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CARBON FOOTPRINT OF A CONCRETE TRANSPORT STRUCTURE - A DEEP TUNNEL

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Abstract. The research object of this scientific work is the massive concrete structures of underground low-deep transport tunnels, reinforced with steel and non-metallic composite reinforcement. Circular-section tunnels with the frame nominal diameters of 5, 10 and 15 m are considered.

The subject of the research study is the assessment of the averaged carbon footprint in both types of the constructive solution throughout their entire life cycle. The presented research is due to the need to implement the European Climate Law (the European Green Agreement. At the same time the Paris Agreement (2016) recommends to stop producing and using carbon steel in construction by 2030. The ecological impact of both types of transport tunnels is expressed in the form of carbon footprint, as the equivalent of carbon dioxide emissions, which is calculated separately for each stage of their existence in accordance with the current European Codes, including the recommendations of the proprietary methodology.

To determine the required sizes of the tunnels concrete frames and their reinforcement, the numerical routine (B_3) experiment was carried out in PLAXIS software complex in accordance with the current regulations.

Averaged according to three different diameters and generalized carbon dioxide emissions during the life cycle of the reference structure (type 1) and proposed one (type 2) of the underground transport tunnel with the length of 1 m.p. were, respectively, 15.97 t CO_2 eq and 11.551 t CO_2 eq, i.e. decreased by almost 1.4 times.

The conducted research made it possible to analyze the carbon dioxide emissions into the atmosphere, to systematize the existing factors and impact factors of the specified building on the environment, and to determine the ways of their reduction. The possibility and expediency of using basalt-plastic reinforcement instead of steel in monolithic concrete structures, incl. transport tunnels, according to the criterion of reducing greenhouse gas emissions are proved.

Keywords: carbon footprint, carbon dioxide emissions, underground transport tunnel, monolithic heavy concrete, steel and non-metallic composite reinforcement, construction life cycle, stage, information group (module).

Introduction. In 2015, 193 UN member nations recognized the undisputed success of the Millennium Development Goals Program until 2015, adopted by the UN General Assembly in 2000, and the need to adopt a new agenda. At the beginning of August that year, they reached the consensus and adopted the final document "Transforming of our world: The 2030 Agenda for Sustainable Development", which was approved at the UN Summit on September 25, 2015 with the final formulation of 17 global Sustainable Development Goals (SDG). Among them № 12 is ensuring the rational models of consumption and production; № 13 is taking the urgent measures to combat climate change and its consequences.

The sustainable development concept of the world community appeared in the process of combining three main points of view: economic, social and environmental. It provides to adopt the measures aimed at the optimal use of limited resources and to apply ecological nature-, energy- and material-saving technologies for ensuring the stability of social and cultural systems, as well as the integrity of biological and physical natural systems.

In December 2019, the countries of the European Union defined 6 priorities of Sustainable Development (European Green Agreement) in Brussels. In particular, the European Climate Law sets the goal of achieving climate neutrality of the territory by 2050, and by 2030 – to reduce harmful emissions by at least 50 %.

Taking the above mentioned into consideration, it is obvious that in the construction industry, which is one of the most capital-intensive, it is vital to make innovative decisions to fulfill the global goals, in particular № 13 – to reduce harmful emissions of greenhouse gases and, first of all, CO_2 carbon dioxide.

Analysis of recent research and publications. Based on the available experience and analysis of the latest researches and publications, it is known that any construction object exerts its ecological impact on the environment throughout its entire life cycle. As a rule, everything begins with the production of raw materials and continues until the demolition of the structure, waste recycling for the secondary use and material recovering. According to [1], about 50 % of the total carbon dioxide emissions into the atmosphere are due to the activities of the construction industry. The reduction of energy consumption and the negative impact of construction on the modern ecosystem is provided by the directives [2, 3] and the diffusion [4] approved by the European Commission. They regulate the main principles of energy efficiency, environmental friendliness and economy in the construction industry. Their observance will ensure high energy efficiency, cost-effectiveness of buildings and structures with low values of carbon dioxide emissions and other greenhouse gases.

International green building standards of the latest generation [5–7] recommend to consider the greenhouse effect of harmful gases from any building or structure at the stage of their design.

The examination of harmful emissions from the construction and the arrangement of structures, the assessment of the impact of their main parameters on the environment are carried out by various scientists with the aim of finding optimal solutions and implementing them into the Building Code. Among them, it should be noted the work [8], in which there is the analysis of greenhouse gas emissions in construction, software and computer evaluation of their effects, data on carbon emissions of construction materials and products.

The research work [9] provides data on the environmental impact of 20 individual buildings and established criteria for its evaluation, and the suggestions for its simplification are made. The study [10] proposes the analytical method for calculating the carbon content of a building object. However, it does not take into account carbon dioxide emissions during its demolition work and waste recovery.

The academic paper [11] provides the method for calculating greenhouse gases from individual residential buildings, which takes into account various stages of their life cycle, from raw material production to waste recovery. At the same time, the emissions from their assembly are not taken into account.

Scientific works [12, 13] describe the parametric studies results of concrete reuse and carbon steel component materials after reinforced concrete structures recovery which life cycle has ended.

Among the home studies the pioneering works [14, 15] should be highlighted, in which the analysis of the construction impact on the environment was made, with the methodology development and the carbon footprint assessment of a multi-story hybrid wooden and reinforced concrete building. Two types of 15-story building with reinforced concrete and hybrid framework made of glued timber and reinforced concrete rigid core are considered. The use of hybrid structural system instead of reinforced concrete made it possible to reduce carbon dioxide emissions into the atmosphere by 3.7 times and confirms its effectiveness.

In summary it should be emphasized that despite the achievements of science and the world community's awareness of the possible catastrophic consequences of the global environmental crisis associated with harmful emissions of carbon dioxide and other greenhouse gases into the atmosphere, the certain measures for their radical reduction are still being planned in the modern construction industry, in particular in design. In addition, almost half of the time allotted for the implementation named by SDG has already passed... However, it is obvious that the environmental requirements are neglected at most modern local construction sites, starting from the design stage. So **the purpose of this work** is to demonstrate the necessity and expediency of the system approach and methodology [2–5, 16] to determine the carbon footprint throughout its life cycle in order to find the ways to reduce it using a specific example of the underground transport tunnel.

Research tasks:

– to systematize the existing factors and negative environmental impact factors of the specified tunnel on the environment;

– to improve the existing methodology [14–16] for estimating of carbon dioxide emissions into the atmosphere by determining the carbon footprint in the form of CO_2 equivalent during the construction interacting with the foundation soils;

– to prove the technical functionality and the ecological expediency of steel replacing with basalt-plastic reinforcement in monolithic concrete structures of deep transport tunnels according to the criterion of reducing greenhouse gas emissions into the atmosphere.

Research methodology. The assessment of the material impact of the main load-bearing structures on the carbon footprint of the underground transport structure was carried out on the example of three underground transport tunnels with different diameters (Fig. 1). The main load-bearing elements of the tunnels are monolithic concrete frameworks with the annular cross-section, the horizontal disks of surfaces for vehicles, which rest on the external annular frameworks at the edges, and in the middle part – on the longitudinal walls-partitions, with steel (standard reference modification) and non-metallic composite (BFRP) reinforcement (proposed modification). The construction of the tunnels is planned to be carried out using the proven shield method in medium-hard rock by excavating the soil with a tunneling machine and arranging the tunnel frame behind it.

Analytical and numerical methods of finite elements using PLAXIS software complex were used to determine the internal forces in the tunnels frames and possible ground subsidence during their construction. Three-factor three-level numerical experiments were implemented according to Box-Benkin B_3 plan, which is based on planning theory.

In these modifications the tunnels have nominal (median surface) diameters of 5.10 and 15 m (X_1 factor), which are located, respectively, at the depths of 20.0; 22.5 and 25.0 m to their horizontal axis from the ground surface (X_2 factor including the level of underground water). The geological cross-section is typical for the southern region of Ukraine. It is characterized by the presence of four main layers (X_3 factor – the type of soil conditions). The upper layer with the thickness of 13 m consists of loess loam the stiffness of which increases linearly with the depth. Under the layer of loam there is the layer of fine-grained sand with the thickness of 2.0 m which was used as a bearing layer for the piles of the ancient building – the monument of architecture and urban planning (probably larch timber). Uneven settlement of these piles during and after the installation of the mentioned tunnels is extremely undesirable for the landmark.

Below the sand layer there is a deep layer of red and brown loams and clays with the thickness of 5.0, respectively; 7.5 and 10.0 m. This is one of the layers where the upper part of the tunnel is erected. And its lower part is placed in a deep layer of shelly limestone of the Pontic layer with the inclusions of recrystallized shelly limestone in its covering. This layer is rather hard so only 5 m of this layer is included in the finite element model. The distribution of pore water pressure is hydrostatic. The groundwater level can be at the depths of 3.9 and 15 m (X_2 factor) below the ground surface, i.e. at the mark $y = 0$ in PLAXIS software complex.

Since the tunnels frame are also soil: the layering is more or less symmetrical with respect to the vertical axis of the tunnel, only one (right) half of their framing and the soil base was taken into account in the considered models of plane deformation. In the horizontal direction, the design soil model extended 33, 39, and 45 m, respectively.

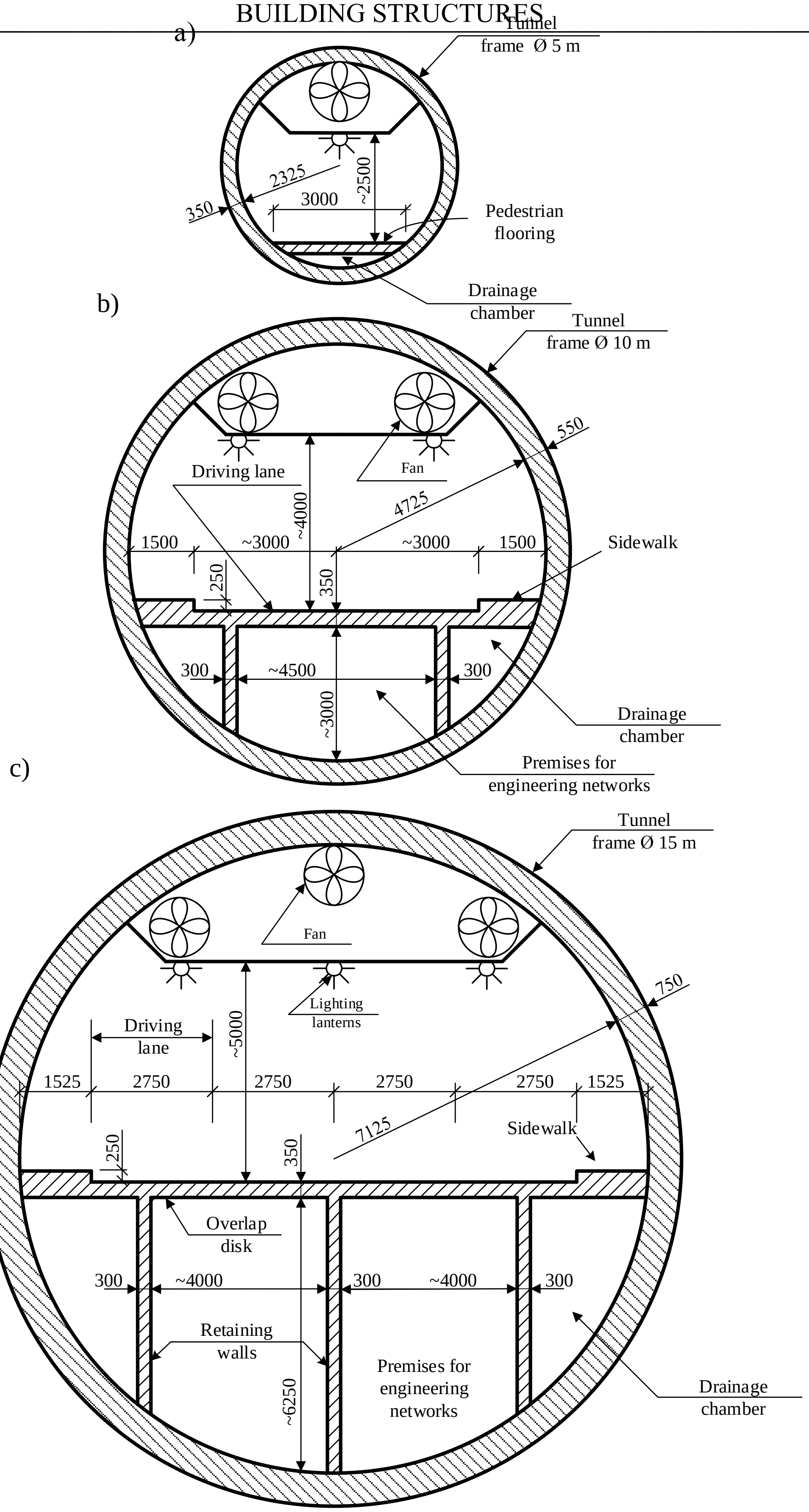

Fig. 1. The main load-bearing structures of transport tunnels with the diameters 5 m (a), 10 m (b), 15 m (c)

Research results. *Environmental impact assessment of the life cycle of any building structure.* The scientific research in this branch shows that carbon footprint should be expressed in terms of carbon dioxide equivalent, and its assessment for a specific building structure should consider all the emissions that happen not only during the useful life. At the same time, it is necessary to take into account any possibility of reuseing or processing of constituent elements and materials after its demolition.

For analyze convenience of the calculated environmental indicators it is advisable to organize and record the obtained data according to the stages of the life cycle listed in Table 1.

Table 1 – Stages of the useful life cycle of the structure and the components

Useful life cycle of the structure			
Pre-operational stage		Operational stage	Completion of the life cycle
Extraction and transportation of raw materials	Installation and construction work	Operation	Demolition
		Service	
Production of materials and components		Renovation	Destruction
		Replacement	
Additional information that does not belong to the life cycle of the structure:			
– external impact beyond the building structure;			
– reusing, processing, recycling.			

According to the recommendations of the European Standard [16], researches [14, 15], the considered groups of the life cycle of the building are presented in the form of a modular system (Table 2), which takes into account all its stages, divided into separate information groups, which are sometimes intertwined.

Table 2 – Characteristics of the information modules and the stages of buildings life cycle formed by them according to [16]

Life cycle stage	Information group (module)	Process
Pre-operational stage	A1	Supply of raw materials
	A1	Transportation
	A3	Production
Construction stage	A4	Transportation
	A5	Construction works
Operational stage	B1	Operation
	B2	Maintenance
	B3	Repair
	B4	Replacement
	B5	Major repair
	B6	Energy use
	B7	Water use
The stage of the life cycle completion	C1	Demolition
	C2	Transportation
	C3	Waste processing
	C4	Destruction
Benefits and burdens outside the system	D	Potential for reuseing and recycling

The conducted studies [14–16] establish that the results of the emissions assessment during the life cycle should be presented in the form of CO_2 carbon dioxide equivalent (kg CO_2 eq) for each stage (Table 3).

Table 3 – Before the carbon dioxide emissions assessment during the building life cycle

Life cycle stage	Measurement units of carbon footprint assessment results
A1 – A5 B1 C1 – C4 D1 – D2	kg CO_2 eq/m^2 of useful internal area of any building or structure
B2 – B7	kg CO_2 eq/m^3 of useful internal volume of any building or structure

The carbon footprint assessment of buildings and structures during their life cycle.

According to the recommendations [14–16], in the building made of several parts, it is advisable to calculate the carbon footprint from carbon dioxide emissions during the entire life cycle using the expression:

$$CF = CF_{A1-A3} + CF_{A4-A5} + CF_{B1-B7} + CF_{C1-C4} - CF_{Д}, \tag{1}$$

where $CF-$ the estimated amount of carbon dioxide emissions during the entire life cycle;

$CF_{A1-A3}-$ the estimated amount of emissions at the pre-operational stage;

$CF_{A4-A5}-$ the estimated amount of emissions at the construction stage;

$CF_{B1-B7}-$ the estimated amount of emissions at the stage of operation;

$CF_{C1-C4}-$ the estimated amount of emissions at the completion stage of life cycle;

$CF_{Д}-$ the estimated amount of emissions beyond the structure life cycle.

The components of formula (1) are calculated as the sum of estimated emissions for the its building element for each information group from Table 2. There are:

$$CF_{A1-A3} = \sum CF_{A1,i-A3,i}, \tag{2}$$

$$CF_{A4-A5} = \sum CF_{A4,i} + \sum CF_{A5,i}, \tag{3}$$

$$CF_{B1-B7} = \sum CF_{B1,i} + \sum CF_{B2,i} + \sum CF_{B3,i} + \sum CF_{B4,i} + \sum CF_{B5,i} + \sum CF_{B6,i} + \sum CF_{B7,i}, \tag{4}$$

$$CF_{C1-C4} = \sum CF_{C1,i} + \sum CF_{C2,i} + \sum CF_{C3,i} + \sum CF_{C4,i}, \tag{5}$$

$$CF_{Д} = \sum FC_{Д,i}, \tag{6}$$

where $i-$ the number of the component or building element.

Carbon dioxide emissions during the production of "simple" monomaterials (extraction, transportation and processing of raw materials) are determined by multiplying their mass by the reduction coefficients of carbon equivalents:

$$CF_{A1,i-A3,i} = V_i \cdot \rho_i \cdot k_{mat,i}, \tag{7}$$

where V_i- the volume of the i-th material for the manufacture of building elements;

ρ_i- the density (thickness) of its material;

$k_{mat,i}-$ the reduction coefficients of greenhouse gas (carbon dioxide) emissions.

Carbon dioxide emissions during the manufacture of "complex" components made of different materials (for example, facade systems, solar panels, etc.) are determined using the environmental impact statement results of the products by the manufacturer or using the data of a close analogue by introducing one or another reduction coefficient:

$$CF_{A1,i-A3,i} = Q_i \cdot k_{red,i} \cdot k_{ref,mat,i}, \tag{8}$$

where Q_i- the number of units of a complex component (for example, the total volume or area);

$k_{red,i}-$ the reduction coefficient;

$k_{ref,mat,i}$ – the reduction coefficient of carbon dioxide emissions to the analogue.

Carbon emissions during the transportation from the manufacturing plant to the construction site (information group A4) are calculated by multiplying the mass of the corresponding element (M_i) by the transportation distance (L_i) and by the reduction coefficient $(k_{tr,i})$ of emissions of the specified gas, considering the type of transport:

$$CF_{A4,i} = M_i \cdot L_i \cdot k_{tr,i} . \tag{9}$$

The arrangement of a structure or the construction of a building (information group A5) is a complex process, during the implementation of which many techniques, equipment and devices are used, as well as data from another similar project. All considered:

$$CF_{A5,i} = A_{tot} \cdot k_{constr} , \tag{10}$$

where A_{tot} – the total useful area of the building;

k_{constr} – the coefficient of carbon dioxide emissions per m^2 of the total internal area of a similar building.

At the stage of preliminary design the experts recommend using approximate data of similar projects with the use of appropriate coefficients k_{constr}. So the volumes of carbon emissions during the estimated operation period (information group B1) are determined:

$$CF_{B1,i} = V_{tot} \cdot k_{constr} , \tag{11}$$

where V_{tot} – the construction volume of the building.

The emissions caused by the operations related to the maintenance (B2) are recommended to be calculated using the expression:

$$CF_{B2,i} = n_m \cdot T_{op} \cdot Q_i \cdot k_{m,i} , \tag{12}$$

where n_m – the number of maintenance operations of the building during the year;

T_{op} – the estimated period of building operation;

Q_i – the number of the units of the corresponding components (for example, the area of windows, facades, etc.);

$k_{m,i}$ – the coefficient of carbon dioxide emissions for the maintenance of the i-th component.

Similarly, the emissions of the specified gas during repair work are determined (module B3):

$$CF_{B3,i} = n_{rep} \cdot T_{op} \cdot Q_i \cdot k_{rep,i} , \tag{13}$$

where n_{rep} – the number of maintenance operations during the year;

$k_{rep,i}$ – the emission factor CO_2 during the maintenance (repair) of its components.

The emission assessment according to the information groups B4 and B5 in the process of replacing some elements or major repairing of the structure includes the emissions caused by the production of materials necessary for the implementation of the modules B4 and B5 (information groups A1 – A3), their transportation and the execution of construction work (modules A4 and A5):

$$CF_{B4,i} = n_{repl} \left(\sum CF^{repl}_{A1,i-A3,i} + \sum CF^{repl}_{A4,i} + \sum CF^{repl}_{A5,i} \right); \tag{14}$$

$$CF_{B5,i} = n_{refurb} \left(\sum CF^{refurb}_{A1,i-A3,i} + \sum CF^{refurb}_{A4,i} + \sum CF^{refurb}_{A5,i} \right), \tag{15}$$

where $n_{repl,}$ n_{refurb} – accordingly, the number of replacements and major repairing during the service life;

$CF^{repl}_{A1,i-A3,i}$, $CF^{refurb}_{A1,i-A3,i}$ – the total emissions during the production of necessary materials for replacement of elements or major repairs;

$CF^{repl}_{A4,i}$, $CF^{refurb}_{A4,i}$ – the total emissions during transportation of necessary materials for replacement and major repairs;

$CF_{A5,i}^{repl}$, $CF_{A5,i}^{refurb}$ – the total emissions when using the necessary materials in the process of construction works for replacement and major repairs.

The total amount of emissions at the end of the life cycle is calculated using the expression:

$$FC_{1-C4} = A_{tot} \cdot k_{dem} + \left(M_{w,r} + M_{w,lf}\right) \cdot L \cdot k_{tr} + M_{w,lf} \cdot k_w, \tag{16}$$

де $M_{w,r}$ – the weight of the construction waste that is suitable for processing and reuse;

$M_{w,lf}$ – the weight of construction waste that must be buried;

L – the distance from the construction site to the processing plant or to waste burial sites;

k_w – the coefficient of carbon dioxide emissions when processing or waste burying.

The materials obtained after processing can be used for the further arrangement of a similar structure or building. The expediency consideration of the following use of the specified materials is carried out according to the following formula:

$$FC_{Д,i} = \sum FC_{A1,i-A3,i}^{recycled}, \tag{17}$$

where $FC_{A1,i-A3,i}^{recycled}$ – the total emissions of carbon dioxide during extraction, transportation and production of i-th processed material.

Average emissions of carbon dioxide per 1 m.p. of buildings. The average carbon emissions during the estimated operation period of both construction types (module B1) are 1312 t CO_2 eq per 1 m.p. of the tunnels, which include the emissions during air conditioning, heating, cooling, water supply, drainage, lighting for the accepted energy efficiency class B. At the same time, the carbon emission factor was taken as for electric energy $К_{CO2}$= 420g/kWh in accordance with the recommendations [14, 15] and others.

The underground transport deep-level tunnels belong to the structures that cannot be dismounted because it is associated with uncontrolled subsidence and movement of soil masses. Therefore, CO_2 carbon dioxide emissions were not carried out for this information group (C1).

The emissions of CO_2 carbon dioxide during the transportation of the construction waste (module C2) and during their burial (information group C3) are not determined in the work due to their small amount.

The carbon emissions according to the D module, which could be formed during the materials processing of the destructed building and their reuse (recycling), are not considered in this work for the reason mentioned above.

Summarizing the above, according to three important and most widespread transport tunnels with nominal diameters of their middle surfaces of 5, 10 and 15 m and the length of 1 m.p. the averaged carbon footprint of the standard reinforced concrete (reference) structure is 15.977 t CO_2 eq, and the basalt concrete (proposed structure) is 11.551 t CO_2 eq, which is approximately 1.4 times less than the reinforced concrete one. Therefore, the largest emission reduction occurs at the pre-operational stage during the production and use of basalt plastic (BFRP) non-metallic composite reinforcement instead of steel.

It is obvious that at the operational stage, the carbon dioxide emissions can be significantly reduced also at the major repair (module B5) and replacement (module B4) of structural part with steel reinforcement, which received significant damage due to its corrosion on a monolithic concrete section of the structure with non-metallic composite reinforcement, for example, basalt plastic.

Conclusions:

1. The performed analysis of CO_2 carbon dioxide emissions into the atmosphere made it possible to systematize the existing factors and the factors of the negative environmental impact of the building, which are characterized by the processes from the extraction of raw materials for the production of the necessary materials to its destruction with the reuse of the obtained materials and recycling.

2. In accordance with the requirements of current European standards [16], the adapted and improved estimating methodology of carbon dioxide emissions into the atmosphere (carbon footprint in the form of CO_2 equivalent), which takes into account all the stages of the building life cycle and the possibility of reusing the obtained materials after its dismounting (recycling).

3. The technical feasibility and ecological expediency of basalt plastic reinforcement (BFRP) instead of steel in monolithic concrete structures of deep-level transport tunnels according to the

criterion of greenhouse gas emissions reducing into the atmosphere have been revealed. At the same time, the averaged carbon footprint 1 m.p. for three different diameters of the specified building is in the proposed version of the structure was 11.551 t CO_2 eq against 15.977 t CO_2 eq in the traditional (reference) version of the reinforced concrete structure, so it decreased by approximately 1.4 times. The specified CO_2 emissions can be reduced by almost 25 % during the repair or replacement of the horizontal road blocking and its supporting structures due to the use of non-metallic BFRP reinforcement instead of steel and recycling of materials.

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ВУГЛЕЦЕВИЙ СЛІД БЕТОННОЇ ТРАНСПОРТНОЇ СПОРУДИ–ТУНЕЛЮ ГЛИБОКОГО РОЗТАШУВАННЯ

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Анотація. Об’єктом дослідження даної роботи являються масивні бетонні конструкції підземних транспортних споруд-тунелів глибокого розташування, армовані сталевою і неметалевою композитною арматурою. Розглядаються тунелі кільцевих перерізів з номінальними діаметрами 5, 10 і 15 м їхніх оправ.

Предметом дослідження є оцінювання усередненого вуглецевого сліду в обох варіантах конструктивного вирішення споруд напротязі всього їхнього життєвого циклу. Представлені дослідження зумовлені необхідністю виконання Європейського закону про клімат (Європейської зеленої угоди. При цьому, у Паризькій угоді (2016 р.) рекомендовано перестати виробляти і використовувати у будівництві вуглецеву сталь до 2030 року. Екологічний вплив обох варіантів транспортних тунелів виражений у вигляді вуглецевого сліду, як еквіваленту викидів вуглекислого газу, який обчислюється окремо для кожної стадії їх існування згідно чинних Європейських Норм з урахуванням рекомендацій авторських методик.

Для встановлення необхідних розмірів бетонних оправ тунелів та їх армування був реалізований числовий планований (B_3) експеримент в ПК “PLAXIS” згідно чинних норм.

Осереднені за трьома різними діаметрами та узагальнені викиди вуглекислого газу протягом життєвого циклу еталонної (варіант 1) і запропонованої (варіант 2) конструкції підземної транспортної споруди-тунелю довжиною 1 м.п. становили, відповідно, 15,97 т CO_2екв і 11,551 т CO_2екв, тобто зменшилися майже в 1,4 рази.

Виконані дослідження дозволили зробити аналіз викидів вуглекислого газу в атмосферу, систематизувати наявні чинники і фактори впливу зазначеної споруди на довкілля та визначити напрямки їх зменшення. Доказана можливість та доцільність використання базальтопластикової арматури замість сталевої у монолітних бетонних конструкціях, в т.ч. транспортних тунелів, за критерієм зменшення викидів парникових газів.

Ключові слова: вуглецевий слід, викиди вуглекислого газу, підземний транспортний тунель, монолітний важкий бетон, сталева і неметалева композитна арматура, життєвий цикл споруди, стадія (етап), інформаційна група (модуль).

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