±3.1	-15.4 ±2.0
PMB 45/80-55	–	–	–	–	–	–	–	63.7 ±2.5	66.6 ±2.8	-17.7 ±1.8
PMB 45/80-65	–	–	–	–	–	–	–	72.0 ±2.1	58 ±2.9	-18.5 ±1.6

Modification of binders with plastomers can also affect the results obtained during Fraass breaking point testing. Studies indicate that commercially used SBS polymer-modified bitumens achieve decidedly better low-temperature properties than laboratory-modified bitumens with waste polymers. However, this does not mean that the properties of PET- and PP-modified binders are at an unacceptable level. It is noteworthy that 20/30 bitumen is less sensitive to changes in low-temperature properties with higher polymer content. The results obtained for bitumen no. 3 indicate that softer bitumens like 70/100 will probably require shorter mixing times and lower polymer content compared to harder bitumens like 20/30 in order to achieve the most favorable low-temperature properties.

4.2. Microstructure of polymer-modified bitumens

To perform microstructure analysis of bitumens modified with PET and PP as well as bitumens modified with PmB 45/80-55 and PmB 45/80-65, digital images of the surfaces of prepared samples were captured using an epi-fluorescence microscope. Example microstructure images of the bitumens are presented in Figure 1. The microstructure images of the binders were processed, which enabled the determination of descriptive statistics and a box and whisker plot for the surface area of the polymer particles dispersed in the bitumen matrix.

All bitumens modified with waste polymers were characterized by a right-skewed asymmetric distribution of polymer particles. This is indicated by the skewness values given in Table 3. Such a distribution seems to be true for modified bitumens under the assumption

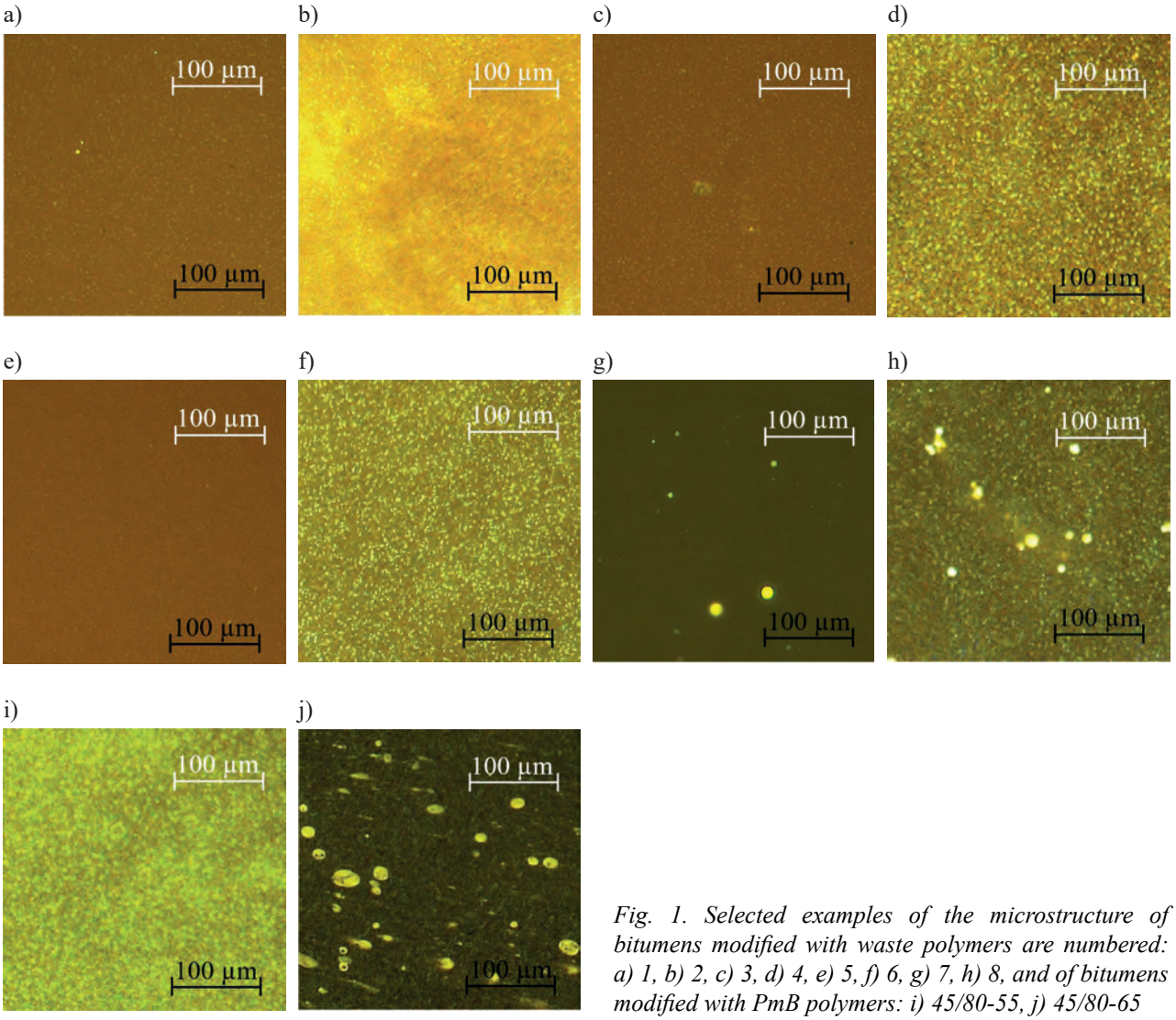

Fig. 1. Selected examples of the microstructure of bitumens modified with waste polymers are numbered: a) 1, b) 2, c) 3, d) 4, e) 5, f) 6, g) 7, h) 8, and of bitumens modified with PmB polymers: i) 45/80-55, j) 45/80-65

Table 3. Descriptive statistics of the surface area of polymer particles dispersed in polymer-modified bitumens

Feature	Case									
	1	2	3	4	5	6	7	8	45/80-55	45/80-65
Mean	2.1	3.3	1.9	10.3	3.2	9.7	7.3	9.2	12.4	119.1
Standard error	0.0	0.1	0.0	0.1	0.1	0.2	1.9	0.3	0.2	19.1
Median	1.9	2.1	1.4	8.3	2.3	7.4	1.4	6.5	9.3	37.4
Standard deviation	2.0	3.6	2.7	8.7	3.9	8.8	26.9	12.3	11.0	183.4
Variance	4.1	12.8	7.4	75.7	15.3	76.8	722.4	150.4	120.5	33640.7
Kurtosis	374.4	4.3	4782.5	4.5	146.7	4.6	50.9	59.1	3.8	5.5
Skewness	11.0	1.9	58.6	1.7	7.8	1.8	6.8	6.2	1.6	2.3
Range	88.9	22.0	236.0	72.2	108.8	69.0	257.3	184.2	79.6	946.6
Minimum	0.5	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1
Maximum	89.3	22.1	236.5	72.7	109.2	69.4	257.8	184.6	80.1	946.7

of a polymer dispersion scheme in the bitumen matrix involving primarily the dispersion of small particles, which at higher polymer content can agglomerate into larger clusters. This assumption is also confirmed by the frequency distribution of the commercially available PMB 45/80-55. Produced by a Polish refinery, this modified bitumen also exhibits a right-skewed asymmetric distribution of particle size frequency. Comparing the microstructure images of PMB 45/80-65 and PMB 45/80-55 modified bitumens also reveals larger polymer particle sizes in the former binder. This indicates a tendency for the polymer to group into larger clusters at higher bitumen modification levels. The increase in polymer particle size observed under the microscope with increasing polymer dosage is also confirmed by image analyses conducted by other researchers [20].

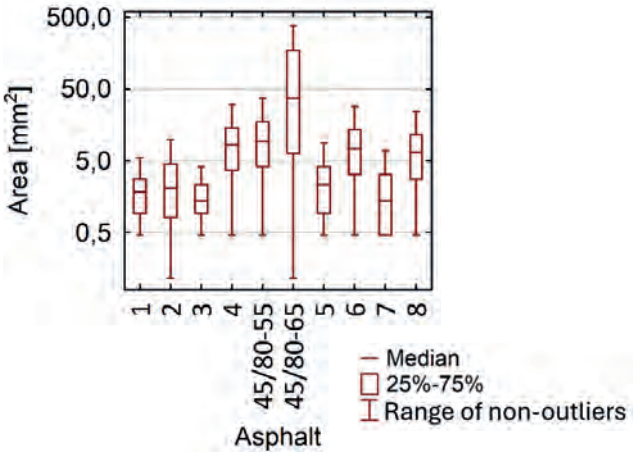

Fig. 2. A box and whisker plot of polimer particle surface area

A box and whisker plot presented in Figure 2 shows the size range of polymer particles dispersed in the bitumens. It should be noted that PmB 45/80-65 bitumen has significantly larger dispersed particle sizes than the other modified bitumens. The other commercially available bitumen, PmB 45/80-55, was characterized by much smaller particle sizes most similar to the polymer-modified bitumens numbered 2, 6, and 8. These were PP and PET modified bitumens produced at higher homogenizer rotational speed. It can therefore be hypothesized that a higher rotational speed influenced the coagulation of the dispersed particles, thus increasing their size. The first and third quartiles of bitumens numbered 1, 3, 5, and 7 fall within the (0;5 µm) range. These were bitumens modified at low rotational speed. The median surface area of these bitumen particles seems to confirm the rule that low rotational speed is a factor influencing the achievement of smaller dispersed polymer particle sizes. An exception to this rule is bitumen no. 2. Its production according to the experimental plan required high rotational speed, but the obtained polymer particle sizes were similar to those obtained under low rotational speed conditions. Explaining this anomaly requires further examination of other independent experimental variables. Bitumen no. 2 was produced at lower temperature and shorter mixing time. Therefore, despite high rotational speed during the modification process, the polymer particles did not have time to coagulate and thus form larger surface area particles. The bitumen with the largest polymer particle surface area was PmB 45/80-65.

The arithmetic mean was found not to be an adequate measure of central tendency for the obtained frequency distributions, as illustrated by descriptive statistics in Table 3. Both analysis of variance and the sample standard deviation revealed a large dispersion of polymer particle surface areas from the arithmetic mean. The results showed a wide range of particle surface areas dispersed in the bitumen matrix. Furthermore, the frequency distribution

was leptokurtic for all investigated cases. Notably, bitumens numbered 2, 4, and 6 were the most similar to PMB bitumens in this respect. For the remaining bitumens, it can be inferred that there is a greater number of outlier observations.

The analysis of the microstructure images of polymer-modified binders provided information about the morphology of the bitumens (Table 4). According to EN 13632 [20], the structure of modified bitumens is described using a set of letter codes. The code set characterizes the bitumen with the following letter notations:

1. For describing phase continuity:
   a. Continuous polymer phase – „P”,
   b. Continuous bitumen phase – „B”,
   c. Continuity of both phases – „X”.
2. For describing phase homogeneity:
   a. Homogeneous – „H”,
   b. Heterogeneous – „I”.
3. For describing polymer particle size:
   a. Small (<10 μm) – „S”,
   b. Medium (10 – 100 μm) – „M”,
   c. Large (>100 μm) – „L”.
4. For describing the shape of dispersed particles:
   a. Round – „r”,
   b. Elongated – „s”,
   c. Other – „o”.

Table 4. Mikrostructure of polimer-modified bitumens according to EN 13632 [20]

Feature	Case									
	1	2	3	4	5	6	7	8	45/80-55	45/80-65
Phase continuity	B	B	B	B	B	B	B	B	B	B
Homogeneity	H	H/I	H	H	H/I	H	H	H/I	H	H
Size	S	S	S/M	S	S	S	S/M	S/M	S	S/M
Shape	r	r/s	r	r	r	r	r	r/o	r	r/s

Mixed notations were also used when polymer particles with different shapes, such as round and elongated, were observed in samples of a given bitumen. It is worth noting that all polymer-modified bitumens had a continuous bitumen phase. Presumably, a significantly higher polymer content would be required to reverse the phases, where the polymer would form the continuous phase and bitumen would be dispersed within it, acting as a plasticizer. Bitumens modified with PET and PP, similar to PMB, exhibited similar shapes of dispersed particles. Bitumens numbered 1, 3, 4, 5, 6, and 7, like PMB 45/80-55, had microstructures characterized by round, smooth-shaped particles. Meanwhile, PMB 45/80-65, in addition to round particles, also had elongated particles, similar to bitumen number 2. It should be noted that not all modified bitumens were classified as homogeneous. This may indicate the need to improve polymer-bitumen compatibility in some cases. Bitumens 2, 5, and 8, depending on the observed sample, had either homogeneous or heterogeneous phases, with their common feature being the use of polymer particles larger than 5.6 mm, suggesting the influence of polymer particle size on bitumen homogeneity.

5. CONCLUSIONS

The article focuses on the evaluation of selected properties of bitumens modified with waste polymers: polyethylene terephthalate and polypropylene. Based on the conducted studies, the following conclusions were drawn:

- It is possible to select mixing process parameters to change selected bitumen properties without significant change in binder consistency.
- Modified bitumens exhibited a right-skewed asymmetric distribution of dispersed polymer particle surface areas.
- The morphology of bitumens modified with waste polymers was more similar to PMB 45/80-55 bitumen than to PMB 45/80-65, which contains polymer particles with larger surface area.
- Higher rotational speed in the bitumen modification process may result in coagulation of polymer particles.
- Modification with waste polymers can cause significant change in bitumen consistency.
- Modification with waste polymers can lead to a significant increase in softening temperature, suggesting a beneficial effect of waste polymers on resistance to permanent deformation of mineral-asphalt mixtures at high service temperatures.
- Appropriately selected process parameters for modification of bitumen with waste polymers allow maintaining favorable low-temperature properties compared to base bitumen.
- Modification of 70/100 bitumen using waste polypropylene allowed obtaining a consistency corresponding to 20/30 bitumen with a beneficially higher softening temperature and better low-temperature properties compared to 20/30 bitumen properties. This indicates the potential for practical use of waste polymer-modified bitumens in constructing durable road pavements.

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INFLUENCE OF RANDOM VARIABLE CORRELATION ON THE RELIABILITY OF STEEL STRUCTURES

WPŁYW KORELACJI ZMIENNYCH LOSOWYCH NA NIEZAWODNOŚĆ KONSTRUKCJI STALOWYCH

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Abstract

The study investigated the influence of correlations between random variables on the reliability index of selected structural systems. The structural design parameters were defined as deterministic quantities and random variables, and the correlation between them was modeled using four correlation-matrix variants. The ultimate limit state was adopted as the safety criterion, and appropriate limit state functions were formulated to identify structural failure. A sensitivity analysis of the reliability index with respect to the random variables was carried out using the Hasofer-Lind reliability index as the performance measure. The First-Order Reliability Method served as the primary computational approach, with Monte Carlo simulation as the reference method. All calculations were performed using the NUMPRESS Explore. The analyses demonstrated that increasing the correlation coefficient leads to higher values of the reliability index. The results confirm that the correlation coefficient significantly affects the reliability assessment and should not be neglected in structural safety evaluations.

Keywords: correlation coefficient, FORM method, Monte Carlo method, random variables, reliability index, sensitivity analysis

Streszczenie

W pracy analizowano wpływ korelacji zmiennych losowych na wartość wskaźnika niezawodności wybranych układów konstrukcyjnych. Parametry projektowe konstrukcji zdefiniowano jako wielkości deterministyczne oraz zmienne losowe. W analizie uwzględniono korelację zmiennych losowych poprzez zastosowanie czterech wariantów macierzy korelacji. Stan graniczny nośności przyjęto jako kryterium oceny bezpieczeństwa konstrukcji, a do identyfikacji stanu awarii zastosowano odpowiednie funkcje graniczne. Przeprowadzono analizę wrażliwości wskaźnika niezawodności względem zmiennych losowych, przyjmując wskaźnik Hasofera-Linda jako miarę niezawodności. Podstawową metodą obliczeniową była metoda niezawodności pierwszego rzędu (FORM), natomiast metodę Monte Carlo wykorzystano jako metodę referencyjną. Obliczenia przeprowadzono z wykorzystaniem oprogramowania NUMPRESS Explore. Na podstawie przeprowadzonych analiz zaobserwowano, że wzrost wartości współczynnika korelacji prowadzi do zwiększenia wartości wskaźnika niezawodności. Uzyskane wyniki potwierdziły, że współczynnik korelacji wywiera istotny wpływ na wartość wskaźnika niezawodności, wobec czego nie powinien być pomijany w ocenie bezpieczeństwa konstrukcji.

Słowa kluczowe: współczynnik korelacji, metoda FORM, metoda Monte Carlo, zmienne losowe, wskaźnik niezawodności, analiza wrażliwości

1. INTRODUCTION

A primary concern in the design of engineering structures is ensuring an adequate level of safety throughout the intended service life. The concept of safety is inherently linked to assessing structural reliability. Reliability assessment of structures is a fundamental aspect of engineering analysis, aimed at quantifying the probability of safe performance

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under variable loading conditions. Approximate methods such as the First-Order Reliability Method (FORM) and the Second-Order Reliability Method (SORM) are commonly employed. FORM linearly approximates the limit state surface, enabling rapid calculation of the reliability index β. In contrast, SORM accounts for the curvature of this surface, thereby improving accuracy for nonlinear limit-state functions. Simulation-based approaches, including Monte Carlo methods and variance-reducing variants, allow precise estimation of the probability of failure, albeit at a higher computational cost. The assessment relies on a probabilistic description of the random variables representing loads and material strength, considering both their distributions and mutual dependencies. Correlation between variables can significantly affect failure probabilities; therefore, its proper modeling – using classical correlation coefficients or copula-based approaches – is a crucial element of reliability analysis. Comprehensive discussions and theoretical foundations of structural reliability methods used in civil engineering can be found in classical works [1-6].

In recent years, accounting for correlations among random variables in structural reliability analysis has become increasingly important. Classic assumptions of independence among random parameters – such as loads, material strengths, or material properties – can lead to underestimating or overestimating failure risk. In practice, many variables are interdependent, and their relationships significantly influence the probability of exceeding the limit-state function. Early foundational work by Hasofer and Lind [7] and later by Ditlevsen and Madsen [8] emphasized that the reliability index and failure probability can be significantly affected when dependencies among loads, material properties, and geometrical parameters are ignored. Subsequent studies expanded on these findings by demonstrating that independence assumptions often lead to misestimating reliability – either overly conservative or unconservative – depending on the nature and magnitude of correlations.

Classical correlation coefficients, such as Pearson's or Spearman's, measure linear or monotonic relationships but are limited for non-normal or nonlinear variables. In particular, copula-based approaches [9-11] have gained prominence for their flexibility in capturing complex, nonlinear dependence patterns. A copula is a function that separates the marginal distributions of individual variables (i.e., the behaviour of each variable on its own) from their dependence structure (i.e., how the variables are interdependent), allowing realistic modelling of nonlinear, asymmetric, or tail-dependent correlations. These methods provide more accurate joint distributions in structural systems, especially when variables follow different probability distributions, and are widely applied in structural reliability analysis.

In parallel, reliability methods such as FORM and SORM [12] and simulation-based techniques (Monte Carlo, Importance Sampling) [13] have been adapted to handle correlated inputs. Work by Der Kiureghian [14] has shown that correlation effects can substantially change the geometry of the limit-state function, highlighting the importance of accurate modeling for both component and system reliability evaluation.

Modern approaches to modeling dependencies among variables include the use of copulas, which capture both linear and nonlinear correlations. Bai et al. [15] proposed a method that accounts for multiple correlation features, including dependencies among stress and strength, failure mechanisms, and structural components. A time-varying hybrid copula was employed to realistically model evolving dependency structures, and the results showed that including correlations yields more conservative and safer reliability estimates.

Similarly, Zhang and Yan [16] analyzed parallel-series systems in a stress-strength model, assuming a correlation between stress and strength using a Clayton copula. They applied a two-step maximum-likelihood estimation and the maximum-product-spacing method to estimate parameters, and conducted Monte Carlo simulations to assess the effectiveness of the estimation methods. The results indicated that ignoring dependencies among variables can lead to significant errors in determining system reliability.

In engineering applications, Kubicka and Radoń [17] focused on the system reliability of steel trusses, accounting for correlations among the strengths of individual members. FORM (First-Order Reliability Method) and Subset Simulation were employed, along with a sensitivity analysis to identify which components most influence overall structural reliability. Their study showed that increasing correlation among member strengths decreases the reliability index, thereby increasing the risk of structural failure.

Additional methodological contexts include reports from IFTR PAN and doctoral research [18] on third-level reliability methods that fully account for the joint distribution of random variables, including correlations. The literature also highlights that correlations may change over time due to aging or

material fatigue, necessitating dynamic methods, such as time-varying copulas.

In summary, the literature analysis shows that accounting for correlations among random variables is crucial for a realistic assessment of structural reliability. Copulas and probabilistic simulation methods, such as Monte Carlo or Subset Simulation, enable accurate risk evaluation, while sensitivity analysis helps identify which correlations have the most significant impact on structural safety. Contemporary studies confirm that ignoring dependencies can lead to significant errors in design and reliability assessment, whereas accounting for them enhances the credibility of analyses and improves the safety of engineering projects.

In the present study, the primary method employed was the First-Order Reliability Method (FORM). In contrast, the Monte Carlo method, recognized as the most accurate approach in structural safety assessment, was used as a reference to verify the correctness of FORM-based calculations. The Hasofer-Lind reliability index β served as the measure of structural reliability. A significant advantage of the FORM method is its ability to compute the sensitivity of the reliability index with respect to the random variables. This sensitivity, denoted by α, is calculated as the first derivative of the reliability index β with respect to the specified variable.

2. RESEARCH ASSUMPTIONS AND METHODS

2.1. Correlation between random variables

It is assumed in this paper that only one failure mode is considered and that a reliability measure for this failure mode is to be estimated. Further, it is believed that this failure mode can be mathematically formulated. An important step in a reliability analysis is to decide which quantities should be modelled as probabilistic variables and which as deterministic parameters. The probabilistic variables are denoted $\boldsymbol{X} = \{X_1, X_2,\ldots, X_n\}$. Then probability could model physical uncertainty, model uncertainty or statistical uncertainty. The physical probabilistic can be load variables (e.g., traffic load), resistance variables (e.g., yield strength) or geometrical variables (e.g., length or cross-sectional area of a beam). The variables in $\boldsymbol{X}$ are also denoted basic variables. Realizations of the basic variables are denoted $x = \{x_1, x_2,\ldots, x_n\}$, i.e., x is a point in the n-dimensional basic variable space.

The joint density function for the probabilistic variables X is denoted $f_X(x)$. The elements of the vector of expected values and the covariance vector are:

$$\mu_i = E\left[X_i\right], \quad i = 1,\ldots,n \tag{1}$$

$$C_{ij} = Cov\left[X_i, X_j\right], \quad i,j = 1,\ldots,n \tag{2}$$

The standard deviation of X_i is denoted σ_i. The variance of X_i is $\sigma_i^2 = C_{ii}$. The coefficient of correlation between X_i and X_j is defined as:

$$\rho_{ij} = \frac{C_{ij}}{\sigma_i \sigma_j}, \quad i,j = 1,\ldots,n \tag{3}$$

It is easy to see that $-1 \le \rho_{ij} \le 1$.

A complicated part of reliability analysis with correlated random variables (from the $\boldsymbol{X}$ vector) is calculating the covariance vector: covariance vector:

$$C_{ij} = Cov\left[X_i, X_j\right] = E\left[\left(X_i - \mu_{X_i}\right)\left(X_j - \mu_{X_j}\right)\right] = E\left[X_i X_j - X_i \mu_{X_j} - \mu_{X_i} X_j - \mu_{X_i}\mu_{X_j}\right] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(x_i - \mu_{X_i}\right)\left(x_j - \mu_{X_j}\right) f_{X_i X_j}\left(x_i x_j\right) dx_i dx_j \tag{4}$$

For the n-dimensional variable, we have n variances and n (n-1) covariance. We present this collection in the form of a covariance matrix:

$$C = \begin{bmatrix} C_{ii} & C_{ij} & \cdots & C_{in} \\ C_{ji} & C_{jj} & \cdots & C_{jn} \\ \vdots & \vdots & \ddots & \vdots \\ C_{ni} & C_{nj} & \cdots & C_{nn} \end{bmatrix} \quad i,j = 1,\ldots,n_{i,j=1,\ldots,n} \tag{5}$$

In analogy to the covariance matrix, a symmetrical correlation matrix is defined:

$$\rho = \begin{bmatrix} \rho_{ii} & \rho_{ij} & \cdots & \rho_{in} \\ \rho_{ji} & \rho_{jj} & \cdots & \rho_{jn} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{ni} & \rho_{nj} & \cdots & \rho_{nn} \end{bmatrix} \quad i,j = 1,\ldots,n_{i,j=1,\ldots,n} \tag{6}$$

Knowledge of the distribution parameters of the random variables (mean, standard deviation, and probability density function) does not allow direct estimation of their correlation coefficient. Therefore, the primary objective was not to precisely determine the correlation coefficient for individual variable pairs, but rather to demonstrate that the values of the correlation coefficient influence overall structural safety. In the reliability analysis, well-established methods for assessing the probability of failure, such as FORM and Monte Carlo simulations, were used.

2.2. Reliability software

In the examples presented below, the NUMPRESS Explore software [19] was employed for the reliability analysis. The NUMPRESS is a computational system developed at the Institute of Fundamental

Technological Research, Polish Academy of Sciences (IFTR PAN), dedicated to the probabilistic reliability analysis of engineering processes.

The core of software is its probabilistic module, which allows users to define parameters of random variables: mean, standard deviation, and probability density function. The next step is to define the limit-state functions representing critical conditions in standard mathematical notation, expressed as functions of the basic random variables. A correlation matrix, which represents relationships among random variables, can also be defined. The next stage involves selecting the method of reliability analysis and starting the computations. The basic information generated by the reliability program is the reliability index β and its corresponding failure-probability level.

Reliability software also offers advanced post-processing capabilities, including visualization of probability distributions and sensitivity analyses. These tools help identify critical parameters, evaluate their influence on system performance, and support the design of processes resistant to uncertainty. By integrating reliability analysis with numerical simulations, NUMPRESS provides an effective environment for realistic risk assessment. It enables engineers and researchers to improve the safety, stability, and predictability of engineering processes affected by variability.

3. RESULTS

In this study, the reliability of three types of steel structures was assessed, and the Hasofer-Lind reliability index β was estimated. The sensitivity of the reliability index to the considered random variables was also evaluated. Correlation matrices were defined based on engineering judgment and available statistical data. Correlations were assumed among variables that are physically or functionally related, such as material properties, cross-sectional dimensions, and loads, because they significantly affect structural behavior and the reliability index. Less related variables were treated as independent to simplify the model without compromising accuracy. The effect of the assumed correlation coefficients was examined through four cases of the correlation matrix. For each structure, four scenarios representing different relationships among the random variables were analyzed:

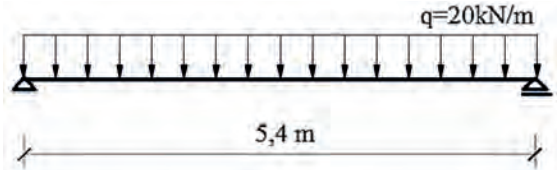
Case A – uncorrelated $\rho = 0$,
Case B – weak correlation $\rho = 0.3$,
Case C – medium correlation $\rho = 0.5$,
Case D – strong correlation $\rho = 0.9$.

A linear-elastic material model and the assumption of small displacements were adopted in the analysis. All random variables were assumed to follow a normal distribution. The coefficients of variation were selected based on statistical studies of building strength, construction materials, and products [20]. For variables related to loads, the coefficients of variation were chosen in accordance with the recommendations of the Joint Committee on Structural Safety [21]. For each structure, the following parameters were defined for the random variables considered in the reliability analysis (Table 1-Table 3): the random variable (X_i), its probability density function (p_f), the mean value (μ_x), the standard deviation (σ_x) and the coefficient of variation (v_x). These parameters provide a complete statistical characterization of the uncertainties associated with each variable and form the basis for subsequent probabilistic and sensitivity analyses.

3.1. Example 1 – steel beam

In Example 1, the reliability analysis was performed for a steel I-beam IPE270. The elements were made of S235 steel with a yield point $f_y = 235$ MPa and a beam section modulus $W_{pl,y} = 4.84 \cdot 10^{-4}$ m^3. The structural element is a simply supported beam under a uniform load q = 20 kN/m (Fig. 1). A detailed numerical analysis of the reliability problem of this element has been presented earlier [22], but it did not include correlations among random variables. The details of the steel beam are shown in Figure 1.

a)



b)

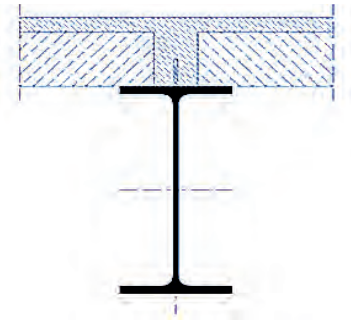


Fig. 1. Steel beam geometry, showing (a) structural scheme and (b) cross-sectional details [22]

The structural design parameters were treated as random variables. The probabilistic quantities incorporated into the analysis include: X_1 – uniform load q, X_2 – beam length L, X_3 – plastic section modulus $W_{pl,y}$ and X_4 – yield strength of S235 steel f_y. A detailed specification of these random variables is presented in Table 1.

Table 1. Characteristics of the random variables for the steel beam

X_i	p_f	μ_X	σ_X	v_X
X_1	Normal	20 kN/m	2 kNm	10%
X_2	Normal	5.4 m	0.0054 m	0.1%
X_3	Normal	$4.84 \cdot 10^{-4}$ m^3	$0.242 \cdot 10^{-4}$ m^3	5%
X_4	Normal	$235 \cdot 10^3$ kN/m^2	$18.80 \cdot 10^3$ kN/m^2	8%

The limit state function, representing the condition that the section's bearing capacity is not exceeded under bending moment, was formulated. The maximum bending moment, expressed as a function of the random variable vector $\boldsymbol{X} = \{X_1, X_2, X_3, X_4\}$, was then determined using the following expression:

$$M_{Ed} = \frac{X_1 X_2^2}{8} \tag{7}$$

Limit function connected with ultimate limit state was formulated as follows:

$$G_1(\boldsymbol{X}) = 1 - \frac{M_{Ed}}{M_{c,Rd}} \tag{8}$$

where: for the first class elements

$$M_{c,Rd} = M_{pl,Rd} = \frac{W_{pl,y} f_y}{\gamma_{M0}};\ \gamma_{M0}=1.$$

By substituting all relevant parameters and representing the function in terms of the random variable vector $\boldsymbol{X} = \{X_1, X_2, X_3\}$, the limit state function is expressed as follows:

$$G_1(\boldsymbol{X}) = 1 - \frac{X_1 X_2^2}{8 X_3 X_4} \tag{9}$$

The Hasofer-Lind reliability index was determined using the FORM method, and the Monte Carlo method was used solely to verify the accuracy of the calculations. The reliability index values for the simply supported beam, corresponding to different correlation-matrix cases, are presented in Table 2.

Table 2. Calculated values of the reliability index (β)

Probabilistic method	Case of correlation matrix			
	Case A ($\rho = 0$)	*Case B* ($\rho = 0.3$)	*Case C* ($\rho = 0.5$)	*Case D* ($\rho = 0.9$)
FORM	3.86	4.28	5.29	7.89
Monte Carlo	3.88	4.31	5.30	7.90

3.2. Example 2 – steel arch with hangers and tie beam

In Example 2, the reliability of a steel arch with hangers and a tie beam under a uniformly distributed load was analyzed (Fig. 2). The structure was designed using I-beam 200 sections, and all elements were made of S235H steel with a yield point of $f_y = 215$ MPa.

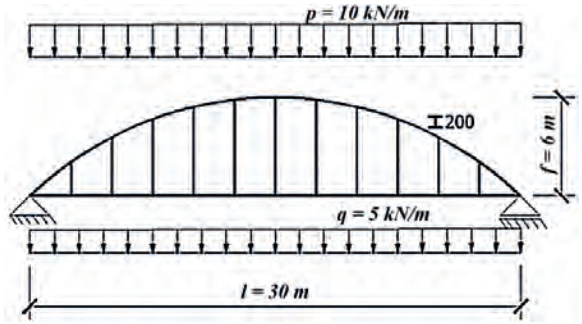


Fig. 2. Schematic of the steel arch with hangers and tie beam

The structure was assumed to be restrained against torsional instability perpendicular to the plane in which it is located, and the ultimate limit state function was defined based on the maximum compressive force. The cross-sectional area of the elements (A), the span (l), the arch rise (f), and the angle (ψ), defined as the angle between the tangent to the arch and the horizontal, were considered deterministic parameters. In the reliability analysis, the random variables considered were X_1, representing the permanent load (p); X_2, representing the variable load (q); and X_3, representing the yield point for S235H steel (f_y). A detailed description of these random variables is provided in Table 3.

Table 3. Description of the random variables for steel arch

X_i	p_f	μ_X	σ_X	v_X
X_1	Normal	10 kN/m	0.6 kN/m	6%
X_2	Normal	5 kN/m	1 kN/m	20%
X_3	Normal	$235 \cdot 10^3$ kN/m^2	$18.80 \cdot 10^3$ kN/m^2	8%

The strength of the tie beam is expressed by the following relation:

$$H = \frac{(X_1 + X_2)l^2}{8f} \tag{10}$$

where: l indicates the beam span (l = 30 m) and f denotes the arch's rise (f = 6 m).

The maximum compressive force, corresponding to the axial force at the support, is then determined using the expression:

$$N_{ed} = \frac{H}{\cos\psi} = \frac{(X_1 + X_2)l^2}{8f\cos\psi} \tag{11}$$

The limit state function for the ultimate limit state, used in the reliability assessment, was formulated as follows:

$$G_2(\boldsymbol{X}) = 1 - \frac{|N_{ed}|}{N_{b,Rd}} \tag{12}$$

where: $N_{b,Rd}$ – I-beam capacity due to buckling is given by the formula $N_{b,Rd} = \chi \cdot A \cdot X_3 / \gamma_{M0}$ (A = 0.00335 m^2, γ_{M0} = 1), χ – buckling factor (χ = 0,315).

By substituting all relevant parameters and representing the function in terms of the random variable vector $\boldsymbol{X} = \{X_1, X_2, X_3\}$, the limit state function is expressed as follows:

$$G_2(\boldsymbol{X}) = 1 - \frac{900(X_1 + X_2)}{0.0396\,X_3} \tag{13}$$

The Hasofer–Lind reliability index was determined using the FORM method, and the Monte Carlo method was used solely to verify the accuracy of the calculations. The values of the reliability index for the steel arch under different correlation matrix cases are presented in Table 4.

Table 4. Calculated values of the reliability index (β)

Probabilistic method	Case of correlation matrix			
	Case A (ρ = 0)	*Case B* (ρ = 0.3)	*Case C* (ρ = 0.5)	*Case D* (ρ = 0.9)
FORM	3.49	3.84	4.63	7.36
Monte Carlo	3.43	3.72	4.58	7.34

3.3. Example 3 – steel industrial building

In Example 3, the reliability of a steel industrial building was analyzed. The structure consists of steel frames with rigid ridge, column-to-foundation, and beam-to-column connections (Fig. 3). Elements are made of S235JR steel f_y = 235 MPa, E = 210 GPa, with columns of HEB 450 and girts of HEA 700 I-shaped beams. A detailed numerical analysis of the reliability problem of this element has been presented earlier [23]. Previous analyses did not account for correlations between random variables.

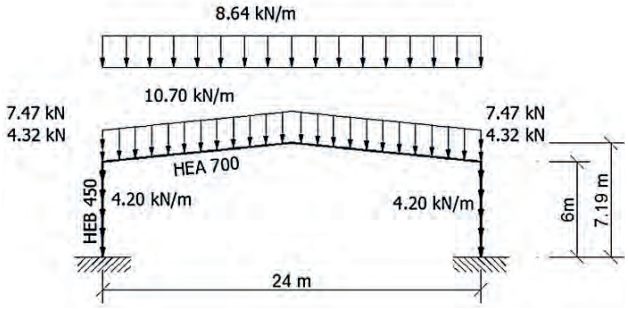


Fig. 3. Supporting structure of the steel industrial building with the most critical load combination [23]

Member section areas, member inertia moments, and column and beam lengths were assumed to be deterministic quantities. In the reliability analysis the following random variables were considered – roof self-weight per meter, – curtain wall self-weight per meter, – roof and wall fragment at the eave as a concentrated column load, – uniform snow load on the roof, – eave fragment as a concentrated column load, – modulus of elasticity of S235JR steel, and – yield strength of S235JR steel. The characteristics of the random variables are summarized in Table 5.

Table 5. Characteristics of the random variables for the steel industrial building

X_i	p_f	μ_X	σ_X	v_X
X_1	Normal	10.70 kN/m	0.642 kN/m	6%
X_2	Normal	4.20 kN/m	0.252 kN/m	6%
X_3	Normal	7.47 kN	0.4482 kN	6%
X_4	Normal	8.64 kN/m	1.728 kN/m	20%
X_5	Normal	4.32 kN	0.864 kN	20%
X_6	Normal	$210 \cdot 10^6$ kN/m^2	$10.5 \cdot 10^6$ kN/m^2	5%
X_7	Normal	$235 \cdot 10^3$ kN/m^2	$18.80 \cdot 10^3$ kN/m^2	8%

The first stage involved a static analysis performed using Robot Structural Analysis Professional, which enabled the identification of the location of the maximum bending moment for the most critical load combination (Fig. 3). A preliminary analysis showed that the highest internal forces in the cross-sections

of columns and beams were obtained for the load combination of permanent load Q and snow S, defined as KOMB1: 1.35·0.85·Q + 1.5·S. Other combinations, including wind effects, produced similar distributions of internal forces (with no change in the sign of the bending moments), but with lower magnitudes. Therefore, in the subsequent calculations, wind effects are neglected. The next step was a symbolic analysis conducted in Mathematica. By incorporating both deterministic values and random variables into the finite element method algorithm, a formula for the maximum bending moment as a function of random variables grouped in vector: $\boldsymbol{X} = \{X_1, X_2, X_3, X_4, X_5, X_6, X_7\}$.

The limit state function associated with the ultimate limit state is formulated as follows:

$$G_3(\boldsymbol{X}) = 1 - \frac{\left|\frac{M_{max}}{W_s}\right|}{f_y} \tag{14}$$

where: f_y – yield point for S235JR steel ($f_y = X_7$), W_s – denotes the elastic index of column strength. For HEA700 profile, $W_s = 0.00624\ m^3$.

After substituting all input data and transforming the expressions into functions of the random variable vector, the limit state function can be formulated as follows:

$$G_3(\boldsymbol{X}) = 1 - \frac{\left|-35.44X_1 - 35.44X_4\right|}{0.00624X_7} \tag{15}$$

The Hasofer-Lind reliability index was determined using the FORM method, and the Monte Carlo method was used solely to verify the accuracy of the results. The reliability index values for the steel industrial building under different correlation matrix scenarios are presented in Table 6.

Table 6. Calculated values of the reliability index (β)

Probabilistic method	Case of correlation matrix			
	Case A ($\rho = 0$)	*Case B* ($\rho = 0.3$)	*Case C* ($\rho = 0.5$)	*Case D* ($\rho = 0.9$)
FORM	5.82	6.86	7.98	11.65
Monte Carlo	5.80	6.85	8.01	11.68

4. DISCUSSION

The analyses of all structures indicate that an increase in the correlation coefficient is associated with a corresponding rise in the reliability index. Across all investigated structural examples, the magnitude of this increase is generally consistent. Specifically, for a correlation coefficient of $\rho = 0.3$, the reliability index β increases by approximately 10%; for $\rho = 0.5$, the increase ranges from 30% to 40%; and for $\rho = 0.9$, the increase reaches approximately 100%. The precise percentage differences in the reliability index across structural scenarios are summarized in Table 7.

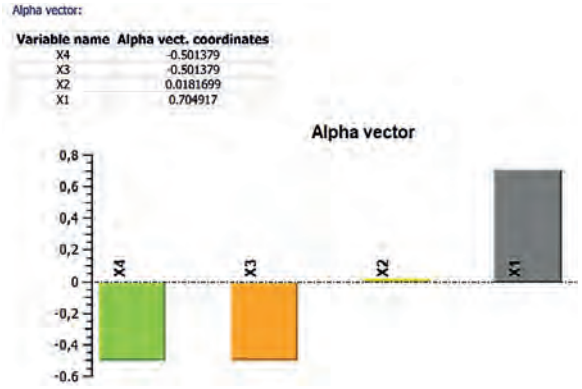
Table 7. Percentage increase in the reliability index (β) by correlation coefficient level, relative to Case A (no correlation)

Example	Case of correlation matrix		
	Case B ($\rho = 0.3$)	*Case C* ($\rho = 0.5$)	*Case D* ($\rho = 0.9$)
1 – „steel beam"	11%	37%	104%
2 – „steel arch"	10%	32%	110%
3 – „steel industrial building"	10%	37%	101%

Another key aspect of the study was to investigate how sensitive the reliability index is to variations in the correlation coefficient. The analysis revealed similar sensitivity values for the reliability index across the four cases (*Case A–Case D*) of the correlation matrix. Consequently, only two representative graphical results of the sensitivity analysis are presented for each example: *Case A* ($\rho = 0$) and *Case D* ($\rho = 0.9$). The corresponding results are illustrated in Figures 4-6.

In the FORM method, the α-vector indicates both the magnitude and the direction of each variable's influence on the reliability index β. The absolute values of the components of the α-vector provide a quantitative measure of the influence of each corresponding variable on the reliability index β. Specifically, variables associated with larger α components exert a greater impact on the reliability index β, whereas those with smaller components contribute less significantly. The sign of each element determines the direction of influence: a positive α increases the probability of failure, reducing the reliability index β, whereas a negative α decreases the probability of failure, increasing β.

a)



b)

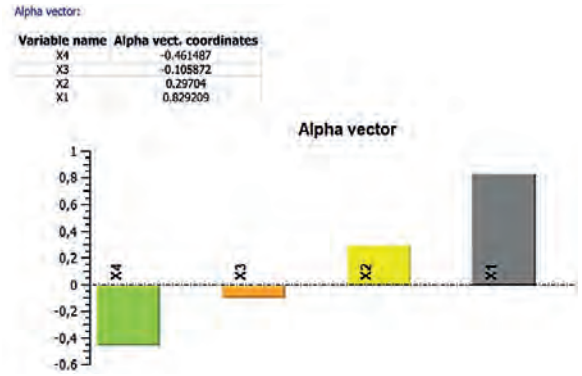
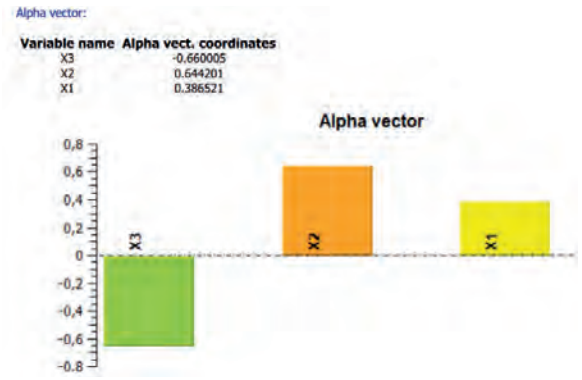


Fig. 4. Sensitivity of the reliability index to random variables for a steel beam: a) $\rho = 0$, b) $\rho = 0.9$

a)



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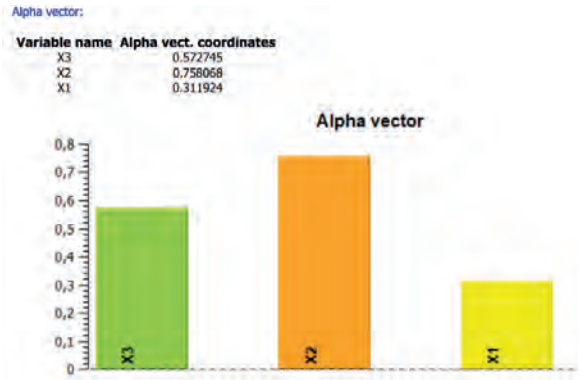
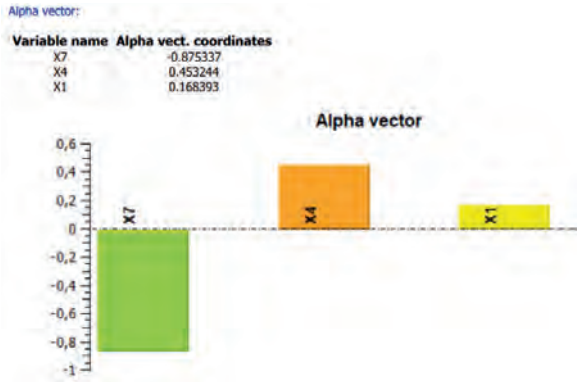


Fig. 5. Sensitivity of the reliability index to random variables for a steel arch: a) $\rho = 0$, b) $\rho = 0.9$

a)



b)

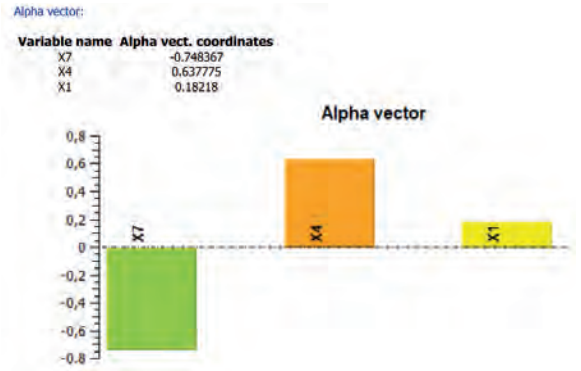


Fig. 6. Sensitivity of the reliability index to random variables for a steel industrial building: a) $\rho = 0$, b) $\rho = 0.9$

The analysis of the results for Example 2 and Example 3 (Figures 5 and 6) indicates that the sensitivity of the reliability index is generally similar across all random variables, regardless of whether they are correlated. In Example 2, the variable X_2 (variable load) exhibits the most significant influence, whereas X_1 (permanent load) has the least impact. Likewise, in Example 3, X_7 (yield point of S235JR steel) exerts the most decisive influence on the reliability index, while X_1 (roof self-weight per meter) has the lowest impact. An interesting phenomenon was observed in Example 2 (Fig. 5). The change in the sign of the α-vector component for variable X_3 from negative to positive indicates that X_3, which previously decreased the probability of failure and increased the reliability index β, now increases the probability of failure, thereby reducing the reliability index β after accounting for correlations. The situation differs in Example 1. For $\rho = 0$, the highest impact on the reliability index is attributed to X_1 (uniform loading), with X_2 (beam length) exerting the least influence. For $\rho = 0.9$, the variable with the lowest impact shifts to X_3 (section modulus of the beam).

It can be concluded that the magnitude of the correlation coefficient significantly influences the sensitivity analysis results.

5. CONCLUSIONS

The analysis of the obtained results confirms that the FORM method provides sufficient accuracy compared with the Monte Carlo method, which is commonly regarded as a reference approach in structural reliability analysis. This observation aligns with conclusions from previous studies, which show that FORM provides reliable estimates of the reliability index β with significantly lower computational effort.

The results clearly indicate that the correlation coefficient between random variables plays a crucial role in the evaluation of structural safety and should not be neglected in reliability analyses. In particular, an increase in the correlation coefficient generally leads to higher values of the reliability index β, in line with trends observed in earlier investigations. Previous research has shown that both the magnitude and the sign of correlation significantly affect the estimated reliability, depending on the characteristics of the limit state function and the interaction between variables.

The study further confirms that proper consideration of correlations between random variables is essential for realistic reliability assessment. Similar conclusions have been reported in the literature, where neglecting correlations can lead to either underestimating or overestimating structural safety. Therefore, developing reliable tools and methodologies for accurately estimating correlation coefficients remains an important research challenge.

An essential aspect of the present study is the sensitivity analysis of the reliability index. The results show that the correlation coefficient directly influences the sensitivity of the reliability index with respect to individual random variables. This observation aligns with previously published findings, which emphasize that correlations affect not only the reliability index itself but also its sensitivity measures. If the sensitivity of the reliability index to a particular random variable X_i is relatively low compared with other variables, that variable may be treated as deterministic in subsequent analyses. Such an approach reduces the number of random variables included in the mathematical model, leading to a significant decrease in computational time without a noticeable loss of accuracy. This strategy has also been recommended in earlier studies as an effective way to improve computational efficiency in reliability analysis.

In summary, the results show that accurately determining correlation coefficients is crucial for accurately describing the behavior and safety of the analyzed structures. Sensitivity analysis is a powerful tool for identifying the most influential random variables and supporting rational model simplification. Together, these aspects contribute to more efficient and reliable structural safety assessments.

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DATA-DRIVEN PREDICTION AND NORMALIZATION OF MECHANICAL PROPERTIES IN JUTE FIBER–REINFORCED CONCRETE

PROGNOZOWANIE I NORMALIZACJA WŁAŚCIWOŚCI MECHANICZNYCH BETONU ZBROJONEGO WŁÓKNAMI JUTOWYMI NA PODSTAWIE WYNIKÓW BADAŃ

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Abstract

Using fiber in the concrete is one of the methods to improve its capacity for the load resisting especially for the bending and tensile loading, but this process has two challenges, the first one is the energy usage, the waste gas emission which produced in these fiber's industry, while the second challenge is the increase in the solid waste materials in the land which is include natural plant fiber. The usage of natural fiber instead of these industrial fibers will have a double advantage. This article deals with investigating the effect of using jute fiber on the properties of concrete, also proposing statistical models to predict the compressive strength of concrete by collecting the experimental data from previous experimental work. By using three different models, including the quadrant support vector machine, Integration Linear, and squared exponential Gaussian, and using 80 experimental data points. Based on the obtained results between the proposed models to predict the compressive strength of concrete, SVM provides higher accuracy and efficiency compared to the other proposed models, when the value of the coefficient of determination is higher than the IL, and SEG by 10.98%, and 1.09% respectively.

Keyword: reinforced concrete, jute fiber, modeling, compressive strength

Streszczenie

Zastosowanie włókien w betonie to jedna z metod poprawy jego wytrzymałości na obciążenia, zwłaszcza zginanie i rozciąganie. Proces ten wiąże się z dwoma wyzwaniami. Pierwszym z nich jest zużycie energii i emisja spalin powstających w przemyśle włókienniczym, a drugim – wzrost ilości odpadów stałych w glebie, w tym naturalnych włókien roślinnych. Zastosowanie włókien naturalnych zamiast włókien przemysłowych przyniesie podwójną korzyść. Niniejszy artykuł analizuje wpływ zastosowania włókien jutowych na właściwości betonu, proponując również modele statystyczne do przewidywania wytrzymałości betonu na ściskanie poprzez zebranie danych eksperymentalnych z poprzednich badań laboratoryjnych, z wykorzystaniem trzech różnych modeli, w tym kwadrantowej maszyny wektorów nośnych (SVM), interakcji liniowej (IL) i gaussowskiej radialnej funkcji bazowej (SEG), a także 80 punktów danych eksperymentalnych. Na podstawie uzyskanych wyników pomiędzy proponowanymi modelami przewidywania wytrzymałości betonu na ściskanie SVM zapewnia wyższą dokładność i wydajność w porównaniu z innymi proponowanymi modelami, podczas gdy wartość współczynnika determinacji jest wyższa niż w przypadku IL i SEG, odpowiednio o 10,98% i 1,09%.

Słowa kluczowe: beton zbrojony, włókna jutowe, modelowanie, wytrzymałość na ściskanie

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1. INTRODUCTION

The growing demand for sustainability in the construction sector has motivated researchers particularly in developing countries to explore environmentally responsible alternatives to conventional building materials [1]. Among these materials, concrete and mortar are the most widely used, forming the backbone of modern infrastructure systems due to their versatility, availability, and cost-effectiveness [2].

Concrete, which is the second most consumed material on Earth after water, is composed primarily of a binder (typically Portland cement), water, and aggregates [3]. Globally, its use is estimated at approximately 1.7 m^3 per person per year, reflecting the essential role it plays in construction and urban development [4]. Despite its widespread use and ability to provide sufficient compressive strength for structural applications, conventional concrete suffers from an inherent brittleness, which limits its deformation capacity and resistance to cracking [5, 6]. This mechanical limitation has led researchers to investigate modifications and alternative materials that can enhance its ductility, durability, and overall performance while also reducing environmental impacts.

One of the solutions to improve the ductility of the concrete is the usage of fibers such as steel, glass, carbon, and polypropylene fiber, which change the concrete to reinforced concrete [7-9]. Many researches has been done on the usage of different types of fiber in concrete with various rates [10-13]. Many factors affect the behavior or working of the fiber in the concrete, including fiber forms, mixing proportion, fiber geometry, surface condition of fiber, and curing method [14, 15]. The production process of each type of these fibers will need a high rate of energy and lead to a high rate of greenhouse gas emission into the air [16, 17]. With the population increase, the solid waste materials production including agricultural wastes will increase day by day [18-20]. One of the agricultural wastes is agricultural material that can be able to make fibers [21-23]. The usage of the plant or natural fiber in the construction has long history due to easy availability in the nature and did not required high effort for preparation, low density, renewable, biodegradable and ready available [24-26]. Available fibers which consider as a member in natural fiber groups are bamboo, coconut, sisal, straw, aloe vera fibers, banana, and pine [27-30].

Jute Fiber is obtained from the jute plant, which is low-cost, durable, has high moisture retention capacity, and is biodegradable. The jute fiber during the degradation process will not generate gas or toxic material since it is composed of cellulose [31-34]. Bangladesh is considered the main producer of the jute fiber, which produces more than half of the total jute produced in the world [35-37]. The use of the jute fiber in the concrete will cause an increase in the concrete's ability against tensile stress, flexural stress, fatigue, and thermal shock [38-41].

Islam and Ahmed [42] investigate the usage of jute fiber in concrete at four different rates, including 0, 0.25, 0.5, and 1%, to demonstrate its effect on concrete properties, including compressive strength. According to the obtained result with the increase of the used rate of jute fiber increase compressive strength of the concrete by 0.76, and 3.03% with using 0.5% of jute fiber in 7 and 28 days curing, while when prepared samples have been tested at 91 days, the compressive strength of the modified concrete will be higher than control mix by 17.14% when modified by 0.25%, but the mix that contains 0.5% of jute fiber provide same compressive strength as control mix. Razmi and Mirsayar, [43], used jute fiber in the normal strength concrete with four different rate (0, 0.1, 0.3, and 0.5%), to measure its effect on the compressive strength property which showed that, the usage of the jute fiber provide compressive strength higher than control mix by 40, 36.5% with using jute fiber up to 0.5% at both curing time 7, and 28 days. Asaduzzaman and Islam [44] used jute fiber with five different rates (0, 0.1, 0.2, 0.3, and 0.4%), in the normal strength concrete at three different curing times (7, 14, and 28 days). The compressive strength test result showed that at the seven days curing all the mixed which modified with jute fiber provide compressive strength lower than the control mix, while by 28 days the concrete mixes which modified with 0.1, and 0.2% of jute fiber provide compressive strength higher that the control mix by 5.88, 2.94%. The usage of the jute fiber more than 0.2%, will provide compressive strength lower than control mix. Using 0.3 and 0.4% of jute fiber decrease the compressive strength by 3.03, 5.88%. Ahmad et al. [46] used three different statistical models, including linear regression, non-linear regression, and artificial neural networks, to propose an accurate and efficient model for predicting the compressive strength of mortar modified with different rates of carbon nanotubes, based on 86 data points collected from previous experimental work. Based on the obtained result, the artificial neural network provides higher accuracy and efficiency compared to the other models. Karim et al, [47], investigated the usage of the statistical

models to predict the compressive strength of mortar modified with palm oil fuel ash by using three different statistical model including linear regression, non-linear regression, and artificial neural network to propose an accurate and efficient model through the usage of 142 number data which collected from previous experimental work. Based on the obtained result the artificial neural network provide higher accuracy and efficiency compare to the other models. Askari et al. [48] collected 124 experimental data points about the usage of different pozzolanic materials in ultra-high-performance concrete to propose an efficient and accurate statistical model to reduce the time and the cost for predicting the compressive strength of the mixed material. For that reason, three different statistical models have been used, including a support vector machine, an ensemble boosting tree, and an artificial neural network. In this article, ensemble boosting tree provides more accurate and efficient predicted values of compressive strength compared to the other models used. This article deals with the usage of jute fiber in the normal-strength concrete with investigation of the jute effect on the slump, compression, flexural, and tensile strength of concrete based on the collected data from previous experimental work. Lastly, a statistical model is proposed to predict the compressive strength of the concrete modified with jute fiber at different rates.

2. RESEARCH SIGNIFICANT

In this article, instead of the usage of industrial fiber in the concrete, natural fiber will be used, which causes (i) a reduction in the effect of the industrial production on the environment since it causes a reduction in the energy usage and lower waste gas production due to the reduction in the production of industrial fiber. (ii) Can be obtained from nature, which means it can be obtained at a lower cost compared to the other type of fiber, which is produced industrially. (iii) Propose the statistical models with using different form of models (Squared Exponential Gaussian, Quadratic SVM, Interation Linear) to predict the compressive strength of the reinforced concrete with Jute fiber with variable dosages and without trail mx, with choosing the most efficient model according to the obtained value of the assessment tools, (iv) showing the effect of using jute fiber in the properties of concrete such as the slump, flexural, tensile, and compressive strength, with explaining the role of fiber length.

3. RESEARCH METHODOLOGY

At the first step in this article, the experimental data about the usage of the jute fiber with different dosages in the previous experimental work in the literature have been collected with knowing the value of water to cement ratio, cement content, sand content, coarse aggregate content, curing time, and the used rate of fiber. From the collected data, the effect of using Jute fiber on the slump, compressive strength, flexural strength, and tensile strength has been explained. At the final step, the collected data will be statistically analyzed, and randomly divided into two groups of data, one a which is training data, and testing data. The numbers of collected data are 80 data points, with dividing them to two groups: 56 training data, which was used to propose the form of the model, and 24 as testing data, which was used to test the accuracy of the proposed model. The used form of models in this article, are Squared Exponential Gaussian (SEG), Quadratic SVM (Q-SVM), and Interation Linear (IL) as shown in Figure 1. For each models which proposed the value of Coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE) and scatter index (SI), have been found to compare to the other models value with selecting the most efficient and accurate model between proposed models.

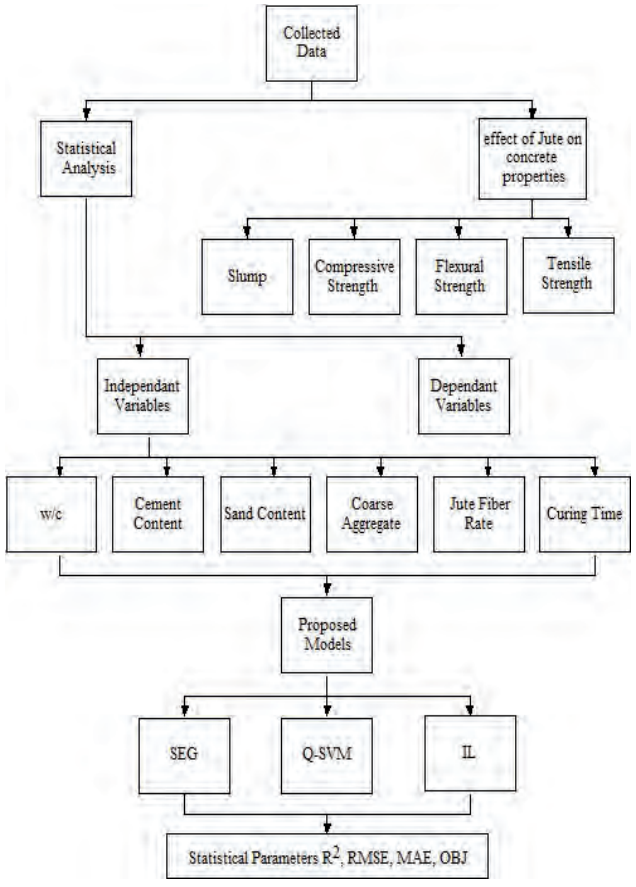

Fig. 1. Research program and methodology

4. EFFECT OF JUTE FIBER ON THE CONCRETE PROPERTIES

4.1. Slump

As explained in Figure 2, with the increase in the jute fiber usage the slump value of the concrete decreases due to the water absorption ability, that effects the mix composition. Islam and Ahmed, [42], used jute fiber with four different rate (0, 0.25, 0.5, and 1%) to investigate their effect on the slump value, when 0.25% of jute fiber has been added to the concrete, the slump value has been decreased by thirty percent compare to the control mix, also when the used rate become 1% the decrease rate become 90%. The changing process in the slump value was the same in the shape and decrease when Asaduzzaman and Islam. [44], used jute fiber in the concrete with five different rates (0, 0.1, 0.2, 0.3, and 0.4%).

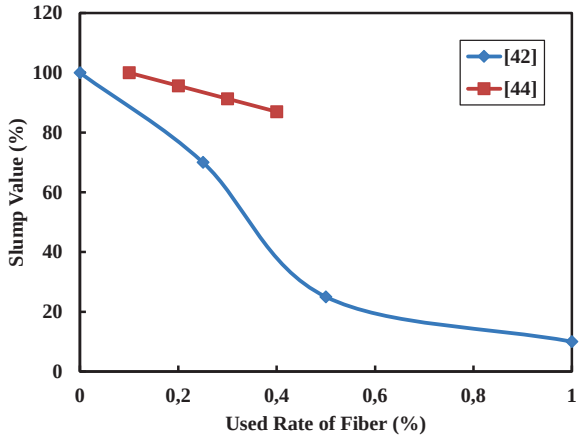

Fig. 2. Slump value based on the used rate of the jute fiber

4.2. Compressive Strength

Based on the collected data from previous experimental work on the effect of jute fiber on the compressive strength of normal strength concrete, which has been expressed in Figure 3, the optimum rate of the jute fiber will be change based on many factors, which are the length, diameter of the fiber, w/c, with many other factors. On the article which is published by Islam and Ahmed, [42], which obtained that when the concrete has been modified with different rate of jute fiber, the usage of 0.25% of jute fiber provide optimum increase in the compressive strength value which is 12.12% higher than control mix compare to the control mix. When Gupta et al. [45], has used jute fiber in the contrete the obtimum usage rate of jute fiber was 0.3% that increase the compressive strength by 12.45% compare to th contro mix, but the optimum rate was 0.5% in the published investigation by Razmi and Mirsayar, [43], with change in the increase rate of compressive strength value compare to the control mix which was 36.91%. The obtained result by Asaduzzaman and Islam [44], were differed from other expressed manuscripts, since by using 0.1% of jute fiber, the increase in the compressive strength was 5.88%.

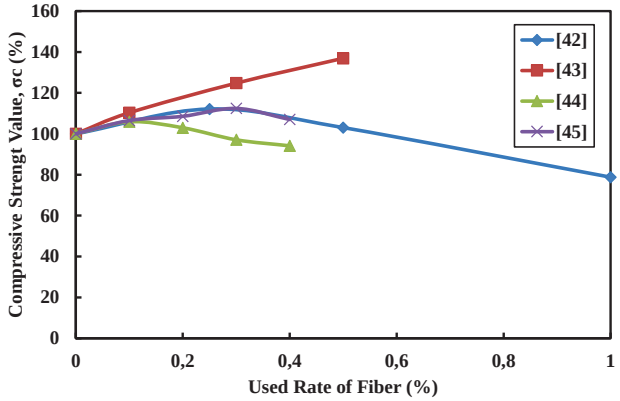

Fig. 3. Compressive strength value based on the used rate of the jute fiber

4.3. Flexural Strength

Due to the role of the fiber as the crack raster in the concrete mix, the concrete is more able to resist the flexural strength when subjected to the bending load. The same result has been obtained compared to the Razmi and Mirsayar [43], when using jute fiber with four different rates, including 0, 10, 30, and 40%. When the control mix does not contain jute fiber, the flexural strength will be 100. When the used rate of jute fiber becomes 0.1% the flexural strength increases by 5.53%. When the used rate of the jute fiber becomes 0.4% the increase rate in the flexural strength becomes 10.31%.

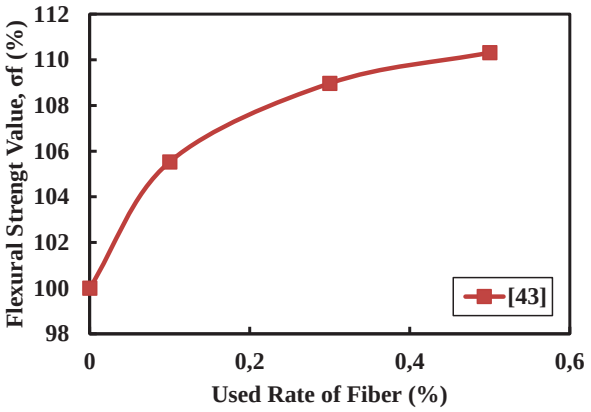

Fig. 4. Flexural strength value based on the used rate of the jute fiber

4.4. Tensile Strength

Fiber, when used in the concrete, increases the bond between the mix composition particles, bridging the crack together, increases the time of the failure due

to the lateral or bending stress, but the optimum rate, as shown in Figure 5, will change based on the factor discussed in the previous work. The optimum rate or dosage of the jute fiber were 0.5% where investigated by Razmi and Mirsayar, [43], since increase the tensile strength by 16.95%, but the optimum dosage changes and become 0.1% in the investigation by Asaduzzaman and Islam, [44], and the increase rate in tensile strength become 6.66%, while the optimum dosage become 0.3% in the investigation by Gupta et al. [45], the increase rate in the tensile strength become 58.2%.

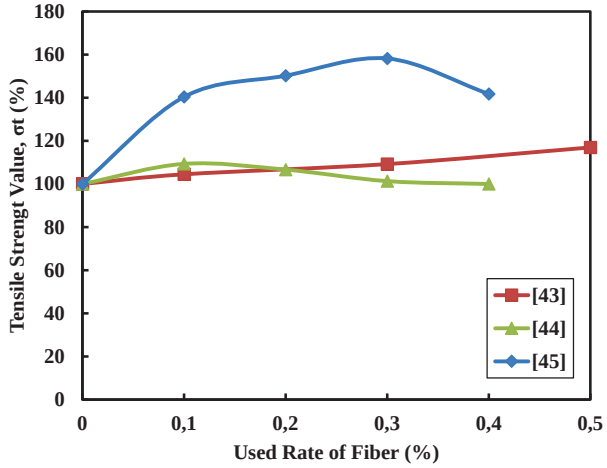

Fig. 5. Tensile strength value based on the used rate of the jute fiber

4.5. Effect of fiber length on compressive strength of modified concrete

Based on the obtained result as expressed in the Figure. 6, when Islam and Ahmed, [42], used jute fiber in the concrete by four different rate with two different length, in both length using 0.25% of jute fiber provide optimum increase in the compressive strength compare to the control mix while when the fiber length was 10 cm, the increase rate in the compressive strength was higher compare to the used fiber when its length is 20 cm. Opposite result obtained by Asaduzzaman and Islam, [44]. When jute fiber was used at four different rates with two different lengths. In both sets of jute fiber usage, the optimum rate was 0.1% but the increase rate in the compressive strength compared to the control mix was higher when the fiber length was 25 cm compared to the jute fiber with a 20 cm length.

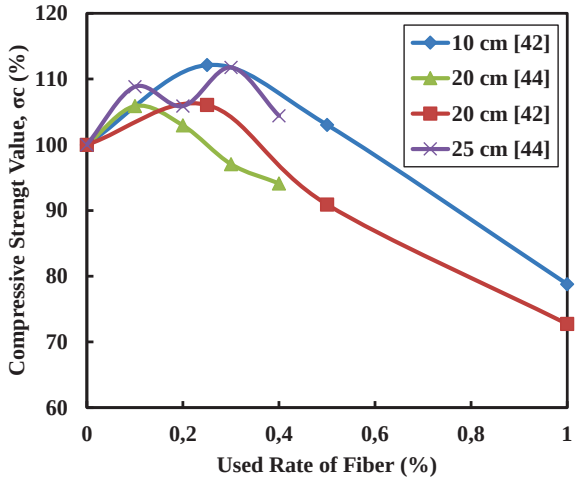

Fig. 6. Compressive strength value based on the used fiber length

5. DATA COLLECTION AND STATISTICAL ANALYSIS:

5.1. Data Collections

The collected data from previous experimental work are as expressed in Table 1.

Table 1. The collected data from previous experimental work

References	w/c	Cement Content (kg/m^3)	Sand Content (kg/m^3)	Coarse Aggregate (kg/m^3)	Fiber rate (%)	Curing Time (Days)	Compressive Strength (MPa)
[42]	0.42	467.4	595.1	999.1	0	7	26
	0.42	467.4	595.1	999.1	0.25	7	27
	0.42	467.4	595.1	999.1	0.5	7	28
	0.42	467.4	595.1	999.1	1	7	24
	0.42	467.4	595.1	999.1	0	7	26
	0.42	467.4	595.1	999.1	0.25	7	27
	0.42	467.4	595.1	999.1	0.5	7	22
	0.42	467.4	595.1	999.1	1	7	18
	0.42	467.4	595.1	999.1	0	28	33
	0.42	467.4	595.1	999.1	0.25	28	37
	0.42	467.4	595.1	999.1	0.5	28	34

References	w/c	Cement Content (kg/m^3)	Sand Content (kg/m^3)	Coarse Aggregate (kg/m^3)	Fiber rate (%)	Curing Time (Days)	Compressive Strength (MPa)
[42]	0.42	467.4	595.1	999.1	1	28	26
	0.42	467.4	595.1	999.1	0	28	33
	0.42	467.4	595.1	999.1	0.25	28	35
	0.42	467.4	595.1	999.1	0.5	28	30
	0.42	467.4	595.1	999.1	1	28	24
	0.42	467.4	595.1	999.1	0	91	35
	0.42	467.4	595.1	999.1	0.25	91	41
	0.42	467.4	595.1	999.1	0.5	91	35
	0.42	467.4	595.1	999.1	1	91	30
	0.42	467.4	595.1	999.1	0	91	35
	0.42	467.4	595.1	999.1	0.25	91	36
	0.42	467.4	595.1	999.1	0.5	91	34
	0.42	467.4	595.1	999.1	1	91	25
[43]	0.46	350	972	862	0	7	35
	0.46	350	972	862	0.1	7	40
	0.46	350	972	862	0.3	7	43
	0.46	350	972	862	0.5	7	49
	0.46	350	972	862	0	28	41
	0.46	350	972	862	0.1	28	45
	0.46	350	972	862	0.3	28	51
	0.46	350	972	862	0.5	28	56
[44]	0.44	405	755	1000	0	7	31
	0.44	405	755	1000	0.1	7	31
	0.44	405	755	1000	0.2	7	31
	0.44	405	755	1000	0.3	7	27
	0.44	405	755	1000	0.4	7	26
	0.44	405	755	1000	0	14	33
	0.44	405	755	1000	0.1	14	33
	0.44	405	755	1000	0.2	14	33
	0.44	405	755	1000	0.3	14	32
	0.44	405	755	1000	0.4	14	31
	0.44	405	755	1000	0	28	34
	0.44	405	755	1000	0.1	28	36
	0.44	405	755	1000	0.2	28	35
	0.44	405	755	1000	0.3	28	33
	0.44	405	755	1000	0.4	28	32
	0.44	405	755	1000	0	7	31

References	w/c	Cement Content (kg/m^3)	Sand Content (kg/m^3)	Coarse Aggregate (kg/m^3)	Fiber rate (%)	Curing Time (Days)	Compressive Strength (MPa)
[44]	0.44	405	755	1000	0.1	7	30
	0.44	405	755	1000	0.2	7	28
	0.44	405	755	1000	0.3	7	27
	0.44	405	755	1000	0.4	7	26
	0.44	405	755	1000	0	14	33
	0.44	405	755	1000	0.1	14	32
	0.44	405	755	1000	0.2	14	32
	0.44	405	755	1000	0.3	14	31
	0.44	405	755	1000	0.4	14	30
	0.44	405	755	1000	0	28	34
	0.44	405	755	1000	0.1	28	37
	0.44	405	755	1000	0.2	28	36
	0.44	405	755	1000	0.3	28	38
	0.44	405	755	1000	0.4	28	36
[45]	0.379	566	565	999	0	7	21
	0.383	566	565	999	0.1	7	25
	0.385	566	565	999	0.2	7	26
	0.39	566	565	999	0.3	7	26
	0.392	566	565	999	0.4	7	26
	0.381	566	565	999	0.1	7	23
	0.385	566	565	999	0.2	7	24
	0.39	566	565	999	0.3	7	25
	0.393	566	565	999	0.4	7	24
	0.379	566	565	999	0	28	37
	0.383	566	565	999	0.1	28	39
	0.385	566	565	999	0.2	28	40
	0.39	566	565	999	0.3	28	41
	0.392	566	565	999	0.4	28	39
	0.381	566	565	999	0.1	28	37
	0.385	566	565	999	0.2	28	38
	0.39	566	565	999	0.3	28	39
	0.393	566	565	999	0.4	28	38

5.2. Statistical Analyses

For the collected data as expressed in the Table 1, histogram distribution has been drawn for each independent parameters including, w/c, cement content, sand content, coarse aggregate content, used rate of fiber, curing time as shown in Figures 7, 9, 11, 13, 15, 17, also the scatter relation between each independent parameters lonely has been drawn with dependent parameters (compressive strength) as shown in Figures 8, 10, 12, 14, 16, 18.

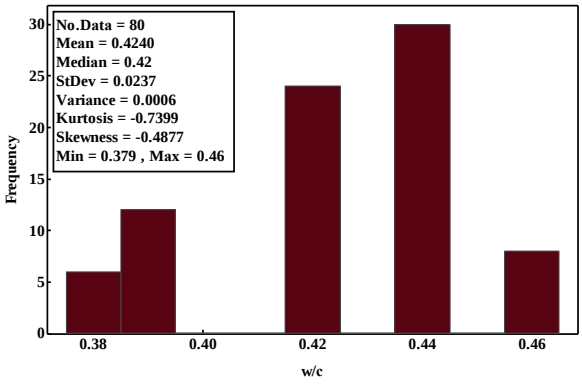

Fig. 7. Histogram distribution of w/c

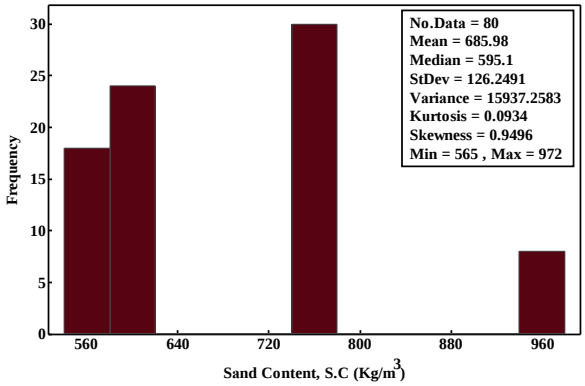

Fig. 11. Histogram distribution of sand content

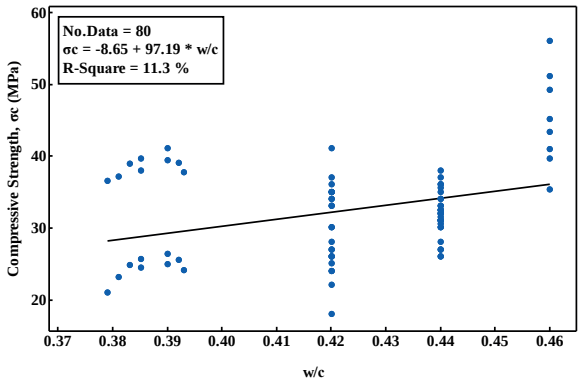

Fig. 8. Scatter relation between w/c and compressive strength

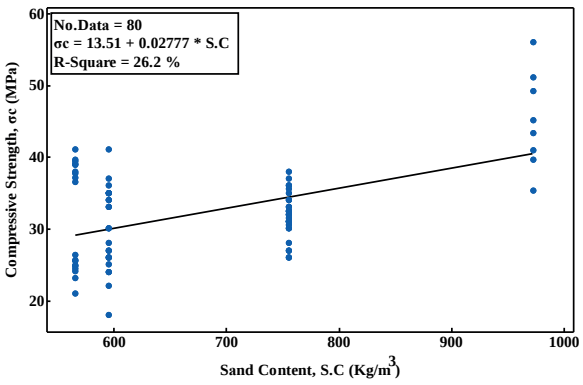

Fig. 12. Scatter relation between sand content and compressive strength

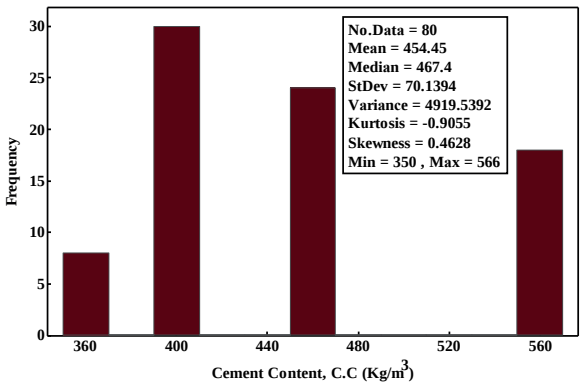

Fig. 9. Histogram distribution of cement content

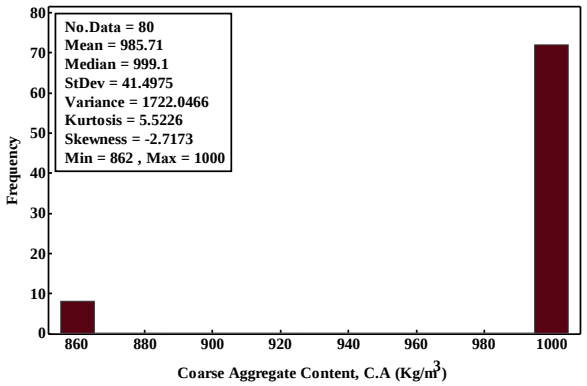

Fig. 13. Histogram distribution of coarse aggregate content

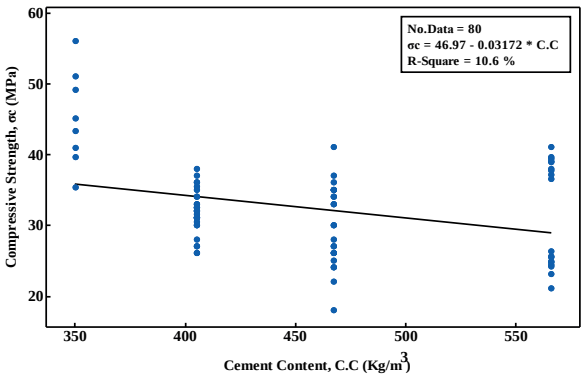

Fig. 10. Scatter relation between cement content and compressive strength

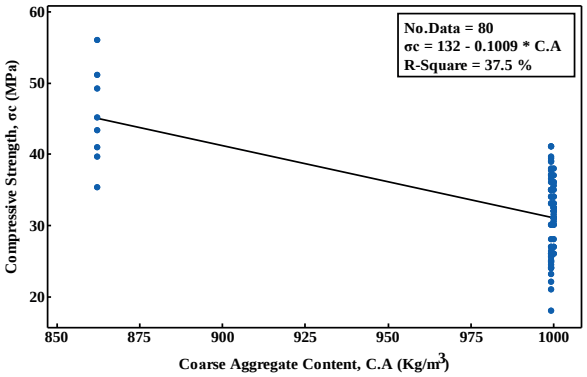

Fig. 14. Scatter relation between coarse aggregate and compressive strength

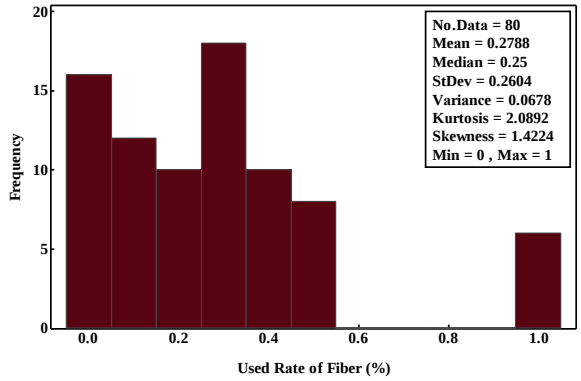

Fig. 15. Histogram distribution of used ratio of fiber

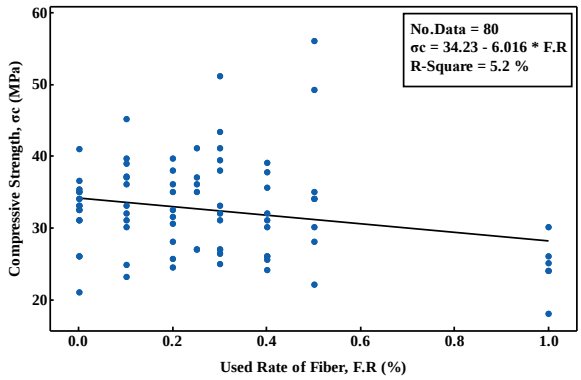

Fig. 16. Scatter relation between used rate of fiber and compressive strength

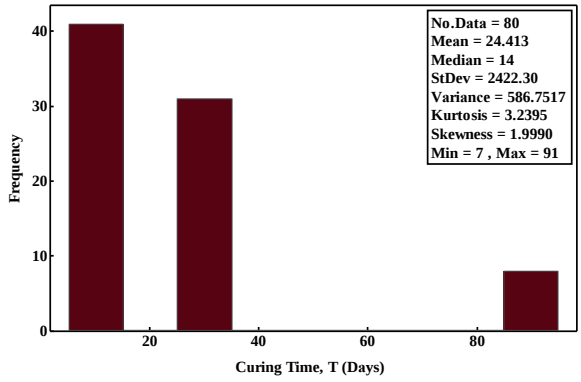

Fig. 17. Histogram distribution of curing time

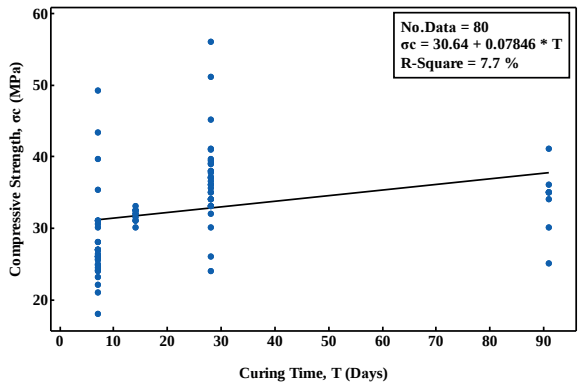

Fig. 18. Scatter relation between curing time and compressive strength

5.3. Modeling

Since the relation between independent parameters lonely with dependent parameters were not with adequate accuracy and efficiency, all the independent parameters have been used in the form of one model to create the relation with dependent parameter as expressed in the following section.

5.3.1. Squared Exponential Gaussian

The Squared Exponential Gaussian, also known as the Radial Basis Function (RBF) kernel, is widely used in statistical modeling and machine learning, particularly within Gaussian Processes (GPs). It is a type of covariance function that assumes that points closer in input space have more similar output values.

This kernel assumes infinitely differentiable functions, making it suitable for modeling very smooth processes. It is commonly used in applications such as time series forecasting, regression, and spatial statistics. However, one of its limitations is that it can be overly smooth and may not perform well when modeling functions with high variability or discontinuities [49].

In practice, the Squared Exponential Gaussian is valued for its mathematical convenience and strong prior assumptions about function smoothness. It is often contrasted with other kernels such as the Matérn kernel, which allows for rougher functions and offers more flexibility in some real-world scenarios [50].

5.3.2. Integration Linear

Linear interaction refers to the inclusion of interaction terms in a linear model to capture the effect of two or more variables acting together on a response. In a basic linear regression, the assumption is that each predictor contributes independently to the outcome. However, when variables interact, the effect of one variable depends on the level of another. This is modeled by adding a product term to the equation [51].

For example, in social sciences, the effect of education on income might depend on gender. Without modeling this interaction, we risk oversimplifying complex relationships. Including interaction terms helps improve model accuracy and interpretability in such contexts [52].

5.3.3. Quadratic Support Vector Machine

A Quadratic Support Vector Machine (QSVM) is a type of Support Vector Machine (SVM) that uses a quadratic kernel to separate data that is not

linearly separable. Unlike linear SVMs, which draw a straight hyperplane, QSVMs project input data into a higher-dimensional space using a second-degree polynomial kernel, allowing for more flexible decision boundaries. This method is particularly effective in complex classification problems where the relationship between features is nonlinear. The kernel function, often written as $K(x, y) = (x^T y + c)^2$, helps the SVM to identify curved boundaries in the feature space, increasing classification accuracy in various applications, such as image recognition and bioinformatics [53, 54].

5.3.4. Assessment tools for proposed modeling

The following parameter is taken while comparing the results for the above modeling:

$$R^2 = 1 - \frac{\sum(Yi - Yp)^2}{\sum(Yi - Mean)^2} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum(Yi - Yp)^2}{N}} \quad (2)$$

$$SI = \frac{RMSE}{Mean} \cdot 100 \quad (3)$$

$$MAE = \frac{\sum(Yi - Yp)}{n} \quad (4)$$

Based on the used statistical parameters, the higher R^2 value will be more desirable and the model with $SI > 0.3$ will consider as bad performance while $0.2 < SI < 0.3$ consider acceptable performance and $0.1 < SI < 0.2$ consider excellent performance but if $0 < SI < 0.1$ will measure as great performance [55-57].

6. RESULT AND DISCUSSIONS

6.1. Squared Exponential Gaussian (SEG)

Due to the usage of the algorithm, by using collected data, the model has been proposed as black box system, based on the proposed models for the testing data which has been separated randomly on the collected data set, the value of the compressive strength or each measured compressive strength have been predicted. The scatter relation between measured and predicted compressive strength using squared exponential Gaussian models as in the Figure 19. The measured value of the coefficient of determination in the model was 0.9.

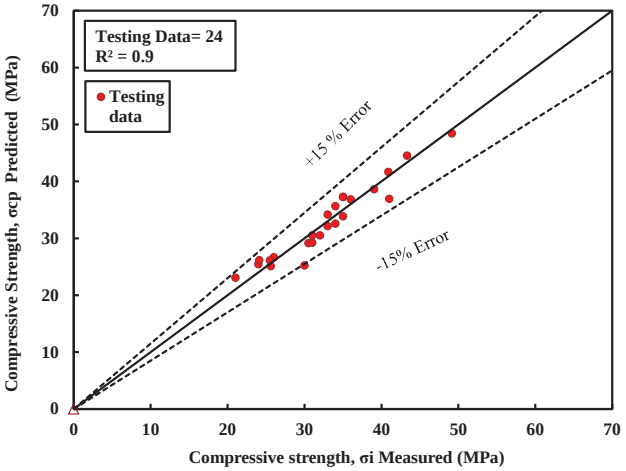

Fig. 19. Correlation between measured and predicted compressive strength using SEG

6.2. Integration Linear (IL)

With the previous model, two other algorithm have been used, to chose most efficient and accurate model. By using collected data, the model has been proposed as black box system, based on the proposed models for the testing data which has been separated randomly on the collected data set, the value of the compressive strength or each measured compressive strength have been predicted. The scatter relation between measured and predicted compressive strength using Integration Linear models as in the Figure 20. The measured value of the coefficient of determination in the model was 0.9.

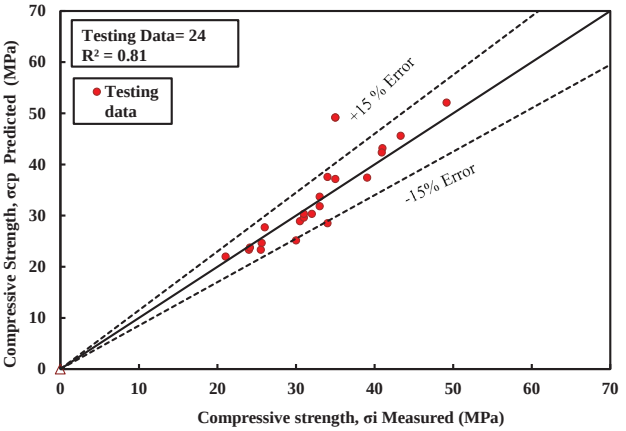

Fig. 20. Correlation between measured and predicted compressive strength using IL

6.3. Quadratic Support Vector Machine (QSVM)

As the third models, this form also has been used to propose model with high accuracy and efficiency. The scatter relation between measured and predicted compressive strength using Integration Linear models as in the Figure 21. The measured value of the coefficient of determination in the model was

0.91 which make it to be most attractive, accuracy, and efficiency model based on the value of coefficient of determination.

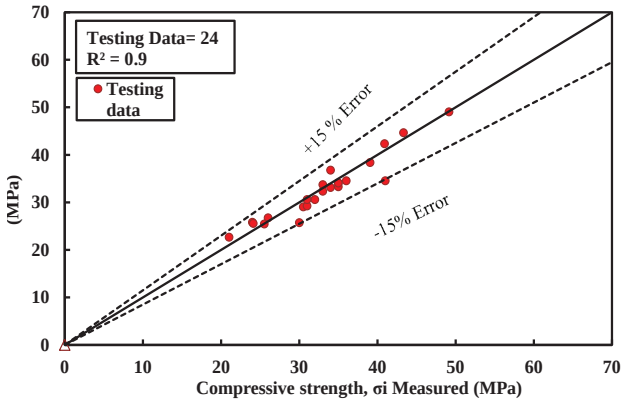

Fig. 21. Correlation between measured and predicted compressive strength using QSVM

6.4. Model Comparisons

Based on the obtained result as expressed in the Table 2, quadratic support vector machine model provide higher accuracy com pare to the Integration Linear, and Squared Exponential Gaussian since the value of coefficient of determination higher that the coefficient of determination in IL, and SEG by 10.98, and 1.09% respectively, the value of root mean square error (RMSE) in QSVM lower than the RMSE in IL, and SEG by 42.25% and 2.91, also value of mean absolute error (MAE) in QSVM lower than the RMSE in IL, and SEG by 30.34, and 10.9%

Table 2. Statistical assessment tools value for different proposed models

Models	IL Testing	SEG Testing	QSVM Testing
R^2 (%)	0.81	0.9	0.91
RMSE (MPa)	3.03	2.192	2.13
MAE (MPa)	1.89	1.609	1.45

7. CONCLUSIONS

After reviewing the previous experimental work on the usage of jute fiber in the concrete, and investigating their effect on the properties of concrete, by proposing different statistical models to predict the compressive strength of concrete, the following conclusions have been drawn:

1. The incorporation of jute fiber into concrete consistently led to a reduction in workability, with the magnitude of this decrease intensifying as fiber content increased. This behaviour is primarily attributed to the high surface area and hydrophilic nature of jute fibers, which promote increased water demand and internal friction within the mix. These findings underscore the necessity for appropriate adjustments in mix design when natural fibers are utilized, particularly in applications where flow ability is critical.
2. The results indicate that jute fiber enhances the compressive strength of concrete up to an optimum dosage, beyond which further increases in fiber content adversely affect strength development. The reduction in strength at higher fiber dosages may be associated with fiber clustering, inadequate dispersion, and the formation of micro-voids. Notably, the optimal fiber content is mix-dependent, varying according to parameters such as water–cement ratio, aggregate characteristics, and fiber geometry. This highlights the importance of conducting mix-specific optimization studies to maximize the mechanical benefits of natural fiber inclusion.
3. Among the evaluated predictive models, the Support Vector Machine (SVM) exhibited superior accuracy and generalization capability for estimating the compressive strength of jute fiber–reinforced concrete. The SVM model achieved a higher coefficient of determination relative to the IL and SEG models by 10.98% and 1.09%, respectively. These outcomes affirm the robustness of SVM for modeling nonlinear relationships in concrete performance and suggest its potential applicability in broader predictive frameworks for sustainable construction materials.
4. The findings indicate that jute fiber–reinforced concrete, when used at optimal dosages, is suitable for various non-structural and semi-structural applications, such as paving blocks, panels, and partition elements where improved toughness is required. The successful use of the SVM model further provides a practical tool for optimizing mix proportions, supporting the broader use of natural fibers as a sustainable and cost-effective alternative in concrete production.

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NEW MODEL OF A THERMAL WASTE TREATMENT PLANT IN THE STRUCTURE OF A SUSTAINABLE CITY – ACCESSIBILITY ANALYSIS ON THE EXAMPLE OF COPENHAGEN

NOWY MODEL ZAKŁADU TERMICZNEGO PRZEKSZTAŁCANIA ODPADÓW W STRUKTURZE MIASTA ZRÓWNOWAŻONEGO – ANALIZA DOSTĘPNOŚCI NA PRZYKŁADZIE KOPENHAGI

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Abstract

Amager Bakke (CopenHill) is an example of a modern architectural solution for a technical facility serving the city. Thanks to its additional recreational and educational functions (ski slope, climbing wall, green terraces, etc.), it constitutes a significant element of the urban fabric, enhancing its attractiveness. Accessibility studies of the facility demonstrated its good integration with the city's public transport system (20/30 points). A strength is its good accessibility thanks to a network of bicycle paths (within 10 minutes of the city center), which is crucial to Copenhagen's mobility plans. A weakness, however, is the lack of efficient multimodality due to the lack of a nearby metro station, which is problematic in such an intensively revitalized area as the district where Amager Bakke is located. From a circular economy perspective, CopenHill is the final element of waste neutralization coupled with energy recovery, which raises questions about the environmental sustainability of the incineration process and the need for its technical support in the absence of waste.

Keywords: Amager Bakke, circular economy, eco-friendly facilities, Copenhagen, sustainable city, waste to energy plant, CopenHill

Streszczenie

Amager Bakke (CopenHill) to przykład nowoczesnego rozwiązania architektonicznego obiektu technicznego zaplecza obsługi miasta, który dzięki dodatkowym funkcjom rekreacyjnym i edukacyjnym (stok narciarski, ścianka wspinaczkowa, zielone terasy i in.) stanowi istotny element rewitalizowanej tkanki miejskiej, podnoszący jej atrakcyjność. Przeprowadzone badania dostępności obiektu wykazały jego dobrą integrację z systemem miejskiego transportu (20/30 pkt). Silną stroną jest jego dobra dostępność dzięki sieci ścieżek rowerowych (dojazd do 10 minut z centrum), tak istotnych w planach mobilności Kopenhagi. Słabą natomiast – brak sprawnie funkcjonującej multimodalności z uwagi na brak bliskiej lokalizacji stacji metra, co jest problematyczne w przypadku tak intensywnie rewitalizowanego obszaru, jakim jest dzielnica, w której mieści się Amager Bakke. Z punktu widzenia circular economy CopenHill jest ostatnim elementem neutralizacji odpadów sprzężonym z odzyskiem energii, co rodzi jednak pytania o ekologiczność procesu spalania i konieczności jego technicznego podtrzymywania w przypadku braku odpadów.

Słowa kluczowe: Amager Bakke, gospodarka obiegu zamkniętego, obiekty proekologiczne, Kopenhaga, miasto zrównoważone, zakład termicznego przekształcania odpadów, ekospalarnia

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1. INTRODUCTION

The significant increase in municipal waste production – apart from the obvious impact on the human environment – also has an indirect but significant impact on the transformations taking place in the structures of European cities. European Union member states have been obliged by Directive (EU) 2018/850 of 30 May 2018 [1], which amends Directive 1999/31/EC [2], to dispose of a maximum of 10% of municipal waste in landfills by the end of 2035, and to find alternative solutions for managing the waste generated. At the same time, numerous scientific studies demonstrate the harmful impact of landfills [3-5]. Both research findings and legal regulations make it necessary to find alternative waste management methods. This applies not only to the previously mentioned European Union member states but is also a topic of global discussion [6, 7]. The most effective way to solve the waste problem is to reduce its generation. This method, while obvious, requires comprehensive and coordinated action at the level of multidimensional economic processes (on an international, national, and urban scale) as well as individual, informed practices of residents. These initiatives encompass waste management solutions, technological and technical innovations, and, above all, environmental education initiatives. Both these processes, and the resulting increase in environmental awareness among residents, take time. However, solving the problem of municipal waste treatment is needed now. An effective and relatively quick solution is the construction of new, environmentally friendly waste incineration plants. As mentioned earlier, this isn't the best possible solution, but-as demonstrated by the experience of countries that have decided to build such facilities [8, 9] – it provides an effective and feasible solution for neutralizing waste generated today. Contemporary facilities built for this purpose resemble their 19'th-century predecessors only in name. New technical and technological solutions have enabled them to meet environmental protection standards consistent with international regulations and individual national regulations. Nevertheless, in many cases, their construction sparks heated debate and may provoke strong public opposition [10]. In addition to their primary function, contemporary eco-incinerators also serve two roles:

- Due to the potential offered by current developments in waste processing technologies, they produce electricity and heat through cogeneration. However, it should be noted that obtaining energy in this way is not an end in itself, but rather provides added value to the waste processing process. Energy produced through waste incineration is not considered a renewable energy source that can compete with wind or solar energy, because – by definition – the idea of unrestricted waste generation and then extracting energy from it, for example, through incineration, is unsustainable and highly detrimental to environmental protection [11].
- Due to new technical and technological solutions, design possibilities, and architectural ideas, eco-incinerators are also often implemented as hybrid facilities [12], combining waste processing, heat and electricity generation, with additional functions such as recreation or environmental education. Thus, due to their multifunctionality, they can play a significant role in the urban fabric, becoming centers of activity for the surrounding urban structure. This can be particularly important when implementing such investments in suburban areas. The chaotic development of such areas due to urbanization processes has often meant that they are not equipped with attractive places for activity.

1.1. Literature review

Modern waste incineration plants are not just urban engineering. Eco-incinerators, built according to the hybrid concept, are also essential elements of urban structures, both visually and functionally [12]. Due to the topical nature of this topic, research on how to reduce the amount of waste generated, how to process it, and how to dispose of it is one of the most important and intensively developed research topics. These include activities on a very broad scale, from sociological analyses to technical and technological experiments. Due to the functional transformation of such facilities, and the resulting changes in their location, they are increasingly becoming a focus of research in urban planning, spatial planning, and social initiatives. In this context, research on residents' acceptance (or lack thereof) of the location of thermal waste treatment plants is particularly intensive [13]. This phenomenon can be considered multidimensionally – for example, depending on the intensity of the country's economic development, the level of environmental education in society, and others. Such technological solutions can often generate negative social relations. This is most often related to a lack of environmental education and, above all, neglect of social dialogue during

the investment siting and design process. Concerns primarily concern air pollution, and consequently, the long-term health risks to residents, as well as the potential for project failure [14]. An example of this dynamic is the attempt to build eco-incinerators in Central European countries, where such facilities are a relatively new solution and where the relationship between effective information activities on the part of investors (e.g., city authorities) and the intensity of local protests is noticeable. Reliable information activities also influence not only public reactions during the construction process but are also clearly felt during the preparation of planning documents containing the actual locations of such facilities [15]. However, it should be emphasized that increasingly detailed sociological studies demonstrate that the scale of protests and manifested public reluctance is not identical to the individual opinions of the majority of residents. It is more common to speak of an intensely protesting representative group than of a collective rejection of the project itself or its location by the entire studied community. Interesting research on this topic was conducted in Greece [4], which had no previous experience with the construction of such facilities. Thus, the sociological research on social acceptance was conducted on a raw root. Contrary to the researchers' initial assumptions that social reactions would be overwhelmingly negative, surveys revealed that a significant portion of the residents of the analyzed area positively assessed the proposed thermal waste treatment plant design and its location. Positive reactions intensify when a landfill site is proposed as an alternative to an eco-incinerator. Negative public reactions, however, stem from the lack of transparency on the part of municipal authorities regarding waste management. Researchers point out that, in the process of informing residents, community involvement is particularly important, including in decision-making regarding investment risks. They also emphasize that shared responsibility among all stakeholders for solving the waste management problem is key to more effective cooperation in this field.

As mentioned in the previous paragraphs, the advancement of waste processing technologies toward environmental safety – compared to solutions used at the end of the 20th century – has led to them being equipped with functions that complement their primary purpose. These often include educational elements primarily serving environmental education (e.g., educational trails, spaces for educational activities, etc.), as well as elements that can enhance the attractiveness of the space in which they are located (general in nature, such as a café or retail outlet, or elements that utilize the specific features of an eco-incinerator, such as a viewing point on the roof, a climbing wall on the façade). A new approach to shaping a facility visually is also possible. Technological solutions and the resulting dimensions of the facility (a tall chimney, the dimensions of the halls, or a waste storage bunker) largely determine both the height of the thermal processing facility and its proportions.

However, contemporary solutions increasingly move away from merely „encapsulating" technology, focusing instead on architecture as an artistic expression adapted to its functions. Such solutions are possible both due to new possibilities offered by construction technologies, as well as the high level of ecological safety of such structures and their relatively low environmental impact on the surroundings, compared to structures built even at the turn of the 21'st century. As a result, waste incineration plants are increasingly being built based on architectural competitions, with careful attention paid to the overall concept, architectural details, and interior design, as well as the surrounding development. This approach is consistent with the contemporary role of eco-incineration plants as facilities with additional functions, as well as with the facility's location. Waste incineration plants are increasingly being located not in industrial zones or remote areas due to the inconvenience, but rather at city entrances, where they can visually act as a kind of gateway to the city or a significant, eye-catching element of contemporary architecture. Iconic facilities located in this way include the Hundertwasser-designed eco-incinerator in Vienna, located at a transit hub in the city center, and the Amager Bakke (CopenHill) eco-incinerator in Copenhagen, the subject of this study.

1.2. Copenhagen – Potential and Importance of the city

On a European scale, Copenhagen is one of the most ecologically advanced cities in the context of waste processing. Therefore, it can serve as a good practice example for other urban centers that are just beginning to transform their management of both the resources they possess and the waste they produce. At the same time, numerous historical monuments, picturesque canals and bicycle bridges over them, a historic urban fabric, and iconic contemporary architecture, as well as a wide range of accommodation options,

a modern, diverse cuisine, and numerous European-wide events, make Copenhagen an attractive tourist destination. Research shows that the average tourist stay in the capital is 3.5 days [16], and nearly 7 million people annually stay in the city for at least one night, declaring their trip as a tourist. Copenhagen's genius loci defines the city's character and makes it particularly unique in Europe.

Copenhagen is a city whose origins date back to the 11'th and 12'th centuries [17]. Initially a fishing settlement in the Middle Ages, it developed over time into a stronghold, and later into a trading port and a center of regional political importance [17]. The city experienced rapid development (construction of new fortifications) in the 17'th and 18'th centuries. The 19'th century was a period of intense urban transformation for Copenhagen. The demolition of the fortifications enabled intensive urban development, the expansion of the city boundaries to include new development areas, and intensive infrastructural transformations. New communication possibilities and the development of the transport network in the 20'th century led to further spatial transformations of the city. The regional development project „Greater Copenhagen" (the so-called „Finger Plan") from 1947 deserves particular attention as one of the first 20'th-century concepts for transforming the structure of this city. The „Finger Plan" was developed by the Technical Office for Copenhagen Development Planning (Egnsplankontoret) on the initiative of the Danish Urban Planning Laboratory (Dansk Byplanlaboratorium) [18], in a team led by architect Peter Bredsdorf. However, a key role in the plan's design is also attributed to Steen Eiler Rasmussen and Christian Erhardt Bredsdorff. The project envisioned further development of the city along transport corridors, with green wedges for recreational or agricultural purposes located between them. These were intended to balance the transport corridors and provide permanent protection for the city's open spaces. The ring-and-radial layout envisioned a phased development of Copenhagen, based on two pillars: housing policy and plans for the development of the city's recreational areas. The circular railway was intended to enable the harmonious development of the transport network, balanced with urban structures, with particular emphasis on the development of services and jobs at transport hubs, and to provide access to the city center from the most remote planned areas within a 45-minute drive. Although Copenhagen's development was aligned with the above concept, the plan was officially adopted only in 2007 [19] as a binding planning directive adapted to the prevailing conditions, and subsequently updated in 2013 and 2019 [19].

Copenhagen's pursuit of sustainability is currently taking place on many levels. Urban planning is considering a shift from the current „Finger" model to a so-called Loop city. The five-minute city concept is also being implemented in parts of Copenhagen. It is assumed that by 2025, up to 75% of journeys within the city limits will be made on foot, by public transport, or by bicycle. Cycling is currently one of the main means of transport, and the urban transport network is regularly adapted to them (developing bicycle paths, introducing so-called „green waves," i.e., synchronizing traffic lights so that cyclists traveling at a certain speed can cross without stopping at red lights, etc. – these actions mean that Copenhagen is often referred to as one of the most cyclist-friendly cities in the world). Strategies based on the Circular Economy concept are also being implemented in urban policy and at the metropolitan level. This is happening through economic ideas such as flexible public-private partnership policies and broad public involvement in decision-making processes, the coordination of urban projects, the implementation of numerous pilot projects with circular economy features, and intensive waste management efforts. The latter, closely followed by environmentally friendly urban transport solutions, are being intensively implemented. Efforts to develop beneficial solutions for municipal waste management are a response to a problem that intensified in the second half of the 20'th century. The problem of large amounts of waste produced and the linear approach to its disposal forced city authorities to seek other, more ecological solutions, moving towards a circular economy, transforming waste management methods to segregate them to a greater extent than previously accepted, and developing new, pro-ecological solutions for managing both residual waste and waste that cannot be segregated. The city policy documents „Ressource og Affaldsplan 2024" and „Ressource og Affaldstrategi 2030" are intended to minimize the amount of waste produced, increase recycling rates, raise education levels in this area, and maximize the use of waste as a raw material [20]. The 2030 strategy document also describes the difficulties the city faces in this area, such as the risk of waste that should be recycled being sent to an incinerator, legal uncertainties regarding waste sorting, furthermore,

the issue of restricted access for recycling companies. On the other hand, however, the city's collaboration on the circular economy with the industrial and economic sectors, residents, and research institutions is strongly emphasized. In this latter case, the city authorities emphasize a particular openness to new solutions, placing environmental issues at the heart of urban policy as key to the process of urban transformation. Creating a new waste management system was a solution at the level of urban planning and social policies, while the architectural expression of these efforts was the construction of the new Amager Bakke eco-incinerator, also known as CopenHill.

1.3. The Amager Bakke (CopenHill) waste incineration plant as an example of a new approach to engineering facilities for city services

Amager Bakke exemplifies a modern approach to engineering, where the eco-incinerator is not hidden away in an industrial zone or areas far from the city center. Carefully designed and exposed, it has become a prominent element of urban space, both in close compositional relationships and in distant views (Fig. 1).

Fig. 1. The Ameger Bakke (CopenHill) eco-incineration plant in Copenhagen is one of the key examples of combining technical city services with social functions. The photo shows a fragment of the façade and the year-round ski slope – under construction (photo by the author, 2020)

CopenHill is located in the Amager Vest district on Amager Island. The waste-to-energy plant is located in areas that were originally port and industrial areas. However, many of these areas are currently being transformed for various public uses, including recreational, artistic, and other purposes (cultural and event zones in the former shipyards of Refshaleoen, or the beaches of Amager Strandpark). Large-scale former shipyard and relief facilities enable reuse for these new activities. By combining the functions of an engineering infrastructure for city services with recreational functions, Amager Bakke also fits into the transforming area, serving as a compelling new urban icon and a compelling spatial keystone located on the border of the transformed post-industrial and former port areas and the attractive residential districts south of the facility. The facility, financed by a joint venture of five municipalities, was designed by the BIG – Bjarke Ingels Group studio and constructed between 2013 and 2017. Technically, it's an interesting solution that addresses the need to incinerate residual and municipal waste, producing energy through cogeneration. However, its distinctive feature lies in the additional functions effectively implemented within the facility. As a result, CopenHill has become both a landmark architectural landmark for the district in which it is located and a technological response to the emerging need for waste recycling. The plant incinerates approximately 400,000 tons of waste annually, generating electricity and district heating. Advanced exhaust gas treatment systems ensure the facility is environmentally friendly, neutralizing SO_2 and NO_x emissions at a very high level. A key element that distinguishes CopenHill from other waste treatment plants is its numerous features that enhance the urban environment. The facility boasts a year-round artificial ski slope and a park with a viewing terrace located on the building's roof. Recreational facilities were launched at the end of 2019. The facility also features a café, areas for environmentally friendly educational activities, a shop, and a climbing wall. The building's architecture is heavily focused on introducing greenery, which contributes to water retention. In addition to the green areas located directly on the roof, the façade is also adapted to so-called „green solutions," as the façade panels have been designed to function as planters with plants.

Combining city engineering facilities with public functions, with a particular emphasis on pro-ecological activities, including the circular economy, is a new approach. This approach is justified given the development of technological solutions for waste processing. The eco-incinerator is one of the so-called „backyard infrastructure" facilities, which, thanks to

technological changes, is gaining a new role in the urban structure. This is particularly important in the context of the rapid development of pro-ecological activities in virtually all areas of urban functioning and, more broadly, society. However, the intensive transformations that thermal waste treatment plants undergo in urban spaces, both functionally, visually, and semantically, are determined by many factors. When considering the use of additional functions of eco-incinerators and their importance in improving the quality of the space in which they are located, the facility's accessibility, both within the compact structure in which they are located and in its relationship with the entire city, will be particularly important. Therefore, the basic test for assessing whether a facility can potentially become an activating element is not only the number and attractiveness of the proposed additional functions, but above all, the facility's accessibility.

2. MATERIALS AND METHODS

The research is part of an extensive multi-criteria analysis of waste incineration plants [21]. A matrix method was used for the broader analysis, consisting of four basic groups of issues for which eco-incineration plants were analyzed. These are: social, architectural, location (including urban planning), and technical (S.A.L.T.). In general, analyses are conducted to determine whether each group of issues impacts the others, and if so, how. In this case, the Amager Bakke waste incineration plant is analyzed in the context of facility accessibility. This is one of the factors in the location studies and, in the longer term, in the analysis of the facility's significance in the urban context. As part of the above activities, the following accessibility methods were analyzed: walking, cycling, public transport (bus, metro), passenger car, and multimodal solutions.

2.1. Research methods

The following research methods were used during the site investigation:

a) Desk research – analysis of secondary data sources in order to collect initial material for accessibility research:
   - measuring the distance from the facility in terms of the availability of walking, cycling and car routes using the Google Maps and Moovit applications,
   - collecting data from transport applications and websites operating in the Copenhagen area: Rejsenplanen.dk, Google Maps Transit – obtaining data on travel times and frequency of public transport.

b) Analysis of pedestrian and bicycle access isochrones (without taking into account the need to rent a bicycle in applications enabling this) obtained based on desk research and field studies. The aim of this analysis is to determine the range of realistic accessibility of the facility within the urban fabric, which in subsequent urban planning studies can be used to narrow the research field to assess the surrounding functional and spatial structure of the eco-incinerator environment. Based on the literature [22], three accessibility ranges were adopted: up to 400 m, up to 800 m, and up to 2000 m. These analyses make it possible to determine the range of realistic and convenient pedestrian and bicycle access, and to identify areas from which such access is possible or unavailable within specific isochrones.

c) Public Transport Accessibility Analysis – As part of the accessibility analysis, access to Ameger Bakke was examined from three major public transport hubs: Norreport, Kobenhavns Hovedbanegard, and Radhuspladsen. The aim of the analysis is to determine the facility's accessibility via public transport, as one of the most important elements of a pro-ecological, sustainable city's transport system. The analyses were conducted in two time periods: 8:00-8:30 and 19:00-19:30 to obtain access data during peak hours (indicated morning hours) and off-peak hours (indicated evening hours). In the latter case, it was also assumed that public transport must operate in a constant mode, as it does during the working day. Therefore, research was not conducted on days off, at night, or early in the morning, even though the load on the transport network would be the lowest in these cases. During the transport network research, three elements were taken into account: door-to-door access to the CopenHill facility, i.e. taking into account the walking time from the stop, the number of transfers, and the frequency of public transport services.

d) Analysis of access by passenger car – as in the case of the analysis of public transport, the research was carried out in two time periods: the highest and lowest load on the transport network (8:00-8:30 and 19:00-19:30).

e) Analysis of cycling and parking infrastructure and pedestrian path continuity – for this purpose, the

continuity of pedestrian and bicycle paths was analyzed (taking into account terrain obstacles, missing path sections, etc.), and CopenHill's integration with the city's cycling network was assessed, including parking options. The aim of this analysis was to determine whether Ameger Bakke is integrated with the city's cycling network and whether it is attractive for pedestrians.

f) He above analyses allowed for the use of a six-point scale (0-5), with 0 indicating the lowest quality of the analyzed factor (e.g., lack of availability) and 5 indicating the highest quality. Based on the results of the conducted research, a qualitative and quantitative synthesis was outlined, and conclusions were drawn in each of these categories.

3. RESULTS

3.1. Criteria for assessing the accessibility of the facility

The analysis allowed us to define criteria, organized in a table (Table 1), to create a coherent picture of the facility's accessibility by various means of transport. This can directly impact the assessment of CopenHill's attractiveness within the city in relation to the additional functions implemented within the facility. The obtained results are summarized in the table below, categorizing the main analysis criteria. Due to their specific nature, these criteria were divided into two groups: basic criteria – related directly to the means of transport and the mode of travel, and supplementary criteria enabling the use of a given means of transport and ensuring its smooth operation. A summary of the criteria, along with their group assignment and description of the activities, is presented in Table 1.

The above lists indicate that 10 criteria were considered. Four of them are defined as basic criteria, relating directly to a given mode of transport. They focus on fixed and measurable elements, such as the location of stops or stations, their accessibility, and the average accessibility of a given mode of transport. Supplementary criteria are no less important, but they significantly supplement the existing transport network and are less fixed in nature. These include the quality of cycle paths and sidewalks, the availability of bicycle rentals, and parking spaces for both cars and bicycles. Both categories of criteria are highly significant, and examining them from a quantitative and qualitative perspective allows for drawing comprehensive conclusions regarding the accessibility of Amager Bakke by a given mode of transport.

Table 1. Summary of criteria for assessing the accessibility of the Amager Bakke/CopenHill waste incineration plant (author's preparation, 2025)

TYPE OF CRITERION	NAME	CRITERION DESCRIPTION
basic	bus stop availability	The nearest stop is Amager Bakke (Vindmollevej) – located directly next to the CopenHill.
basic	availability of an alternative bus stop	Alternative stops are Amagervaerket (Vindmollevej) which is a 7-minute walk from the CopenHill and Lynetten which is a 10-minute walk.
basic	accessibility of metro stations	Christianshavn Station - not within a few minutes' walking distance – requires alternative transportation (bus, bike rental app). The walk from Nyhavn takes about 25 minutes.
basic	accessibility by bike	From Nyhavn (one of the main city hubs) 10 minutes by bike (system of bike paths), i.e. 2-3 km.
supplementary	car park	Public parking for cars is located directly below the CopenHill facility.
supplementary	bicycle parking and rental stations	Bicycle parking spaces are located directly under the CopenHill facility, and a bicycle rental station is located nearby in the multi-family housing complex.
supplementary	quality of pedestrian accessibility	Pedestrian access is of good quality and well-marked. The sidewalks are narrow in some sections, but they always allow access to the site.
supplementary	quality of bicycle accessibility	Good cycling accessibility, numerous bike paths, consistently maintained, in good technical condition, well marked.

3.2. Facility Accessibility Scoring

Based on the conducted research, summarized in Table 1, a point assessment of individual accessibility criteria by various means of transport was prepared on a six-point scale from 0 to 5. The obtained results are presented in Table 2.

The accessibility scoring was conducted across six groups of criteria. Four of these directly relate to the means of transport or accessibility method (accessibility by foot, public transport, bicycle, or private car), another criterion addresses multimodal accessibility (changing modes of transport during travel), and the last criterion addresses accessibility parameters in terms of their clarity (route and stop markings, the role of the facility itself as a visually dominant feature in the urban space). The total accessibility score for the Amager Bakke / CopenHill facility is 20 points out of a possible 30, placing the facility in the good accessibility category (over 65% of points).

Table 2. Accessibility score for the Amager Bakke/CopenHill waste incineration plant in Copenhagen, (author's report, 2025)

CRITERION	EVALUATION	EVALUATION DESCRIPTION
pedestrian accessibility	3 points	Particular emphasis was placed on walking distance and its quality. Walking access from major hubs and urban centers is not possible, so access from public transport (bus) stops was considered. Besides the bus stop located directly at Amager Bakke, two other stops were considered, which take 7-10 minutes to walk. No significant barriers to walking access were identified within this distance.
accessibility by public transport	3 points	Particular emphasis was placed on travel times from major public transport hubs, the number of transfers, and the frequency of public transport. Direct access is provided when using the bus network. The metro also requires a transfer to a bus line at one of the stations.
bicycle accessibility	4 points	Particular emphasis was placed on bicycle paths, access times to the facility, and bicycle parking. Bicycle access from major city centers and hubs (e.g., Nyhavn) is an average of 10 minutes. Copenhagen has excellent cycling infrastructure, including on the routes analyzed. The parking lot directly serving CopenHill also features a bicycle parking zone, located closer to the main road.
accessibility by private car	3 points	Particular emphasis was placed on accessibility during rush hours, as this significantly determines the facility's accessibility. Access is possible, and public parking is conveniently located directly next to the facility. However, as in the rest of Copenhagen's central zone, car travel is not a priority in terms of convenience, unlike, for example, cycling.
multimodal accessibility	3 points	Particular emphasis was placed on the deliberate creation of transport links to facilitate access to the facility. Access via a combination of different means of transport is not necessary, but it does not significantly shorten the travel route. The lack of a direct metro connection to the facility is a drawback, especially considering the intensive revitalization of the district in which Copenhagen Hill is located.
visual identification	3 points	Particular emphasis was placed on signage for routes, stops, parking lots, and spatial identification of the facility. Due to its dominant position in the area, the facility serves as an easy orientation point, making it visually accessible. Cycling routes are well-marked, while bus stops in the Amager Bakke area are not easily visible.

3.3. Qualitative-quantitative synthesis

Based on the detailed research and the analytical results presented in Tables 1 and 2, a qualitative and quantitative synthesis was prepared. Based on this, conclusions were drawn, which were organized into two categories: quantitative and qualitative.

3.3.1. Quantitative synthesis of facility accessibility

Access to CopenHill from the main areas of the city center is not within a comfortable few minutes' walk. Therefore, walking accessibility can only be considered in the context of access from other public transport stops or stations. The most advantageous access to the facility is by bicycle, thanks to the very well-functioning system of bicycle paths and the city's policy focusing on this mode of transport. Travel time from the city center (Nuhavn) is 10 minutes. Among other modes of transport, public transport is also rated well, due to the stop located directly next to CopenHill. Two other stops are approximately 500-800 meters away, i.e., a 7-10-minute walk. The eco-incinerator has significantly poorer accessibility compared to the metro station. The nearest station is approximately 25 minutes away on foot. Access by car is good due to the very convenient location of parking spaces. However, such access is difficult during peak times. It is also

worth noting that this is an ecologically unfriendly solution, which may be particularly important in terms of access to the facility, which is intended to support pro-ecological activities.

3.3.2. Synthesis of facility accessibility from a qualitative perspective

The Amager Bakke / CopenHill eco-incinerator is located in a rapidly transforming urban fabric. Originally industrial and port areas are undergoing intensive revitalization, both through renovation and functional transformation of existing industrial fabric for public purposes (culture, education, art), as well as the construction of new facilities for residential, recreational, and educational purposes. The newly designed CopenHill fits into this district's operational strategy, simultaneously serving as an engineering infrastructure for the city, but with public functions of pro-ecological significance (a rooftop garden, ski slope, climbing wall, café, skate park, small educational and retail spaces, and more). Thanks to its diverse functions, its openness to Copenhagen residents, and its high-quality, environmentally friendly architecture (greenery on the roof, and sections of the facade used as planters to support rainwater retention), the facility integrates with the urban fabric and simultaneously plays an attractive role in its surroundings. This functional and structural design of the eco-incinerator promotes acceptance of the facility's location within the city and transforms the facility, initially considered a „backyard infrastructure," into an attractive space for the local community. Amager Bakke's role undoubtedly extends beyond its engineering function, so its accessibility is key. Qualitatively, its convenient connection to bicycle paths is an unquestionable advantage, underscoring the direction of Copenhagen's mobility system. On the other hand, the lack of a nearby metro station poses a barrier, particularly in an area with a high development potential, undergoing intensive revitalization.

4. CONCLUSIONS

Amager Bakke (CopenHill) is a structure that represents an innovative approach to shaping urban engineering architecture. This applies to both the structure's form and structure, but above all, to its function and significance within the urban fabric of Copenhagen. In addition to its primary function, CopenHill also possesses numerous public functions. This not only visually fits into the cityscape as a spatial dominant feature but also plays a significant role in enhancing the attractiveness of the location and broadly understood social acceptance. Therefore, the accessibility of the eco-incinerator is particularly crucial. Analyses show that the facility is easily accessible by bicycle, which is one of the most important modes of transportation in Copenhagen. Therefore, easy access by this mode of transportation aligns with the city's mobility plans and concepts. On the other hand, the very poor accessibility to metro stations (especially in the intensively revitalized area where CopenHill is located) contradicts the principles of multimodal mobility, which is considered one of the concepts for improving the quality of accessibility in areas. Modern exhaust gas treatment and energy recovery technology allows this facility to be located within the urban fabric and also accommodate pro-social functions such as recreation and education. Such multifunctional architectural combinations build residents' environmental awareness, not only regarding the facility itself and its role, but also regarding broader concepts of pro-ecological processes and the Circular Economy. The role of the Copenhagen eco-incinerator in the circular economy is significant because even in a process with a very high level of recycling, residual waste remains, requiring neutralization, and products that cannot be reused. At the same time, public discussion has highlighted the unprofitability of decommissioning the eco-incinerator in the absence of waste (a goal Copenhagen aims to achieve), and the consequent need to transport waste from other parts of Denmark (or even other countries) or restart the plant. Each of these solutions has environmental implications. Therefore, the additional pro-social functions of the Amager Bakke waste treatment plant may be one of the key solutions for the facility's long-term operation.

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COGNITIVE FUNCTIONS OF CHILDREN IN GRADES 5-8 – CASE STUDY

EFEKTYWNOŚĆ PRZYSWAJANIA WIEDZY DZIECI KLAS V-VIII – STUDIUM PRZYPADKU

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Abstract

One of the cognitive and practical challenges of the 21st century is unraveling the mystery of the structure and functioning of the most important and the most complicated organ of the human body, which is the brain. Therefore, it is the subject of research by representatives of many fields of science (e.g., medicine, biology, genetics, psychology, and biochemistry). The objective of this study was to evaluate the cognitive functions of school-age children in Poland. The results of research based on tests that diagnose concentration of attention and memory, including short-term and long-term memory, are described. The research was carried out among students from nine primary schools, including a total of 243 children, their parents, and teachers.

Keywords: cognitive functions, concentration of attention, memory, including short-term memory, long-term memory, primary schools students

Streszczenie

Jednym z wyzwań poznawczych i praktycznych XXI wieku jest rozwikłanie tajemnicy budowy i funkcjonowania najważniejszego i najbardziej skomplikowanego narządu ludzkiego ciała, jakim jest mózg. Dlatego też stanowi on przedmiot badań przedstawicieli wielu dziedzin nauki (m.in. medycyny, biologii, genetyki, psychologii i biochemii). Celem niniejszej pracy była ocena funkcji poznawczych dzieci w wieku szkolnym w Polsce. Przedstawiono wyniki badań opartych na testach diagnozujących koncentrację uwagi i pamięć, w tym pamięć krótkotrwałą i długotrwałą. Badania przeprowadzono wśród uczniów dziewięciu szkół podstawowych, w tym łącznie 243 dzieci, ich rodziców i nauczycieli.

Słowa kluczowe: funkcje poznawcze, koncentracja uwagi, pamięć, w tym pamięć krótkotrwała, pamięć długotrwała, uczniowie szkół podstawowych

1. INTRODUCTION

The human brain needs two components to function properly: nutrients (mainly glucose) and oxygen. Deprived of one, it is damaged after just four minutes [1]. Effective human thinking is determined by the oxygen content in the blood in the cerebral arteries. It must be saturated with oxygen by 90%. Even a slight reduction in this level (for example, 5%) causes changes in cell morphology and neuronal functions, resulting in a reduced degree of concentration and

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prevents precise coordination of muscle work [2]. In addition to internal considerations of proper use of oxygen by the brain, external conditions in the body also play an important role. Oxygen is taken in from the air through the respiratory system and transferred from the alveoli to the blood, where it binds to hemoglobin and is carried to various tissues of the body. Human oxygen consumption at rest is nine litres per minute. It is assumed that a change in the oxygen content in air < 2.5 $g \cdot m^3$ is a neutral stimulus, 2.6-5.0 $g \cdot m^3$ – a weak stimulus, 5.1-10.0 $g \cdot m^3$ – a significant stimulus, > 10.0 $g \cdot m^3$ – strong stimulus [3].

The reason for the reduction in the amount of oxygen that reaches the brain is the high concentration of carbon dioxide in the air. When such an unfavourable composition of gases fills a room, it reduces the cognitive function of the people who breathe them. Room ventilation, especially natural ventilation, allows you to shape the level of CO_2 only to a limited extent and in specific situations. When too many people are in a room at the same time, an improperly designed or poorly functioning ventilation system can cause an external air flow too small to dilute indoor air pollutants [4]. In 2018, scientists from the Lodz Institute of Occupational Medicine (Poland) conducted research during the heating season in 12 primary schools located in highly urbanised areas. They checked the concentration of 15 selected volatile organic compounds. They also examined the level of PM 2.5 dust concentration and monitored air quality in terms of comfort: temperature and relative humidity of indoor air and carbon dioxide concentration in rooms. The CO_2 concentration measurements carried out showed that the content of this gas in the air was even higher than 4000 ppm and the average value was 2500 ppm. An increase in its content in the air above 1500 ppm undoubtedly causes a rapid decrease in concentration or a feeling of drowsiness in students.

Indoor air quality is an important element of a healthy school environment. Clean air in classrooms is especially important in schools because growing and developing children are very sensitive to hazardous chemicals. Exposure to poor air quality in classrooms can make it difficult for students to complete tasks and reduce learning effectiveness, as well as lower test scores [5].

Taking into account the above considerations, it can be assumed that facilitating the transport of oxygenated blood to the brain may improve the mood and cognitive functions of students. 'Mood is generally understood as an affective state of moderate intensity and diffuse character, without a clear reference (subjective cause and specific object to which it is directed) and without a clear component of physiological arousal' [6]. It is an important psychological variable because it determines what comes to mind of a person and therefore influences the content of their judgments and behaviours [6].

Numerous areas of the cerebral cortex and subcortical centres participate in the regulation of mood and psychomotor drive. Brain neurones connect these areas to the corticocortical, Cortico-Striato-Thalamo-Cortical (CSTC) circuits, and other circuitry. The created networks of neurones analyse sets of information about the environment reaching the brain through the senses and endogenous signals coming from inside the body. The next behaviour depends on the result of this analysis. In changing human life conditions, natural short-term changes in mood occur, consistent with the situation. In some cases, mood swings are much greater and appear without external factors that justify them. Then we deal with the so-called exogenous changes [7]. A good mood is one of the nodes of the associative network that constitutes our memory. Its activation activates other positively associated plexuses [8]. Research on memory has revealed two phenomena: its compatibility with mood (in a good mood it is easier to remember and recall positive information than negative information; in a bad mood, the opposite) and its dependence on the state of the body (it is easier to recall events in a state similar to where we were at the moment of remembering them) [6]. Mood also influences behaviour. Good feeling confirms the belief that the desired effects can be achieved [9]. In a positive mood, people become more prosocial and polite, behave in a more relaxed and pleasant way, and are more willing to cooperate and less willing to compete [10]. The literature on the subject does not fully agree on what emotions constitute the group called basic emotions, i.e. universally occurring emotions, which are characterised by a specific facial image, the communication of which probably does not require learning [11]. Cognitive processes enable a person to penetrate the environment, participate in the creation of reality, and understand what has already been explained.

Modern man faces increasingly difficult existential challenges. Absence from technological culture means digital exclusion and a certain disregard for the unadapted [12]. In psychology [13-17], cognitive functions are defined as mental activities that help a person gain orientation in the environment, obtain

information about himself and his body, analyse situations, formulate conclusions, make the right decisions, and act. Elementary and complex thought processes are responsible for receiving, processing, and storing stimuli from the environment. The basic mechanisms of brain function include:

- memory – responsible for storing and reproducing information,
- attention – controlling the scope and quality of information processing and reducing its excess,
- perception – allowing the absorption of information coming directly in the form of impressions, observations, and ideas,
- executive functions – enabling an adequate change of reaction depending on the requirements of the situation, such as information processing, problem solving, planning, and applying the plan in a real situation.

Complex brain systems include:

- thinking – a continuous cognitive process consisting of the processing of information encoded as observations, images or concepts, symbols, phrases, and images and sounds, including learning based on classical and operant conditioning, thanks to which an indirect and generalised knowledge of reality occurs,
- language – enabling understanding and describing the reality around us, which may be subject to modifications throughout life.

This is a relative division because all these reactions occur in the brain almost simultaneously. For complex brain systems to function, the elementary ones must first function. Psychologists [18] explain the functioning of the memory mechanism very accurately. It is a set of processes used to encode, store, and retrieve information. There are three types of coding: semantic (coding words and their meaning), visual (memorising images), and acoustic coding (coding sounds, especially words). Storage is related to the creation of a permanent base for information, i.e. permanent memory. For information to reach the memory store, it must go through three separate phases of memory: sensory (ultra-short-term), short-term (working, data storage in it lasts 15 to 30 seconds), and long-term (permanent) responsible for transferring and storing the information we want to remember [18]. Baddeley and Hitch [19] proposed a model of working memory in which short-term memory takes various forms and has limited capacity. The type of memory (pictorial, verbal) depends on the type of information received. The flow of information is controlled by the central executive system (central executive mechanism), whose task is to transfer information to long-term memory (information processing). According to this model, stimuli from the environment first pass through the sensory register, which stores short-term sensory impressions, such as images, sounds, or tastes. It only takes a fraction of a second or a few seconds, but constantly. The brain cannot retain all or even most of the sensory information. Since most of them have no impact on our lives, we dismiss them as irrelevant. Only if we decide that they are important to us in some way, we transfer them to long-term memory [18]. Due to repetition, information is transferred from short-term to long-term memory, while combining new information with what we already know is called elaborative repetition. Studies have shown that short-term memory capacity is 4 ±1 [20]. Once the information reaches long-term memory, consolidation of memory traces must occur at the synaptic level, which takes several hours, and in the memory system, which can take a week or longer [18]. The most important features of memory are:

- durability – time to store information in memory,
- readiness – speed of extracting and reproducing information from memory,
- fidelity – the accuracy with which we remember information, the degree of accuracy of the reproduced content, determines the number of distortions (errors) made,
- speed – how quickly we can remember the material,
- scope – how much material can be remembered [21, 22].

Assuming that the ability to process information is limited, the individual is forced to decide which of them should access the areas of the brain and analyse it there. Attention is such a complex process of selective selection of sensory information or internal activations, thanks to which the available information processing capabilities can be focused on observing or performing a specific task. It also consists of three phases [23]: arousal – activates selected areas of the brain, preparing it to orient itself to receive information that is worth noticing and focussing on, orientation – filtering information, selecting those that require attention (in the case of external stimuli reaching after 100 ms, and in the case of internal ones, after 300 ms), executive control – search. There are at least two attentional networks: automatic reorientation to unexpected events (an external stimulus that the brain considers important enough to analyse it more thoroughly), and conscious

action (creating a map of orientation in space and planning eye and head movements in the appropriate direction). Attention has four basic functions: selectivity – the ability to select one stimulus and ignore others, vigilance – the ability to observe the environment and wait for the appearance of a specific stimulus, searching the perceptual field – the ability to active and systematic examination of the field of perception, the aim of which is to detect appropriate chosen stimulus criterion, switchability – the ability to switch between activities, divisibility – the ability to concentrate on several stimuli [24]. The basic form of cognitive contact between humans and the external world is perception. It involves the active interpretation of sensory data using contextual clues and previously acquired knowledge [25]. The process of perception is the creation of a representation of an object based on data obtained from the sense organs and, in some cases, information contained in memory [29]. Information processing is not only a cognitive feature but also the discovery of emotional content. Psychology also distinguishes three phases of perception: sensory registration – an external stimulus is converted into a nerve impulse, emotional evaluation – valuation, semantic recognition (stimulus categorisation) – comparison of sensory data with categories already existing in memory, searching for a category to which the incoming stimuli would best fit. The learning mechanism itself is immutable. Knowledge acquired by an individual results from his contact with the world, its experience and survival [16]. The basis for understanding various types of relationships through thinking (reason) is sensory perception, which contains "motives" leading to the mental creation of various concepts, categories, patterns, etc. [26]. The processing of information received from the sense organs takes place on two levels: sensory-motor – perception of spatial and temporal wholes, and semantic-operational – perception of objects and signs. An essential role here is played by internal patterns (representations, cognitive schemas) of reality created on the basis of previous experience, which act as specific hypotheses verified as new data arrive. Perception is a process of identification rather than passive recording, going beyond the information provided; therefore, it is possible to accurately identify objects and phenomena despite the gaps in the sensory material, as well as its variability resulting from the conditions in which this process takes place [27]. Perception is not the same as attention because it covers the full cognitive processes of humans, while attention is the ability to focus on selected elements of the environment [28]. According to Gibson [29], research involving its isolation from the natural conditions under which it is used by the body results in the reception of faulty images of its mechanism of action. Executive functions are defined as psychological processes that involve conscious control of thoughts and actions or are responsible for goal-directed behaviour. They constitute the foundation for skills such as refraining from reflex or impulsive reactions, solving problems, planning activities, and initiating them with flexible implementation (even despite the existence of disturbing factors), as well as controlling subsequent phases of goal-orientated activity [30, 31]. Due to the fact that they can be influenced by conscious and unconscious representations of the motivational or affective meaning of a stimulus, they can be distinguished: hot – they participate in solving problems of significant emotional and motivational importance (e.g., strategic games with the prospect of reward) and cold – they participate in solving abstract problems, detached from the context [32, 33]. Executive functions develop gradually and for a relatively long time, even up to the age of 25. The current level of development of the executive functions of the student is the result of the interaction of the pace and dynamics of the developmental changes that result from the maturation of the central nervous system and the stimulation occurring in the sociocultural environment [34-36]. School learning is supposed to be a cognitive activity organised and directed toward a specific goal, which is to acquire knowledge through the processes of memorising and recalling and, at the same time, acquiring the ability to manage them [37].

To identify the impact of student psychological characteristics on their achievements, scientists [38] carried out research that showed that the effectiveness of education is determined by the following psychological characteristics: type of nervous system, level of intelligence, type of motivation, and the coherence of these characteristics. The effectiveness of education also depends on variables such as compliance with elements of the teaching system, teaching strategies, and the living environment of students. The course of the learning process and its effects are influenced by: the general nature of the learner, the nature of the knowledge to be mastered, and the nature of the learning process [39]. In educational psychology, the factors that influence

the course and the effects of learning are divided into three categories: student characteristics, factors that characterise the learning situation, and teacher characteristics [40]. We can therefore summarise that learning depends on who learns, how they learn, and under whose guidance they learn [41]. It is worth mentioning the triad of power of attorney designed by Puślecki [42]. It includes an authorised school, an authorised teacher, and authorised students. All its elements are interdependent, inspire, support, and develop each other. The individual characteristics of a student may be permanent or transformable. The unchangeable feature is gender. Properties that change include intelligence, interests, abilities, and motivations for action [36]. According to Mischel and Shoda [43], people are creatures that interpret situations. They indicate both its value and the importance of perceiving it by an individual. The learning situation is created by everything that happens during it and that is irrelevant to the results. The external conditions in which learning takes place and the methods of conduct used, as a result of which the student acquires new knowledge and skills, are important. The characteristics of the student and the teacher are a variable that depends on internal and external conditions, and these, in turn, are components of the learning situation. It is created by everything that happens during this process and is not indifferent to its effects. Both external conditions and teaching methods are important, under the influence of which the student acquires new knowledge and skills [44]. Facilitating the transport of oxygenated blood to the brain may first contribute to strengthening the basic mechanisms of the brain, which determine the effectiveness of complex cognitive processes.

The purpose of the article was to assess the cognitive functions of children studying in schools, which will allow us in the future to take steps to improve conditions in schools.

2. METHODS AND METODOLOGY

A total of 243 students from grades 5, 6, and 7 attended schools in the swietokrzyskie voivodeship (Fig. 1) were subjected to the study. These students came from 18 classes in 9 different schools with different locations. The survey included students from schools with up to 10-15 children in classes and schools with 30 children in classes. The surveys were completed by students, their parents, and teachers. The results of tests diagnosing students' cognitive functions (concentration of attention, memory, including short- and long-term memory) are presented in percentage form to better illustrate the distribution. The analysis presents distributions considering the age of the students (the class in which the surveyed students currently attend).

Fig. 1. Map swietokrzyskie voivodeship [45]

The analysis included:
- a test measuring students' memorisation and attention,
- interview with the student – interview questionnaire "My emotions and feelings",
- hidden, participant observation – observation sheet completed by parents and teachers,
- measurement of blood saturation using pulse oximeters.

As part of the test measuring students' memorisation and attention, an original sheet of 66 questions was developed, including the following:
- attention test – 5 questions,
- memory level test – 6 questions,
- quantitative tests of the student's mood level – 13 questions (including those regarding mood: 8 questions, regarding physical well-being: 4 questions, general: 1 question),
- observation of students in terms of memory and attention – 22 questions (including 11 questions determining memory, and 11 questions determining attention),
- observation of students in terms of memory and attention – 20 questions (including 10 questions determining memory and 10 questions determining attention).

The maximum number of points for the entire test was 213.5 points. Tasks assessing concentration of attention allowed one to obtain a maximum of 95 points. Long-term memory tasks allowed to obtain a maximum of 36 points. However, tasks that assess

short-term memory allowed a maximum of 82.5 points to be obtained. The methodology used to test the cognitive abilities of children is original, created for the needs of the project, and was created according to the methodology to test the cognitive functions and the guidelines conditioned by theoretical foundations.

3. RESULTS

The results of tests diagnosing students' cognitive functions (concentration of attention, memory, including short-term and long-term memory) are presented as percentages to better illustrate the distributions.

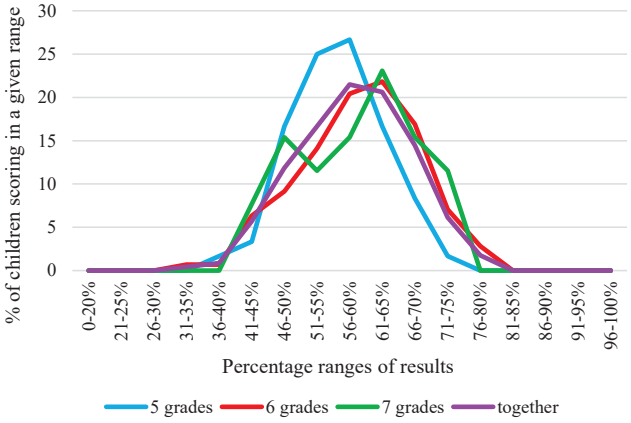

Fig. 2. Distribution of the results of the diagnostic tests for cognitive functions

Analysing the data obtained (Fig. 2), it can be concluded that the distribution of results of 5th grade students is slightly shifted to the left (toward lower results). Statistical analysis of the data obtained (Table 1) can conclude that the average result of the students in the fifth grade is significantly different from the average result of the students in the sixth grade ($Z = 2.81$). This is the only significant difference between the means of individual age groups (grades 5 and 7 $Z = 1.2$, grades 6 and 7 $Z = 0.42$).

Table 1. Summary of the results of the cognitive tests for each age group

Grade	Mean [pts.]	Standard deviation	Median [pts.]	Modal [pts.]	Minimum [pts.]	Maximum [pts.]
5	56.23	7.12	56	54	38	72
6	59.58	9.03	60	63	33	79
7	58.77	8.99	60	63	41	73
Σ	58.61	8.68	59	56	33	79

The test results obtained were compared with the blood saturation levels tested in the students. A low correlation can be found between the test results and the saturation level of the students ($r = 0.11$), which is not statistically significant at the adopted level of $\alpha = 0.05$.

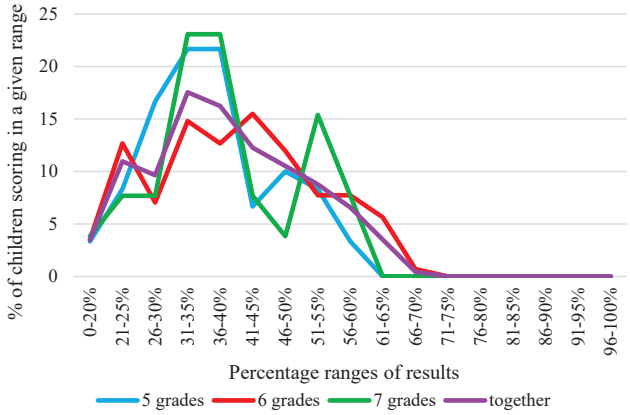

Fig. 3. Distribution of the results of diagnostic tests for concentration of attention

Analysing the data obtained in the results of tests diagnosing concentration of attention (Fig. 3), it can be concluded that the distribution of results of students of grades 5 and 7 is slightly shifted to the left (towards lower results). Statistical analysis of the data obtained (Table 2), it can be concluded that the average result of the students in the fifth grade is significantly different from the average result of the students in the sixth grade ($Z = 2.23$). This is the only significant difference between the means of individual age groups (grades 5 and 7 $Z = 0.91$, grades 6 and 7 $Z = 0.66$).

Table 2. Summary of the statistical results for each age group – an attempt to concentrate attention

Grade	Mean [pts.]	Standard deviation	Median [pts.]	Modal [pts.]	Minimum [pts.]	Maximum [pts.]
5	36.68	9.71	37	38	17	59
6	40.33	12.43	40	44	15	66
7	38.80	10.49	38	33	20	57
Σ	39.20	11.66	38	38	15	66

The test results obtained were compared with the blood saturation levels tested in the students. There is a slight correlation between the test results and the saturation level of the students ($r = 0.03$), which is not statistically significant at the adopted level of $\alpha = 0.05$.

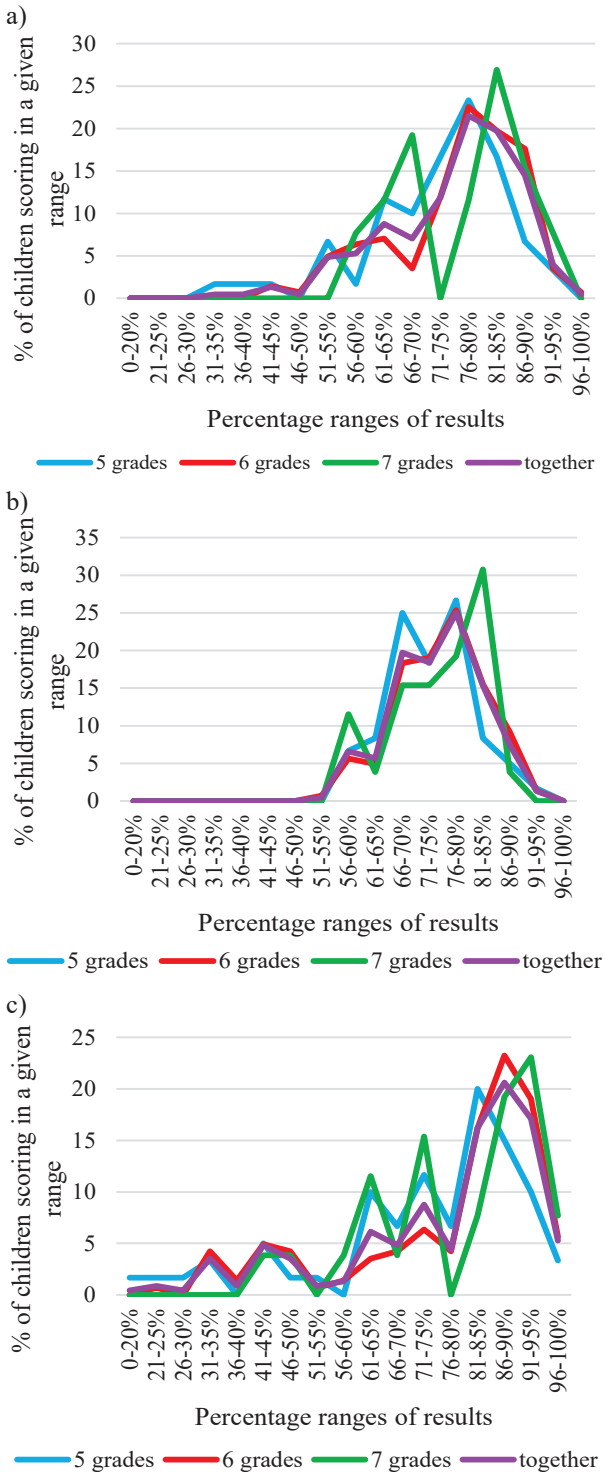

Fig. 4. Distribution of the results of diagnostic tests for the level of memory (a) total memory; (b) short-term memory; (c) long-term memory

Analysing the data obtained, it can be concluded that the distribution of general memory results (Fig. 4a) of fifth-grade students is slightly shifted to the left (toward lower results). Analysis of short-term memory data (Fig. 4b) showed that the distribution of results of seventh-grade students is slightly shifted to the right (toward higher results). However, in the case of long-term memory, the distribution of students' results is similar for all classes. Performing a statistical analysis (Table 3-5) of the data obtained, it can be concluded that the average overall memory score of students in grades 5 does not differ significantly from the average score of students in grades 6 (Z = 1.86) and 7 (Z = 1.44) and that there is no significant difference between the average result of grades 6 and 7 (Z = 0.2). The average short-term memory score of fifth grade students does not differ significantly from the average score of sixth grade students (Z = 1.87) and seventh grade students (Z = 0.76), and there is no significant difference between the average score of sixth and seventh grade of students (Z = 0.47). The average long-term memory score of students in fifth grade does not differ significantly from the average score of students in sixth grade (Z = 1.44) and seventh grade (Z = 1.54), and there is no significant difference between the average score of sixth and seventh grades (Z = 0.46).

Table 3. Summary of statistical results for each age group: level of memory

Grade	Mean [pts.]	Standard deviation	Median [pts.]	Modal [pts.]	Minimum [pts.]	Maximum [pts.]
5	72.96	11.15	76	76	39	94
6	76.21	11.36	79	84	41	96
7	76.69	10.71	80	82	57	91
Σ	75.41	11.33	78	84	39	96

The general results of the memory tests were compared with the blood saturation level of the students. A low correlation can be found between the test results and the saturation level of the students (r = 0.13), which is not statistically significant at the adopted level of α = 0.05.

Table 4. Summary of statistical results for each age group: short-term memory level

Grade	Mean [pts.]	Standard deviation	Median [pts.]	Modal [pts.]	Minimum [pts.]	Maximum [pts.]
5	72.96	7.66	73.5	68.77	57	91
6	75.28	8.22	76	78	53	94
7	74.43	9.29	76	83.84	56	88
Σ	74.58	8.27	75	72	53	94

The results obtained from the short-term memory tests were compared with the blood saturation level tested in the students. A low correlation can be found between the test results and the level of blood saturation of the students (r = 0.14), which is not significant at the adopted level of α = 0.05.

Table 5. Summary of statistical results for each age group: long-term memory level

Grade	Mean [pts.]	Standard deviation	Median [pts.]	Modal [pts.]	Minimum [pts.]	Maximum [pts.]
5	72.96	19.38	78	83	19	97
6	77.15	18.56	83	89	22	97
7	78.95	15.08	83	89.92	44	97
∑	76.25	18.54	83	89	19	97

The results obtained from the long-term memory tests were compared with the blood saturation level tested in the students. A low correlation can be found between the test results and the level of blood saturation of the students (r = 0.09), which is not significant at the adopted level of α = 0.05.

In the next step of the analysis, parents and teachers completed questionnaires that assess the cognitive functions of the students.

A statistical analysis of the results of questionnaires addressed to parents and teachers was performed, the purpose of which was to determine the level of attention and memory of the individual students subjected to the study. A summary of Pearson's correlation coefficients between teachers' and parents' ratings is presented in Table 6.

Table 6. Correlation between teacher and parent ratings

		Together	5 grade	6 grade	7 grade
Memory	Correlation coefficient *r*	0.46	0.6	0.42	0.5
	Correlation strength	Moderate	High	Moderate	Moderate
	T	7.46	4.92	4.61	2.51
	Significance of correlation	Important	Important	Important	Important
Concentration of attention	Correlation coefficient *r*	0.4	0.51	0.41	0.26
	Correlation strength	Moderate	High	Moderate	Short
	T	6.57	3.89	4.5	1.16
	Significance of correlation	Important	Important	Important	Important

Analysing the data obtained, high and moderate correlations can be found between the assessments of cognitive functions made by parents and teachers. In fact, all covariates turned out to be statistically significant at the assumed level of α = 0.05. Only a low and insignificant covariation appeared in the assessment of concentration of attention in seventh grade students.

The results of the described questionnaires were compared with the results of the tests performed on students (Tables 7 and 8).

Table 7. Correlation between parent ratings and student results

		Together	5 grade	6 grade	7 grade
Memory	Correlation coefficient *r*	-0.25	-0.08	-0.33	-0.32
	Correlation strength	Short	Short	Moderate	Moderate
	T	3.3	0.53	3.48	1.48
	Significance of correlation	Important	Unimportant	Important	Unimportant
Concentration of attention	Correlation coefficient *r*	-0.19	-0.05	-0.23	-0.52
	Correlation strength	Short	Short	Short	Moderate
	T	2.48	0.33	2.3	2.67
	Significance of correlation	Important	Unimportant	Important	Important

Table 8. Correlation between teacher ratings and student results

		Together	5 grade	6 grade	7 grade
Memory	Correlation coefficient *r*	-0.28	-0.12	-0.32	-0.3
	Correlation strength	Short	Short	Moderate	Moderate
	T	3.74	0.8	3.37	1.38
	Significance of correlation	Important	Unimportant	Important	Unimportant
Concentration of attention	Correlation coefficient *r*	-0.27	-0.25	-0.21	-0.53
	Correlation strength	Short	Short	Short	Moderate
	T	3.6	1.77	2.19	2.72
	Significance of correlation	Important	Unimportant	Important	Important

The next step was to analyse the results of the cognitive functions divided according to the normal curve (according to the means and standard deviations of the sample) – 243 results (Fig. 5). And evaluations of cognitive functions and concentrate on by parents and teachers (Figs. 6 and 7).

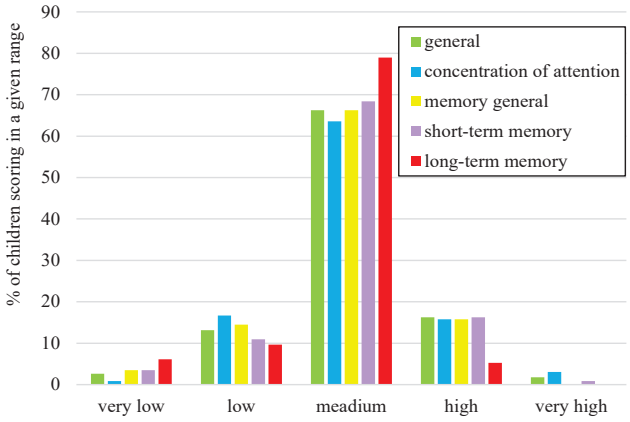

Fig. 5. Distribution of the results of the cognitive functions tests

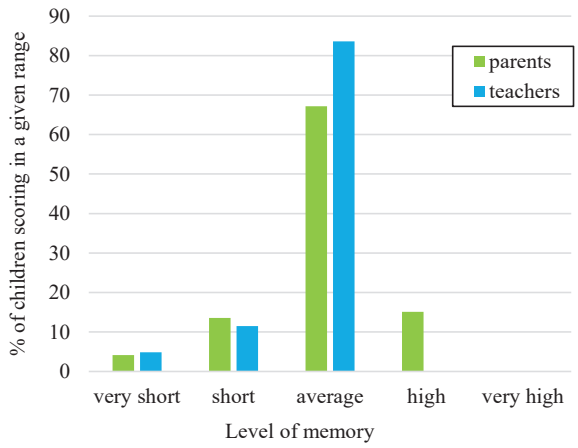

Fig. 6. Student memory level as assessed by parents and teachers

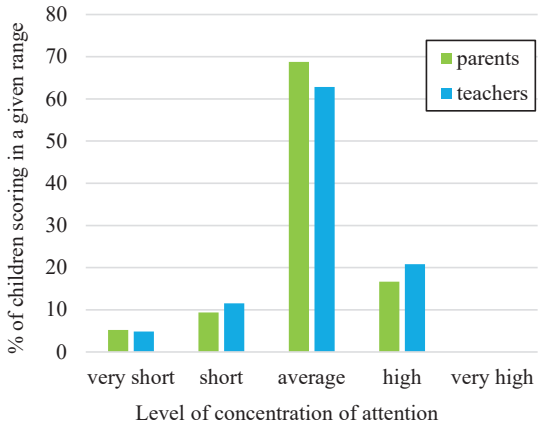

Fig. 7. Level of concentration of attention of students as assessed by parents and teachers

Based on the data obtained (Tables 6-8, Figs. 5-7), it can be concluded that both parents and teachers quite accurately assess the level of memory and concentration of students (moderate and high levels of correlation between test results and parents' and teachers' ratings). No significant correlation was observed between the results and the assessment of parents and teachers only in the fifth grade and in the seventh grade (in terms of memory).

Then, analyses of student well-being and mood were performed (Fig. 8).

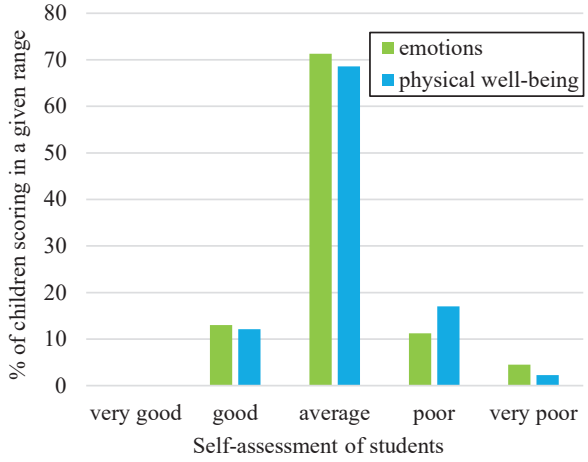

Fig. 8. Assessment of students' well-being

For this purpose, the students completed surveys to determine their mood, physical well-being, and general emotional state (Fig. 8).

Table 9 lists the correlations between individual groups of samples that examine various cognitive functions and mood, well-being, and general emotional state.

Table 9. Correlation between samples examining various cognitive functions and mood, well-being, and general emotional state

	Cognitive function test result	Concentration of attention test result	Memory test result	Short-memory test result	Long-memory test result
Mood	r=-0.01	r=-0.01	r=-0.02	r=-0.002	r=-0.02
Physical well-being	r=0.02	r=0.03	r=0.03	r=0.05	r=0.01
General emotional state	r=-0.08	r=-0.09	r=-0.02	r=-0.08	r=0.01

All described correlations are low. It can be concluded that there is no covariation between mental and physical well-being and general emotional state and the results of cognitive function tests.

4. DISCUSSION

Research on memory has revealed two phenomena: its compatibility with mood (in a good mood it is easier to remember and recall positive information than negative information; in a bad mood, the opposite) and its dependence on the state of the body (it is easier to recall events in a state similar to where we were at the moment of remembering them) [6]. The analysis presented in this article does not confirm this conclusion, as there was no covariation between well-being and the results of cognitive tests. However, the age of the subjects should be taken into account. In the case of this study, these were children under 14 years of age. However, most of the studies conducted so far in this area included adults [45] or elderly people over 60 years of age, most often with medical conditions [47] and preschool children [31]. Therefore, it seems very important to conduct such research on a group of children and minors, especially today, when they are exposed to numerous sources of negative influence.

Some studies in this area show mainly the consistency of negative mood. This result can be explained by the concept of evolution [47]. Information remembered in a negative mood is more important than information remembered in a positive mood because it determines the adaptation to the environment to a greater extent. For adaptive reasons, it is more beneficial to remember information that is associated with a negative mood than that that is associated with a positive mood.

In the next stage, it seems reasonable to expand the research to additional aspects, such as issues of socioeconomic status as indicated by the latest research [48, 49], contact with nature [50] or issues of development in childhood [51] because they can influence the development of cognitive functions.

The literature contains analyses of the impact of various factors on cognitive functions, such as physical fitness [52], playing computer games [53, 54], or cognitive function training [55, 56]. However, there are no analyses that present the level of cognitive functions of school-age children. Our study fills this research gap by showing the level of cognitive functions of children at various levels of education, from fifth grade to seventh grade in primary school.

5. CONCLUSIONS

Analysing the data obtained in the field of cognitive function and memory level testing, it can be concluded that the distribution of results of fifth-grade students is slightly shifted to the left (towards lower results). The average result obtained for the cognitive functions of fifth grade students differs significantly only from the average result of sixth grade students. Statistical analysis of the data obtained allows us to conclude that the average result of the fifth grade students does not differ significantly from the average result of the sixth grade students ($Z = 1.86$) and the seventh ($Z = 1.44$). Analysing the results obtained of concentration of attention, it can be concluded that the distribution of the results of students of grades 5 and 7 is slightly shifted to the left (towards lower results), but the average result of students of grades 5 differs significantly only from the average result of students of grades 6 ($Z = 2.23$). The results obtained for short-term memory show that the distribution of the results for seventh-grade students is slightly shifted to the right (toward higher results). The average result of students in grades 5 does not differ significantly from the average result of students in grades 6 ($Z = 1.87$) and 7 ($Z = 0.76$), and there is no significant difference between the average result in grades 6 and 7 ($Z = 0.47$). In the case of long-term memory, it can be concluded that the distribution of students' results is similar. By performing a statistical analysis of the data obtained, it can be concluded that the average result of students in grades 5 does not differ significantly from the average result of students in grades 6 ($Z = 1.44$) and 7 ($Z = 1.54$), and there is no significant difference between the average result of students in grades 6 and 7 ($Z = 0.46$).

In addition to tests that determine the level of cognitive functions, students completed surveys to determine their mood, physical well-being, and general emotional state. All the correlations described are slight. It can be concluded that there is no covariation between mental and physical well-being and general emotional state and the results of cognitive function tests.

Analysing the data obtained, high and moderate correlations between the cognitive function assessments made by parents and teachers can be found. In fact, all covariates turned out to be statistically significant at the assumed level of $\alpha = 0.05$. Only a low and insignificant covariance appeared in the assessment of attention concentration in seventh grade students. Based on the data obtained, it can be concluded that both parents and teachers quite accurately assess the level of memory and concentration of students (moderate and high levels of correlation between test results and parents' assessments and teachers). Parents' and teachers' ratings for grades 5 did not correlate significantly with test results, and for grades 7 only with memory test results.

The test results obtained were compared with the blood saturation levels tested in the students. In all the groups of questions analysed, there is a low correlation between the test results and the blood saturation level of the students, which is not significant at the adopted level of $\alpha = 0.05$.

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Declaration of Interest Statement
The authors certify that they have no with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non- financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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The authors confirms a research study meets ethical standards.
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Not applicable.

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Data availability
Data will be made available on request.

Authors' contributions
Telejko M.: *Supervision , Writing – review & editing, Writing – original draft.* ***Zender-Świercz E.:*** *Funding acquisition, Formal analysis, Text translation.* ***Galiszewska B.:*** *Data curation.* ***Wojcieszak R.:*** *Data analysis.*

SELECTED PROPERTIES OF POLYMER-MODIFIED BITUMENS

WYBRANE WŁAŚCIWOŚCI ASFALTÓW MODYFIKOWANYCH POLIMERAMI

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Abstract

The article presents an analysis of research results on bitumens modified with waste polymers polypropylene (PP) and polyethylene terephthalate (PET). The bitumens were modified under conditions consistent with the Plackett-Burman experimental design by appropriately selecting the mixing process variables. The results of basic tests are presented. The microstructure of bitumens modified with waste polymers was compared with two commercially available bitumens modified with styrene-butadiene-styrene (SBS) copolymer. The analysis of test results revealed certain similarities between laboratory-prepared bitumens and PmB 45/80-55. Modification of road bitumens 20/30 and 70/100 resulted in improvement particularly in the softening point temperature range. Furthermore, modification of certain binder parameters without changing its consistency proved possible. The possibility of polymer particle coagulation at higher homogenizer rotational speeds was also demonstrated.

Streszczenie

W artykule przedstawiono analizę rezultatów badań asfaltów modyfikowanych odpadowymi polimerami polypropylene (PP) i polyethylene therepthalate (PET). Asfalty zmodyfikowano w warunkach zgodnych z planem eksperymentu Placketta-Burmana, dobierając odpowiednio zmienne procesu mieszania. Przedstawiono wyniki badań podstawowych takich jak temperatura mięknienia, penetracja, temperatura łamliwości wg Fraassa. Porównano mikrostrukturę asfaltów modyfikowanych odpadowymi polimerami z dwoma asfaltami dostępnymi komercyjnie modyfikowanymi kopolimerem styren-butadien-styren (SBS). Analiza wyników badań ukazała pewne podobieństwa pomiędzy asfaltami przygotowanymi w laboratorium a asfaltem PmB 45/80-55. Modyfikacja asfaltów drogowych 20/30 i 70/100 przyniosła poprawę szczególnie w zakresie temperatury mięknienia. Ponadto możliwa okazała się modyfikacja niektórych parametrów lepiszcza bez zmiany jego konsystencji. Wykazano również możliwość koagulacji cząstek polimeru przy wyższych prędkościach obrotowych homogenizatora.

INFLUENCE OF RANDOM VARIABLE CORRELATION ON THE RELIABILITY OF STEEL STRUCTURES

WPŁYW KORELACJI ZMIENNYCH LOSOWYCH NA NIEZAWODNOŚĆ KONSTRUKCJI STALOWYCH

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Abstract

The study investigated the influence of correlations between random variables on the reliability index of selected structural systems. The structural design parameters were defined as deterministic quantities and random variables, and the correlation between them was modeled using four correlation-matrix variants. The ultimate limit state was adopted as the safety criterion, and appropriate limit state functions were formulated to identify structural failure. A sensitivity analysis of the reliability index with respect to the random variables was carried out using the Hasofer-Lind reliability index as the performance measure. The First-Order Reliability Method served as the primary computational approach, with Monte Carlo simulation as the reference method. All calculations were performed using the NUMPRESS Explore. The analyses demonstrated that increasing the correlation coefficient leads to higher values of the reliability index. The results confirm that the correlation coefficient significantly affects the reliability assessment and should not be neglected in structural safety evaluations.

Streszczenie

W pracy analizowano wpływ korelacji zmiennych losowych na wartość wskaźnika niezawodności wybranych układów konstrukcyjnych. Parametry projektowe konstrukcji zdefiniowano jako wielkości deterministyczne oraz zmienne losowe. W analizie uwzględniono korelację zmiennych losowych poprzez zastosowanie czterech wariantów macierzy korelacji. Stan graniczny nośności przyjęto jako kryterium oceny bezpieczeństwa konstrukcji, a do identyfikacji stanu awarii zastosowano odpowiednie funkcje graniczne. Przeprowadzono analizę wrażliwości wskaźnika niezawodności względem zmiennych losowych, przyjmując wskaźnik Hasofera-Linda jako miarę niezawodności. Podstawową metodą obliczeniową była metoda niezawodności pierwszego rzędu (FORM), natomiast metodę Monte Carlo wykorzystano jako metodę referencyjną. Obliczenia przeprowadzono z wykorzystaniem oprogramowania NUMPRESS Explore. Na postawie przeprowadzonych analiz zaobserwowano, że wzrost wartości współczynnika korelacji prowadzi do zwiększenia wartości wskaźnika niezawodności. Uzyskane wyniki potwierdziły, że współczynnik korelacji wywiera istotny wpływ na wartość wskaźnika niezawodności, wobec czego nie powinien być pomijany w ocenie bezpieczeństwa konstrukcji.

DATA-DRIVEN PREDICTION AND NORMALIZATION OF MECHANICAL PROPERTIES IN JUTE FIBER–REINFORCED CONCRETE

PROGNOZOWANIE I NORMALIZACJA WŁAŚCIWOŚCI MECHANICZNYCH BETONU ZBROJONEGO WŁÓKNAMI JUTOWYMI NA PODSTAWIE WYNIKÓW BADAŃ

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Abstract

Using fiber in the concrete is one of the methods to improve its capacity for the load resisting especially for the bending and tensile loading, but this process has two challenges, the first one is the energy usage, the waste gas emission which produced in these fiber's industry, while the second challenge is the increase in the solid waste materials in the land which is include natural plant fiber. The usage of natural fiber instead of these industrial fibers will have a double advantage. This article deals with investigating the effect of using jute fiber on the properties of concrete, also proposing statistical models to predict the compressive strength of concrete by collecting the experimental data from previous experimental work. By using three different models, including the quadrant support vector machine, Integration Linear, and squared exponential Gaussian, and using 80 experimental data points. Based on the obtained results between the proposed models to predict the compressive strength of concrete, SVM provides higher accuracy and efficiency compared to the other proposed models, when the value of the coefficient of determination is higher than the IL, and SEG by 10.98%, and 1.09% respectively.

Streszczenie

Zastosowanie włókien w betonie to jedna z metod poprawy jego wytrzymałości na obciążenia, zwłaszcza zginanie i rozciąganie. Proces ten wiąże się jednak z dwoma wyzwaniami. Pierwszym z nich jest zużycie energii i emisja spalin powstających w przemyśle włókienniczym, a drugim – wzrost ilości odpadów stałych w glebie, w tym naturalnych włókien roślinnych. Zastosowanie włókien naturalnych zamiast włókien przemysłowych przyniesie podwójną korzyść. Niniejszy artykuł analizuje wpływ zastosowania włókien jutowych na właściwości betonu, proponując również modele statystyczne do przewidywania wytrzymałości betonu na ściskanie poprzez zebranie danych eksperymentalnych z poprzednich badań laboratoryjnych, z wykorzystaniem trzech różnych modeli, w tym kwadrantowej maszyny wektorów nośnych (SVM), interakcji liniowej (IL) i gaussowskiej radialnej funkcji bazowej (SEG), a także 80 punktów danych eksperymentalnych. Na podstawie uzyskanych wyników pomiędzy proponowanymi modelami przewidywania wytrzymałości betonu na ściskanie SVM zapewnia wyższą dokładność i wydajność w porównaniu z innymi proponowanymi modelami, podczas gdy wartość współczynnika determinacji jest wyższa niż w przypadku IL i SEG, odpowiednio o 10,98% i 1,09%.

NEW MODEL OF A THERMAL WASTE TREATMENT PLANT IN THE STRUCTURE OF A SUSTAINABLE CITY – ACCESSIBILITY ANALYSIS ON THE EXAMPLE OF COPENHAGEN

NOWY MODEL ZAKŁADU TERMICZNEGO PRZEKSZTAŁCANIA ODPADÓW W STRUKTURZE MIASTA ZRÓWNOWAŻONEGO – ANALIZA DOSTĘPNOŚCI NA PRZYKŁADZIE KOPENHAGI

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Abstract

Amager Bakke (CopenHill) is an example of a modern architectural solution for a technical facility serving the city. Thanks to its additional recreational and educational functions (ski slope, climbing wall, green terraces, etc.), it constitutes a significant element of the urban fabric, enhancing its attractiveness. Accessibility studies of the facility demonstrated its good integration with the city's public transport system (20/30 points). A strength is its good accessibility thanks to a network of bicycle paths (within 10 minutes of the city center), which is crucial to Copenhagen's mobility plans. A weakness, however, is the lack of efficient multimodality due to the lack of a nearby metro station, which is problematic in such an intensively revitalized area as the district where Amager Bakke is located. From a circular economy perspective, CopenHill is the final element of waste neutralization coupled with energy recovery, which raises questions about the environmental sustainability of the incineration process and the need for its technical support in the absence of waste.

Streszczenie

Amager Bakke (CopenHill) to przykład nowoczesnego rozwiązania architektonicznego obiektu technicznego zaplecza obsługi miasta, który dzięki dodatkowym funkcjom rekreacyjnym i edukacyjnym (stok narciarski, ścianka wspinaczkowa, zielone terasy i in.) stanowi istotny element rewitalizowanej tkanki miejskiej, podnoszący jej atrakcyjność. Przeprowadzone badania dostępności obiektu wykazały jego dobrą integrację z systemem miejskiego transportu (20/30 pkt). Silną stroną jest jego dobra dostępność dzięki sieci ścieżek rowerowych (dojazd do 10 min z centrum), tak istotnych w planach mobilności Kopenhagi. Słabą natomiast – brak sprawnie funkcjonującej multimodalności z uwagi na brak bliskiej lokalizacji stacji metra, co jest problematyczne w przypadku tak intensywnie rewitalizowanego obszaru, jakim jest dzielnica, w której mieści się Amager Bakke. Z punktu widzenia circular economy CopenHill jest ostatnim elementem neutralizacji odpadów sprzężonym z odzyskiem energii, co rodzi jednak pytania o ekologiczność procesu spalania i konieczności jego technicznego podtrzymywania w przypadku braku odpadów.

COGNITIVE FUNCTIONS OF CHILDREN IN GRADES 5-8 – CASE STUDY

EFEKTYWNOŚĆ PRZYSWAJANIA WIEDZY DZIECI KLAS V-VIII

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Abstract

One of the cognitive and practical challenges of the 21st century is unraveling the mystery of the structure and functioning of the most important and the most complicated organ of the human body, which is the brain. Therefore, it is the subject of research by representatives of many fields of science (e.g., medicine, biology, genetics, psychology, and biochemistry).

The objective of this study was to evaluate the cognitive functions of school-age children in Poland. The results of research based on tests that diagnose concentration of attention and memory, including short-term and long-term memory, are described. The research was carried out among students from nine primary schools, including a total of 243 children, their parents, and teachers.

Streszczenie

Jednym z wyzwań poznawczych i praktycznych XXI wieku jest rozwikłanie tajemnicy budowy i funkcjonowania najważniejszego i najbardziej skomplikowanego narządu ludzkiego ciała, jakim jest mózg. Dlatego też stanowi on przedmiot badań przedstawicieli wielu dziedzin nauki (m.in. medycyny, biologii, genetyki, psychologii i biochemii). Celem niniejszej pracy była ocena funkcji poznawczych dzieci w wieku szkolnym w Polsce. Przedstawiono wyniki badań opartych na testach diagnozujących koncentrację uwagi i pamięć, w tym pamięć krótkotrwałą i długotrwałą. Badania przeprowadzono wśród uczniów dziewięciu szkół podstawowych, w tym łącznie 243 dzieci, ich rodziców i nauczycieli.