Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XIV, 2025
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

HIERARCHY OF ALTERNATIVES FOR THE REHABILITATION OF ASBESTOS WATER SUPPLY NETWORKS BASED ON ENVIRONMENTAL CRITERIA

Iulian IANCU, Sorin PERJU, Ioan BICA, Alexandru-Nicolae DIMACHE

Technical University of Civil Engineering of Bucharest,
122-124 Lacul Tei Blvd, District 2, 020396, Bucharest, Romania

Corresponding author email: alexandru.dimache@utcb.ro

Abstract

Asbestos water supply networks are not believed to represent a significant hazard to public health in normal use. However, repair, rehabilitation and removal of asbestos pipes involve cutting, and demolition, can release asbestos fibers into the air, posing risks to public health. Many water utilities currently have significant portions of their water mains composed of asbestos pipes that need to be rehabilitated. This paper focuses on the evaluation of four different alternatives to rehabilitate/remove of asbestos pipes, considering the impact on the environment, respectively the total air emissions generated by the activities involved in this rehabilitation. A very performant model, EMEP/EEA air pollutant emission inventory guidebook 2023, was used for this assessment. Results indicate that the replacement of asbestos-cement pipes with no-dig, pipe-bursting technology, which involves laying the new pipe on the inside of the existing pipe, which is broken but remains underground, will have the lowest environmental impact.

Key words: *water supply networks, asbestos-cement pipes, emissions of pollutants.*

INTRODUCTION

Produced and widely used in the construction of water supply networks, asbestos cement pipes were, during the 1950s-1970s, the main type of material used for the design and execution of water distribution networks (Coufal et al., 2014).

Asbestos is an extremely cost-effective material with high tensile strength and good compressive strength. It can withstand alkaline environments, corrosion, heat, electrical conductivity, and bad weather (Pini et al., 2021). The reinforcing properties of Chrysotile fibers greatly increase durability and allow thinner and lighter pipes to be made (World Health Organization, 2011).

The use of asbestos-cement pipes brought several advantages for water operators, thus explaining the wide development of asbestos-cement networks:

- reduced production costs;
- easy installation;
- low weight compared to steel or cast iron;
- resistance to electrochemical erosion;
- relatively low roughness, so low hydraulic load losses;
- low thermal conductivity;
- durability, relatively long-life span.

However, over time it was found that using this material in water supply networks also has some disadvantages, among which are significant:

- risk to human health due to the content of asbestos fibers;
- fragility of pipes; tendency to crack under bending stress;
- difficulties in repairing degraded pipes;
- reduced resistance to vibrations generated by traffic.

Although exposure to asbestos is potentially dangerous, health risks can be minimized. In most cases, the fibers are only released if the asbestos-containing material (asbestos cement) is broken or crumbled (Logsdon, 1983). The product, non-crushed materials containing asbestos, such as water pipes, do not pose health risk. The mere presence of asbestos does not mean that the health of people working with asbestos is threatened. Asbestos is harmless in water because the problem is not ingesting the fibers but inhaling them (Qldwater, 2014).

The natural dissolution of asbestos-containing minerals in the surrounding environment implies the existence of asbestos fibers in water, and research has indicated that most waters, distributed or not through asbestos-cement pipes, contain asbestos fibers (Qldwater, 2014).

Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

Fiber in drinking water consists almost entirely of short fibers, which are considered to pose little risk to public health.

Compared to the reduced health risk associated with the ingestion of asbestos released into drinking water, the repair, rehabilitation and replacement of water mains is of increased health concern as it involves pipe cutting, demolition, transport and disposal, resulting in emissions of very fine asbestos particles into the atmosphere, that could be inhaled (Wang et al., 2010).

Currently, within the urban water infrastructure, the problem of the existence of asbestos-cement pipes is increasingly topical, from the perspective of restrictions on use but also related to the difficulties of decommissioning them from drinking water transport and distribution systems, in which asbestos-cement pipes have been used a long time (Zavašnik et al., 2022). The fact that many of these works have reached the end of their life cycle requires their replacement and rehabilitation.

Asbestos pipe replacement technologies

The potential technologies considered for the replacement of asbestos pipes, which are the subject of this study, are:

- T1 - Replacement of asbestos pipes by placing the new pipe in an open excavation on a route parallel to the replaced pipe and leaving the existing pipe underground by filling it with concrete.
- T2 - Replacement of asbestos-cement pipes by supported open excavation and laying of the new pipe on the same route as the replaced pipe, using a temporary pipe until the new pipe is put into operation; this technology involves the evacuation of the existing pipe from the ground and its transport to an authorized waste landfill having a waste storage cell containing asbestos.
- T3 - Replacement of asbestos pipes by laying the new pipe through horizontal drilling directed along a route parallel to the replaced pipe and leaving the existing pipe underground by filling it with concrete.
- T4 - Replacement of asbestos pipes by no-dig, pipe-bursting technology, which involves laying the new pipe on the inner area of the existing pipe, which is broken, but remains underground.

The carrying out of the works to replace the asbestos-cement pipelines constitutes, on the one hand, a source of dust emissions, and on the other hand, a source of emissions of pollutants specific to the combustion of fuels (distilled petroleum products – petrol and diesel) both in the engines of the necessary machines carrying out the works, as well as the vehicles used to transport the materials (Gottesfeld, 2024).

Dust emissions, which occur during the execution of works specific to the four technologies for replacing asbestos-cement pipes, are generally associated with excavation works, transportation and putting into operation. Dust released into the atmosphere often varies substantially from day to day, depending on the level of activity, specific operations, and weather conditions (Zhang et al., 2002). The temporary nature of the asbestos pipeline replacement works, the specifics of the various execution phases, the continuous modification of the work fronts clearly differentiate the emissions specific to these works from other undirected sources of dust, both in terms of estimation and control of emissions.

The main pollutants associated with the release of dust into the atmosphere from the execution of the construction works are suspended dust - TSP, PM_{10} and $PM_{2.5}$.

As regards the emission sources of pollutants specific to the combustion of fuels, they are differentiated, according to the specifics of the machines, into two categories: heavy construction equipment (construction machinery) and material transport vehicles.

The activity of heavy construction equipment includes, in general, the work that is performed on the pipeline section that is being rehabilitated. The pollution specific to the activity of the machines is assessed according to their type, fuel consumption, period of operation and the area in which they carry out activities.

The main pollutants associated with fuel combustion in engines are CO, NMVOC, NO_x, N_2O, NH_3, SO_2 (Mitra et al., 2002). The amounts of pollutants emitted into the atmosphere by construction machinery depend mainly on the following factors:

- technological level of the engine;
- engine power;
- fuel consumption per power unit;
- machine capacity;

- age of engine/machinery, equipped with pollution reduction devices.

It is obvious that pollutant emissions decrease as the performance of the engine is more advanced, the trend in the world being the manufacture of engines with the lowest possible consumption per unit of power and with the most restrictive control of emissions. It is estimated that the pollution specific to the activities of refueling, maintenance and repair of machinery is reduced because these activities will be carried out mainly in filling stations and specialized repair bases.

The circulation of material transport means can represent an important source of pollution associated with asbestos-cement pipeline replacement technologies. Pollution specific to vehicle traffic is assessed by fuel consumption (polluting substances - NO_x, CO, NMVOC, NO_x, N_2O, NH_3, SO_2, material particles from fuel combustion, etc.) and the distances traveled.

MATERIALS AND METHODS

The evaluation of pollutant emissions into the atmosphere from the activities of replacing asbestos pipes was carried out starting from a series of general calculation assumptions or associated with each technology of replacing pipes separately.

Thus, it was considered:

- the length of the replaced asbestos-cement pipe: 100 m;
- several connections on the new pipe: 10 connections;
- an average transport distance of earth from excavations for disposal: 20 km (round trip);
- an average transport distance of construction materials: 15 km (round trip);
- an average transport distance of asbestos cement waste disposed of at the hazardous waste landfill: 220 km - nearest hazardous waste landfill from Bucharest (round trip);
- fuels used for heavy construction equipment/construction machinery (bulldozer, motor compressor, generator, horizontal directional drilling machine, etc.) and transport vehicles (dump truck, concrete mixer, etc.): diesel (density 860 kg/m^3) and/or gasoline (density 750 kg/m^3);
- fuel consumption was evaluated depending on the transport distances, the volumes of transported materials and the number of operating hours of each construction machine;
- location of construction works – Bucharest, Romania.

As a function of the rehabilitation technology profile, for heavy construction equipment/construction machinery and material transport vehicles used for the replacement of asbestos-cement pipelines, their number and operating time were considered within the activities carried out for each of the four technologies presented. The duration of the works to replace the asbestos-cement pipes, as well as the volumes of excavated earth and the volumes required to restore the filling layers for the length of 100 linear meters of replaced pipe are presented in Table 1.

Table 1. Durations of execution, volumes of excavated earth and volumes required to restore fill layers

Potential technologies	**T1**	**T2**	**T3**	**T4**
Construction period (days)	3	3	4	4
Volume of excavated soil (m^3)	164	160	92	64
Sand (m^3)	49.2	48	22.8	17.76
Gravel (m^3)	8.2	8	3.8	2.96
Crushed stone (m^3)	8.2	8	3.8	2.96
Asphalt mixture (m^3)	8.2	8	3.8	2.96

Based on the assumptions and the data presented, the emissions of pollutants into the atmosphere were calculated for the four categories of emissions:

- dust/particle emissions resulting from the construction activity itself;
- emissions of dust/particles resulting from the transport of materials;
- emissions of pollutants resulting from the combustion of fuels in the engines of construction machinery;
- emissions of pollutants resulting from the combustion of fuels in the engines of material transport vehicles.

Emissions associated with asbestos pipe replacement technologies

The dust/particle emissions from the asbestos-cement pipe replacement activities themselves, for 100 linear m of asbestos-cement pipe replaced, were calculated with the relation (U.S. E.P.A., 1986):

$$EM_{PM_{10}} = EF_{PM_{10}} \times A_{affected} \times d \times (1 - CE) \times \frac{24}{PE} \times \frac{s}{9\%}$$

where:

$EF_{PM_{10}}$ - the corresponding emission factor for PM_{10}

$A_{affected}$ - the area affected by the works

d - the duration of construction works, d = *3 days = 0.00822 years*

CE - coefficient regarding the efficiency of emission control works, $CE = 0$

PE - the Thornthwaite coefficient of precipitation-evapotranspiration, $PE = 49.47$

s - the dust content of the soil, $s = 32\%$.

The results of calculations for dust/particle emissions from the actual asbestos pipe replacement activities, for 100 linear m of asbestos pipe, by the four technologies are presented in Table 2.

Table 2. Dust/particles emissions from asbestos-cement pipe replacement activities

Technology	T1	T2	T3	T4
Affected area [m^2]	320	300	176	162
Duration [days]	3	3	4	4
Total suspended particles – TSP [kg]	1.316	1.234	0.965	0.888
Suspended particles with d<10 µm – PM_{10} [kg]	0.390	0.366	0.286	0.263
Suspended particles with d<2.5 µm – $PM_{2.5}$ [kg]	0.039	0.037	0.029	0.026

Dust/particle emissions from the transport of materials on public roads were calculated per km traveled by a transport vehicle, using the formula (European Environment Agency, 2023):

$$E = k \times 1.7 \times \left(\frac{s}{12}\right) \times \left(\frac{S}{48}\right) \times \left(\frac{W}{2.7}\right)^{0,7} \times \left(\frac{w}{4}\right) \times \left(\frac{365 - p}{365}\right)$$

for which it was considered:

- multiplication factor for the particle size:
    - 0.35 for PM_{10};
    - 0.053 for $PM_{2.5}$.;
- s - dust content of the road surface, $s = 3$;
- S - average speed of vehicles, $S = 30$ *km/h*;
- W - weight of vehicles, $W \approx 20$ *t*;
- w - number of wheels, $w = 6$;
- p - number of dry days, $p = 132$ (for Romania).

The results of the calculations for dust/particle emissions from the transport of materials on public roads, for the four technologies, are presented in Table 3.

Table 3. Emissions of dust/particles resulting from the transport of materials on public roads

Technology	T1	T2	T3	T4
Distance [km]	575	745	330	240
Suspended particles with d<10 µm – PM_{10} [kg]	207.93	449.02	119.34	86.79
Suspended particles with d<2.5 µm – $PM_{2.5}$ [kg]	31.49	67.99	18.07	13.14

The total emissions of pollutants resulting from the combustion of fuels in the engines of heavy construction equipment and in the engines of vehicles transporting construction materials, used for the replacement activities of asbestos-cement pipes (100 linear m of pipe) were calculated based on the "EMEP/EEA" guide air pollutant emission inventory guidebook 2023, 1.A.3.b. Combustion - Road transport, with the relationship (European Environment Agency, 2023):

$$E_i = \sum_j \left(\sum_m \left(FC_{j,m} \times EF_{i,j,m} \right) \right)$$

in which:

E_i - emission of the pollutant i [gr];

$FC_{j,m}$ - fuel consumption of vehicle category j using the fuel m [kg];

$EF_{i,j,m}$ - emission factor for the pollutant i, for the vehicle of category j using the fuel m [gr/kg].

The results of the calculations for the total emissions of combustion fuels in the engines of construction machinery and in the engines of construction material transport vehicles for the four technologies are presented in Table 4.

Table 4. Total emissions resulting from the combustion of fuels in the engines of construction machinery

Technology	T1	T2	T3	T4
NMVOC [kg]	5.107	5.201	1.493	1.340
NO_x [kg]	15.320	16.955	11.759	11.173
PM [kg]	0.497	0.543	0.343	0.325
N_2O [kg]	0.0250	0.0275	0.0183	0.0173
NH_3 [kg]	0.0078	0.0084	0.0049	0.0047
SO_2 [kg]	0.0030	0.0033	0.0022	0.0021
CO [kg]	19.48	19.85	5.76	5.18
CO_2 [kg]	1536.8	1692.0	1132.5	1074.6

RESULTS AND DISCUSSIONS

Following the calculations performed and the results obtained and represented graphically in Figure 1, it is found that the emissions of dust/particle matter for T4 technology for the replacement of asbestos-cement pipes are lower than in the other three technologies, as follows:

- T1 – 1.48 times higher than T4;
- T2 – 1.39 times higher than T4;
- T3 – 1.09 times higher than T4.

This is mainly due to the smaller land areas affected by T4 technology.

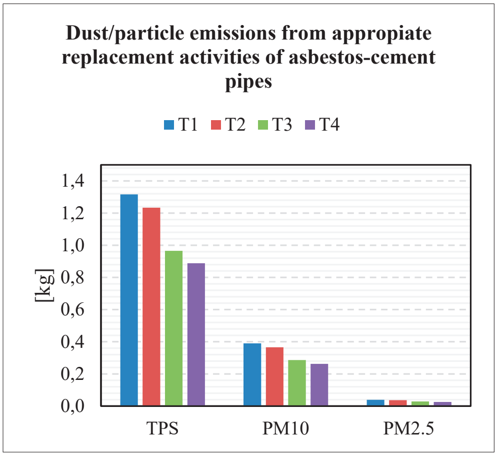

Figure 1. Emissions of dust/particles from the activities of replacing the appropriate asbestos-cement pipes, through the four technologies

For the emissions of dust/particle matter in suspension, generated from the transport of construction materials, shown graphically in Figure 2, it is found that the values obtained for the T4 technology for the replacement of asbestos-cement pipes are lower than the values obtained for the other three technologies, as follows:

- T1 – 2.40 times higher than T4;
- T2 – 5.17 times higher than T4;
- T3 – 1.38 times higher than T4.

The value of dust/particle emissions from the transport of construction materials for T2 technology for the replacement of asbestos-cement pipes, are very high due to the disposal of the disused asbestos-cement pipe at a hazardous waste landfill.

In terms of total emissions of combustion fuels in the engines of heavy construction equipment and construction material transport vehicles, they also vary from one technology to another for the replacement of asbestos-cement pipes, but also from one activity to another.

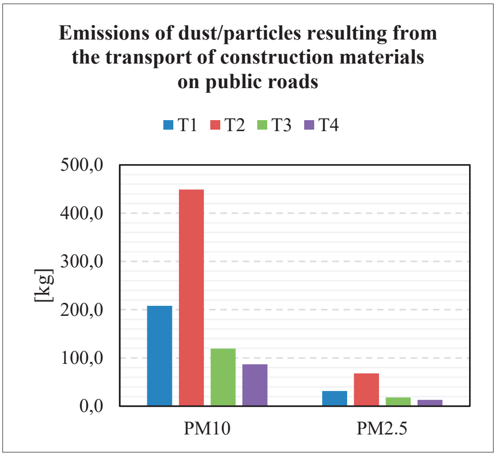

Figure 2. Emissions of dust/particles resulting from the transport of construction materials on public roads, through the four technologies

In comparison, Figure 3 and Figure 4 show, for the four technologies of replacing asbestos-cement pipes, the main emissions (NMVOC, NO_x, PM, N_2O, NH_3 and SO_2) from combustion in the engines of heavy construction equipment.

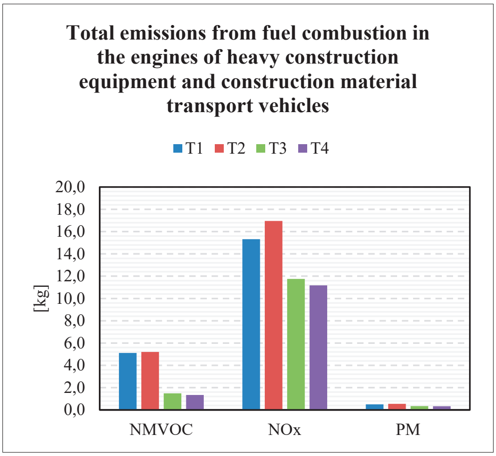

Figure 3. Total NMVOC, NOx and PM emissions resulting from fuel combustion

Analyzing the obtained values, it is found that again the technology with the lowest level of pollutants resulting from fuel combustion is T4 technology (smaller volumes of excavations, shorter transport distances, non-recovery of the replaced asbestos-cement pipe).

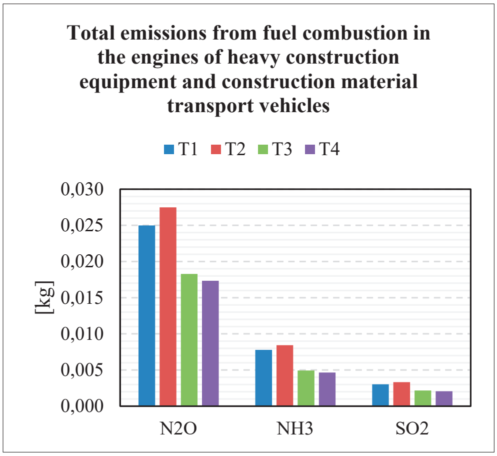

Figure 4. Total N_2O, NH_3 and SO_2 emissions from fuel combustion

It is also found that T4 technology has the lowest levels of pollutants, for the same reasons, both for the CO emission values represented graphically in Figure 5 and for the CO_2 emission values graphically represented in Figure 6.

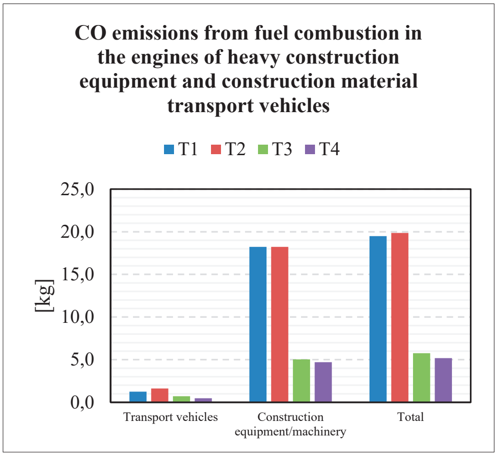

Figure 5. CO emissions [kg], resulting from fuel combustion

The comparative analysis of dust/particle emissions from the actual asbestos pipeline replacement activities, through the four technologies, highlights for any of the four evaluated factors, namely TSP, PM_{10}, $PM_{2.5}$, the fact that the lowest values of them are recorded for T3 and T4 technologies. Technologies T1 and T2 have high values, in the order in which they are listed. Overall, dust/particle emissions for the T4 asbestos-cement pipe replacement technology are lower than the other three technologies.

The emissions of dust/particle matter (PM_{10}, $PM_{2.5}$) from the transport of construction materials for the T4 technology are lower than in the other three technologies.

Emissions from the transport of construction materials for the T2 technology are very high, this fact results from the need to dispose of asbestos pipe waste at a hazardous waste landfill.

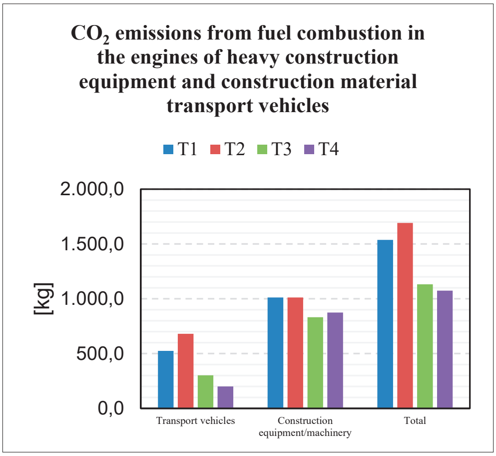

Figure 6. CO_2 emissions [kg], resulting from fuel combustion

NO_x emissions from the combustion of fuels in the engines of heavy construction equipment/construction machinery and vehicles transporting construction materials (NMVOC, NO_x, PM, N_2O, NH_3 and SO_2) also vary from one technology to another, proposed to replace pipelines of asbestos, but also from one activity to another.

The emissions resulting from the combustion of fuels in the engines of heavy construction equipment, for technologies T3 and T4 have the lowest values.

The level of emissions associated with the T2 technology for replacing asbestos pipes is 3.41 times higher than that of the technology with the lowest levels of NO_x emissions T4.

The other two technologies, T1 and T3 record values of 2.63 and 1.51 times higher than technology T4, respectively.

Table 5. Air pollutant emissions associated with the four asbestos-cement pipe replacement technologies

Type of emissions	Emissions			
	T1	T2	T3	T4
Dust/particle emissions from the appropriate asbestos pipe replacement activities, for 100 linear m of asbestos pipe [kg]				
Total suspended particles – TSP	1.316	1.234	0.965	0.888
Suspended particles with d < 10 µm – PM_{10}	0.390	0.366	0.286	0.263
Suspended particles with d < 2.5 µm – $PM_{2.5}$	0.039	0.037	0.029	0.026
Emissions of dust/particles resulting from the transport of materials on public roads [kg]				
Suspended particles with cu d < 10 µm – PM_{10}	207.93	449.02	119.34	86.79
Suspended particles with d < 2.5 µm – $PM_{2.5}$	31.49	67.99	18.07	13.14
Total emissions of pollutants resulting from the fuel combustion in the engines of heavy construction equipment and vehicles transporting construction materials [kg]				
Carbon monoxide – CO	19.48	19.85	5.76	5.18
Non-methane volatile organic compounds – NMVOC	5.107	5.201	1.493	1.340
Nitrogen oxides – NO_x	15.320	16.955	11.759	11.173
Suspended particles – PM	0.497	0.543	0.343	0.325
Nitrous oxide – N_2O	0.0250	0.0275	0.0183	0.0173
Ammonia – NH_3	0.0078	0.0084	0.0049	0.0047
Sulfur dioxide – SO_2	0.0030	0.0033	0.0022	0.0021
Carbon dioxide – CO_2	1536.78	1692.00	1132.53	1074.60

The emission levels of the four technologies were compared by assigning standardized scores to each emission type.

These scores were normalized to a common scale within the [0,1] interval using the following formula:

$$Score_{[0,1]} = 1 - \frac{E - max(E_i)}{max(E_i) - min(E_i)}$$

in which:

E - the emission for a certain type of pollutant;

max(E$_i$*)* - the maximum value of the pollutant emission, from the four technologies;

min(E$_i$*)* - the minimum pollutant emission value, from the four technologies.

A value of "0" was assigned to the highest emission level, while a value of "1" was assigned to the lowest. Based on this approach, Table 6 presents the standardized scores for each technology and type of atmospheric emission, corresponding to the four asbestos–cement pipe replacement methods.

Table 6. Standardized scores by technology and type of atmospheric emissions associated with the four asbestos-cement pipe replacement technologies

Type of emissions	Standardized scores according to technology and type of emissions			
	T1	T2	T3	T4
Dust/particulate emissions from appropriate asbestos pipe replacement activities, for 100 linear m of asbestos pipe				
Total suspended particles – TSP	0	0.19	0.82	1
Suspended particles with d<10 µm – PM_{10}	0	0.19	0.82	1
Suspended particles with d<2.5 µm – $PM_{2.5}$	0	0.19	0.82	1
Final grade (arithmetic average):	0	0.19	0.82	1
Emissions of dust/particles resulting from the transport of materials on public roads				
Suspended particles with d<10 µm – PM_{10}	0.67	0	0.91	1
Suspended particles with d<2.5 µm – $PM_{2.5}$	0.67	0	0.91	1
Final grade (arithmetic average):	0.67	0	0.91	1
Total emissions of pollutants resulting from the fuel combustion in the engines of heavy construction equipment and vehicles transporting construction materials				
Carbon monoxide – CO	0.03	0	0.96	1
Non-methane volatile organic compounds – NMVOC	0.02	0	0.96	1
Nitrogen oxides – NO_x	0.28	0	0.90	1
Suspended particles – PM	0.21	0	0.92	1
Nitrous oxide – N_2O	0.25	0	0.91	1
Ammonia – NH_3	0.17	0	0.92	1
Sulfur dioxide – SO_2	0.24	0	0.91	1
Carbon dioxide – CO_2	0.25	0	0.91	1
Final grade (arithmetic average):	**0.18**	**0**	**0.92**	**1**

CONCUSIONS

The analysis elements presented for the four options highlight the diversity of rehabilitation technologies, respectively their impact on the environment, in particular the emissions of pollutant substances and particles in the atmosphere. At the same time, it was noted that there is still no definitive (dominant) opinion at the international level regarding the solutions applied, or applicable, each country oscillating between various possible options.

Synthesizing the results obtained based on the calculations performed for the emissions of pollutants in the atmosphere highlights the fact that the T1 and T2 technologies have major effects on the environment. However, it can be noted that the T2 technology has higher values of emissions compared to the T1 technology by approximately 18%. T3 and T4 technologies have relatively equal minimum values (slightly better for T4 technology, but the difference is insignificant).

Comparing the scores obtained for the four technologies based on the standardization and normalization of atmospheric emissions in the interval [0,1], various rankings can be made, giving different weights to the three categories of emissions:

- dust/particle emissions from the actual asbestos pipeline replacement activities,
- emissions of dust/particles resulting from the transport of materials on public roads,
- total emissions of pollutants resulting from the combustion of fuels in the engines of heavy construction equipment and vehicles transporting construction materials,

all considered for the replacement of 100 linear m of asbestos-cement pipe.

Regardless of the weightings chosen, technology T4 – replacement of asbestos pipes by no-dig, pipe-bursting technology will get the highest score, and technology T2 – replacement and removal of asbestos pipes by supported open excavation and laying the new pipe on the same route as replaced pipe – will get the lowest score.

REFERENCES

Coufal, M., Václavík, V., & Dvorský, T. (2014). Rehabilitation of asbestos cement water mains for potable water in the Czech Republic. *SGEM2014 Conference Proceedings*, *B31*(S12.075). https://doi.org/10.5593/SGEM2014/B31/S12.075

European Environment Agency. (2023). *EMEP/EEA air pollutant emission inventory guidebook 2023*. https://www.eea.europa.eu/en/analysis/publications/emep-eea-guidebook-2023

Gottesfeld, P. (2024). Exposure hazards from continuing use and removal of asbestos cement products. *Annals of Work Exposures and Health*, *68*(1), 8-18. https://doi.org/10.1093/annweh/wxad066

Logsdon, G. S. (1983). Engineering and operating approaches for controlling asbestos fibers in drinking water. *Environmental Health Perspectives*, *53,* 169 – 176, https://doi.org/10.1289/ehp.8353169

Mitra, A. P., Morawska, L., Sharma, C., & Zhang, J. (2002). Methodologies for characterisation of combustion sources and for quantification of their emissions. *Chemosphere*, *49*(9), 903-22, https://doi.org/10.1016/s0045-6535(02)00236-9

Pini, M., Scarpellini, S., Rosa, R., Neri, P., Gualtieri, A. F., & Ferrari, A. M. (2021). Management of asbestos containing materials: A detailed LCA comparison of different scenarios comprising first time asbestos characterization factor proposal. *Environmental Science & Technology*, *55*(18), https://doi.org/10.1021/acs.est.1c02410

Qldwater. (2014). *Cutting, handling and disposal of asbestos cement (AC) pipe guidelines* (Rev. 1). Queensland Water Directorate. http://www.qldwater.com.au

World Health Organization. (2011). *Guidelines for drinking-water quality* (4th ed.). WHO Library Cataloguing-in-Publication Data.

Wang, D. L., Hu, Y., & Chowdhury, R. (2010). Safety and waste management of asbestos cement pipes. *ASCE Pipeline Conference*, Keystone, Colorado, USA.

U.S. Environmental Protection Agency. (1986). *AP-42: Compilation of air emissions factors from stationary sources*. https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors

Zavašnik, J., Šestan, A., & Škapin, S. (2022). Degradation of asbestos-reinforced water supply cement pipes after long-term operation. *Chemosphere*, *287*(1), https://doi.org/10.1016/j.chemosphere.2021.131977

Zhang, J. J., & Morawska, L. (2002). Combustion sources of particles: 2. Emission factors and measurement methods. *Chemosphere*, *49*(9), 1059-74, https://doi.org/10.1016/s0045-6535(02)00240-0