A New Comparative Analysis of the Environmental Performance Between Large Diameter High Density Polyethylene and Concrete Pipes

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Abstract

The construction sector, which significantly contributes to global carbon emissions, is under increasing pressure to adopt sustainable practices. Given the growing demand for infrastructure involving large-diameter pipes, this study assesses the environmental performance of large-diameter structured wall high-density polyethylene (HDPE) pipes and concrete pipes with internal diameters ranging from 900 mm to 3000 mm, using carbon dioxide equivalent (CO2e) as a measure of emissions. The study examines emissions in two primary stages: the production phase (cradle-to-gate) and the transportation phase (gate-to-site). It evaluates multiple available Environmental Product Declarations for various pipe materials, along with widely recognised carbon footprint resources. The study identifies that the production phase is the most energy-intensive, contributing substantially to the overall carbon footprint. HDPE pipes, despite having a higher embodied carbon per kilogram, demonstrate a lower carbon footprint per meter due to their significantly lighter weight compared to concrete pipes. A detailed comparison of the carbon footprints reveals that, on average, the embodied carbon of concrete pipes is approximately 20% higher than that of equivalent HDPE pipes, particularly for larger sizes. This is also in line with previous studies which has been conducted for smaller diameter pipe sizes. The transportation emissions of HDPE pipes are also considerably lower, as their lighter weight allows for more efficient transport over longer distances. The findings indicate that large-diameter HDPE pipes present a more carbon-efficient alternative to concrete pipes, particularly in terms of production and transportation. The study suggests that adopting HDPE pipes could significantly contribute to the construction industry's efforts to reduce carbon emissions and align with environmental sustainability targets. While the installation phase requires further analysis, the overall environmental performance of HDPE pipes makes them a more promising solution for infrastructure projects aiming to minimise carbon footprints.

Keywords: carbon footprint, climate change, large diameter pipes, High Density Polyethylene, Concrete

Introduction

The issue of climate change and global warming has become a central concern for both political and corporate entities, as evidenced by the significant increase in both academic and commercial research in this domain over recent years [1]. The heightened attention given to this issue is underpinned by a clear and compelling rationale: the concentration of greenhouse gases (GHGs), particularly carbon dioxide (CO2), in the Earth's atmosphere has risen at an unprecedented rate over the past two centuries. It is estimated that the level of GHGs has surged by approximately 40% since the onset of the Industrial Revolution. The Intergovernmental Panel on Climate Change (IPCC) has projected that, if emissions continue unabated, the global average temperature could rise by 2°C to 4°C by the year 2100, a scenario that poses serious risks to ecosystems, human health, and economic stability.

The construction industry, on a global scale, is recognised as one of the most significant consumers of natural resources. In the United Kingdom, the sector is responsible for the consumption of over 400 million tonnes of materials annually, accounting for an estimated 7-10% of the country's total carbon emissions [2]. However, when considering the broader impact of construction-related activities, its contribution to national carbon emissions could be as high as 47% [3]. This highlights the substantial environmental footprint of the industry and underscores the necessity for implementing carbon reduction strategies.

As a result, international policies aimed at mitigating climate change will have profound implications for both the water and construction sectors, from both economic and ethical perspectives. The transition toward a low-carbon economy necessitates that these industries develop and implement strategies to curtail the emissions associated with their operations. This transition must be managed in such a way that it does not compromise the ability to meet the demands of their customers or maintain their overall economic viability of these industries.

One crucial aspect of the built environment that plays a significant role in infrastructure development is the extensive use of buried pipelines. These underground networks, though largely invisible, are integral to the efficient functioning of modern societies. Large-diameter pipes are particularly vital for key infrastructure projects, including water treatment facilities, flood management systems, and general drainage applications. As the scale of such projects

expands, so too does the size of the pipes required, with diameters exceeding 2000mm in many cases. Due to their substantial size, these pipelines are often classified as major underground structures. Historically, concrete has been the predominant material for large-diameter pipes; however, recent advancements in the production of High-Density Polyethylene (HDPE) structured wall pipes especially over the last two decades has led to a shift in industry preferences and large diameter HDPE pipes are an essential component in today's infrastructure sector.

In response to mounting environmental concerns and regulatory requirements, water utility companies have established internal sustainability targets aimed at reducing their carbon footprint. Many organisations have appointed dedicated carbon managers tasked with evaluating and mitigating GHG emissions associated with both ongoing and planned projects. This proactive approach reflects a growing recognition of the need to integrate sustainable practices within the infrastructure sector, ensuring compliance with environmental standards while also fostering innovation in construction methodologies. By focusing on sustainable materials and construction methods for pipelines, the industry can play a significant role in global climate change mitigation and support long-term environmental responsibility.

Scope and Boundaries of this Study

This study conducts a comparative analysis of the environmental performance of large-diameter structured wall high-density polyethylene (HDPE) pipes and concrete pipes, with a specific focus on their carbon footprint. The analysis includes pipe sizes ranging from 900 mm to 3000 mm in internal diameter. This study primarily examines gravity and low-pressure structured wall pipes to enable a direct comparison with equivalent-sized concrete pipes used in similar applications.

In accordance with the majority of recognised carbon footprint assessment standards, the carbon footprint in this study is expressed in terms of carbon dioxide equivalent (CO_2e), incorporating all relevant greenhouse gas (GHG) emissions.

The assessment of the carbon footprint for both pipe materials is carried out in two distinct phases: (1) the production phase, covering the cradle-to-gate lifecycle stage, and (2) the transportation phase. While PAS 2050 [4] permits the carbon footprint of a product to be

assessed based solely on cradle-to-gate emissions, the majority of established carbon footprint standards advocate for a cradle-to-grave approach, encompassing the entire lifecycle of a product. Nevertheless, it is important to recognise that the cradle-to-gate phase is typically the most energy-intensive stage in the lifecycle of water and wastewater pipes, thereby contributing the largest proportion of the overall carbon footprint [5, 6]. Furthermore, the present study focuses exclusively on these two stages due to the fact that both HDPE and concrete pipes have a design life exceeding 100 years, as substantiated by multiple studies from both the concrete and plastic pipe manufacturers' associations.

The concept of a functional unit serves as a standardised reference to quantify the performance of a product. The selection of an appropriate functional unit is critical when assessing the carbon footprint of construction products, as it can significantly influence study outcomes [7]. According to EN 15804 [8], the evaluation of construction products should be conducted within the context of their intended application. Unless otherwise specified, this study adopts pipeline length (m) as the functional unit.

Another critical factor influencing the carbon footprint emissions of both plastic and concrete pipes is the installation and overall construction phase. Assessing carbon emissions during the construction phase is inherently complex due to the unique characteristics of each project. However, the present study aims to provide a generalised evaluation of this stage to offer a broader understanding of its environmental impact.

Methodology

A wide range of resources and databases have been developed in accordance with European and international standards to assess the carbon footprint of various construction products. Notable examples include the Inventory of Carbon and Energy (ICE) developed by Bath University [9], as well as several other online carbon footprint calculators. These resources typically employ standardised conversion methodologies and have been utilized in evaluating the potential environmental impacts of pipe materials [5, 10, 11, 12]. However, the values derived from these resources are subject to interpretation and may be influenced by inherent biases.

The primary objective of this study is to provide a transparent methodology for deriving environmental impact values for both large-diameter concrete and plastic pipes. Over the past decade, various manufacturers of plastic and concrete pipes have developed Environmental Product Declarations (EPDs) in accordance with EN 15804 and ISO 14025. A key resource in this regard is the EPD Hub [13], which contains EPDs for a wide array of construction products, including pipes made from various materials. These EPDs account for the following life cycle stages:

- A1: Raw Material Extraction
- A2: Transport to Factory
- A3: Manufacturing
- A4: Transport to Site
- A5: Installation
- B: Use and Maintenance
- C: End of Life
- D: Recovery Source

This study will primarily focus on stages A1–A3 (cradle-to-gate) and A4 (gate-to-site), with additional generic observations on the installation stage. Stage A5 presents challenges due to the variability in construction parameters, while stages B, C, and D are excluded from consideration due to their relatively low impact when compared to the design life of the materials, which exceeds 100 years.

The study will compare several available EPDs to assess the environmental performance of the materials. Additionally, the UK Environment Agency's carbon calculator, which is widely recognised as a reliable source of carbon footprint data for construction materials and is recommended by the Institution of Civil Engineers (ICE) in the UK, will be used. This tool will be applied both directly and in reference to previous studies on concrete and plastic pipes.

A kgCO2e/kg value will be determined for both concrete and plastic pipes, and a CO2e per meter value will be calculated using the average pipe weight to enable a meaningful comparison.

Cradle to Gate (Concrete Pipes)

In a 2010 study, the British Precast Drainage Association published research [14] presenting kgCO2e per meter values for concrete pipes with internal diameters ranging from 225mm to 2100mm. Using the average weight of concrete pipes provided in the same report, the following figure illustrates the kgCO2e per kilogram for pipe sizes between 900mm and 2100mm in internal diameter.

Pipe Diameter (mm)	kgCO2e per m	Weight (t per m)	kgCO2e / kg
900	131.79	0.8003	**0.165**
1050	175.3	1.0821	**0.162**
1200	223.8	1.3968	**0.160**
1350	273.54	1.8032	**0.152**
1500	341.4	2.1147	**0.161**
1800	457.37	2.8669	**0.160**
2100	559.04	3.5207	**0.159**

Table 1: Values of $KgCO_2e$ / kg for different diameters of concrete pipe [14].

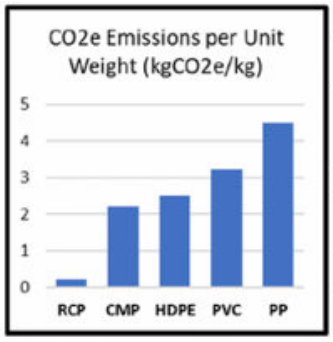
The particular study indicates an average value of 0.160 kgCO2e / kg for concrete pipes.

Study [12] presents a comparative analysis of the carbon footprint of large-diameter concrete and HDPE pipes (ranging from 600mm to 1800mm). It references a value of 0.169 kgCO2e / kg, which was determined based on assumptions regarding the reinforcement of concrete pipes for sizes above 600mm, using the ICE Environment Agency Calculator [9].

A UK concrete pipe manufacturer, FP McCann, provides individual Environmental Product Declarations (EPDs) [15] for pipe sizes with internal diameters of 900mm, 1050mm, 1200mm, 1350mm, 1800mm, and 2100mm. These EPDs report a carbon footprint of 0.15 kgCO2e / kg for stages A1 to A3. Each declaration confirms that the concrete complies with BS 8500 and BS EN 206, assumes a 90% recycled content for steel, and relies on generic industry data for materials, energy, and transport.

Another Environmental Product Declaration (EPD) for Marshalls concrete pipes in UK, included in reference [13], reports a value of 0.207 kgCO2e / kg for a 1200mm internal diameter concrete pipe. Additionally, the American Concrete Pipe Association (ACPA) cites a

value of 0.221 kgCO2e / kg [16], based on a study published by the Canadian Concrete Pipe and Precast Association in 2017.



Cradle-to-Gate Emissions Factors (kg CO2e/kg)		
Material	*Value (kg CO2e/kg)*	*Source*
RCP	0.221	Canadian Concrete Pipe and Precast Association Environmental Product Declaration (2017)
HDPE	2.51	ICE Database for HDPE Pipe (2011)
PP	4.49	ICE Database for Polypropylene, Injection Moulding (2011)
PVC	3.23	ICE Database for PVC Pipe (2011)
CMP	2.21	Corrugated Steel Pipe Institute Environmental Product Declaration (2018)

Figure 1: Cradle to gate emission factors (American Concrete Pipe Association) [16].

Humes, a concrete pipe manufacturer in Australia [17], provides the following range of kgCO2e per kilogram for various classifications and strengths of concrete pipes for stages A1 to A3.

Pipe Diameter (mm)	Range of kgCO2e / kg
900	**0.166 to 0.215**
1050	**0.163 to 0.208**
1200	**0.173 to 0.210**
1350	**0.172 to 0.247**
1500	**0.167 to 0.218**
1650	**0.171 to 0.249**
1800	**0.171 to 0.220**
2100	**0.198 to 0.239**

Table 2: Range of values of $KgCO_2e$ / kg for different diameters of concrete pipe [17].

The same organisation for New Zealand [18] provides values in excess of 0.250 kgCO2e / kg for similar sizes for stages A1 to A3.

Finally, the latest version of the Carbon Planning Tool by Environment Agency UK [19] although it does not provide a direct value for concrete pipes, it provides a reinforce precast concrete value (general) which varies for different strength from 0.206 to 0.257 kgCO2e / kg.

There is significant variation in the reported values of kgCO2e per kg for concrete pipes. Additionally, limited data are available for pipes with an internal diameter greater than 2000mm. Considering these factors, this study adopts a value of 0.179 kgCO2e / kg for pipes with internal diameters ranging from 900mm to 1800mm. For larger sizes, a value of 0.221

kgCO2e / kg will be used, aligning with the figure provided by the ACPA [16] and is within the range of the values provided by Carbon Planning Tool by Environment Agency UK for reinforced precast concrete. While this latter value may underestimate the environmental impact of large concrete pipes, as illustrated in Figure 2, it is considered satisfactory in the absence of more specific data in the literature.

Cradle to Gate (HDPE Pipes)

The Environment Agency UK's latest Carbon Planning Tool [19] and its predecessor, the ICE Environment Agency Calculator [9], estimate the carbon footprint of HDPE pipes at 2.52 kgCO2e / kg . A comparative study [12] analysing the carbon footprint of large-diameter concrete and HDPE pipes (600mm to 1800mm internal diameter) adopts this value but notes that a lower value is anticipated for large-diameter structured-wall HDPE pipes due to the manufacturing process.

EPD Hub library [13] includes several EPDs with values for HDPE pipes of different sizes. The most relevant values and description of the products are summarised in the following table.

Description	Product	Company	Country	Size (mm)	(A1 -A3) $kgCO_2e$/ kg
PE pressure pipes for drainage and sewage	HDPE Pipes	Meltex OY Plastics	Finland	20 to 500	2.39
Double wall PE rainwater and drainage	HDPE Pipes	Meltex OY Plastics	Finland	110 to 900	2.4
Double wall PE pipes	HDPE Pipes	Gigapipe PE	Latvia	300 to 1000	2.16
Double wall PE pipes for rain water	HDPE Pipes	Pipelife	Finland	110	2.1
Pipes for non pressure drainage / sewage	HDPE Pipes	Krah Pipes OU	Estonia	300 to 3000	2.05
PE corrugated pipes	HDPE Pipes	Pestan	Serbia	400	1.92
Sturctured Wall pipes	HDPE Pipes	Uponor	Poland	300 to 3000	2.14
Weholite (Nordics)	HDPE Pipes	Uponor	Sweden	450 to 3000	1.84
PE pressure pipes for drainage and sewage	HDPE Pipes	Uponor	Finland	16 to 1200	2.09
IQ storm water pipes	HDPE Pipes	Uponor	Finland	150 to 1200	2.18

Table 3: Range of values of $KgCO_2e$ / kg for different diameters HDPE pipes [13].

In addition to the values mentioned above, other HDPE plastic pipe EPDs available on EPD Hub, including small-diameter HDPE pipes, have an approximate value of 2.1 $kgCO_2e$ / kg. Considering the previously mentioned values for HDPE pipes, this study will adopt a value of 2.395 $kgCO_2e$/kg, which is 5% lower than the figures cited in [9, 10, 19]. This adjustment ensures a fair comparison between the two materials.

Comparison (Cradle to Gate)

Following a comprehensive review in the literature available the following figure summarises the values that will be used for the comparison between large diameter concrete and HDPE pipes.

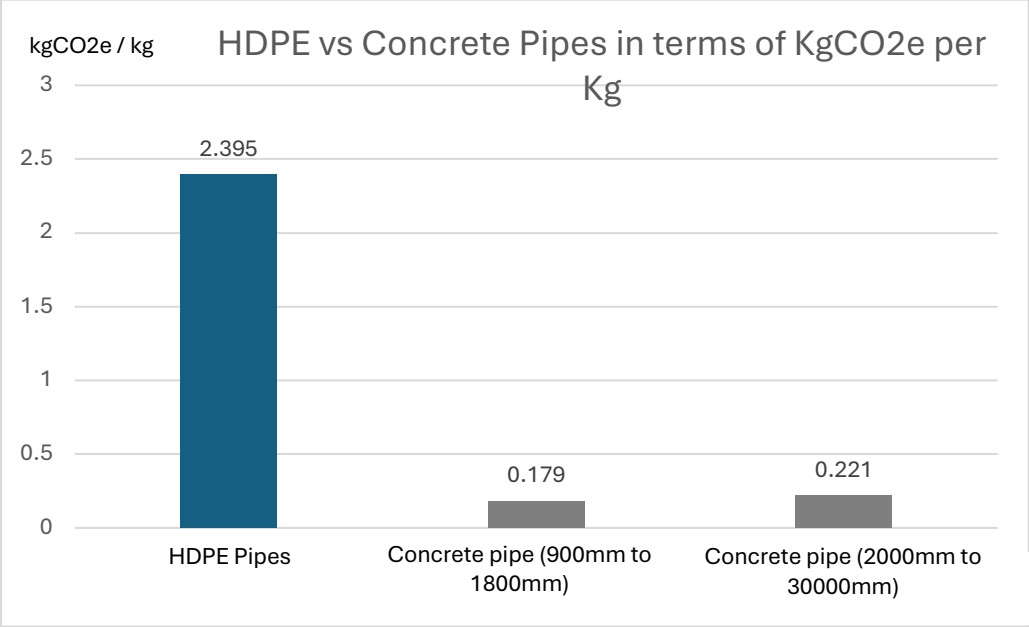


Figure 2: Value of $KgCO_2e$ / kg for concrete and plastic pipes.

The embodied carbon per kilogram in concrete pipe production is notably lower than that of HDPE pipes. However, as this report uses a meter of pipe as the functional unit, which is meaningful as the study refers to pipes, it is essential to compare the materials based on their respective weights. The following figure presents a comparison between concrete and plastic pipes, considering two common stiffness classes for plastic pipes (SN2 and SN4). Average weights for both materials have been used to ensure a balanced evaluation.

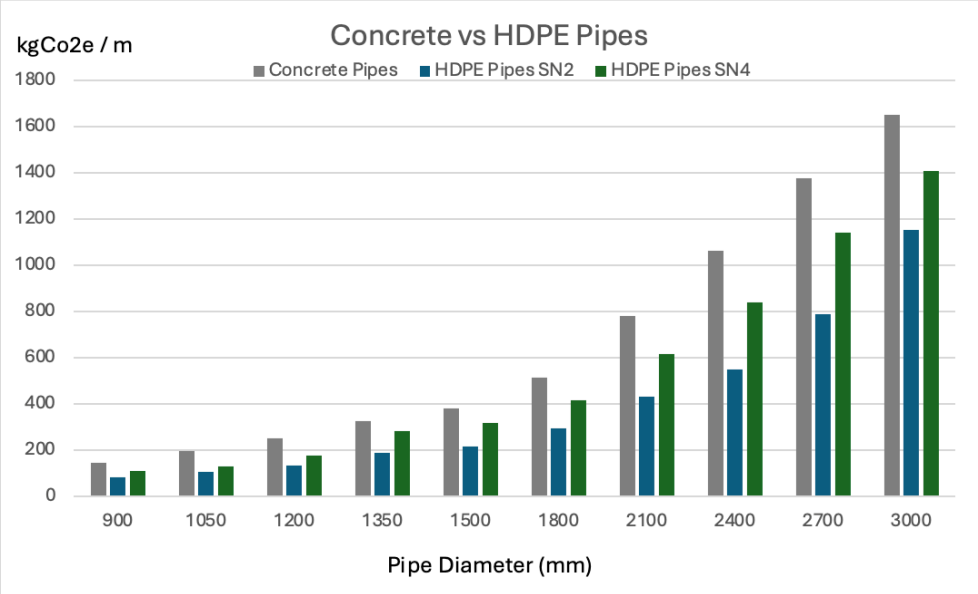


Figure 3: Comparison of carbon emissions per linear meter of pipe (Concrete vs HDPE).

The graph above illustrates that the emissions associated with HDPE structured wall pipes per linear meter are lower than those of concrete pipes, despite the significantly higher embodied carbon per kilogram of plastic. On average, the embodied carbon of a concrete pipe is about 20% higher than that of an equivalent plastic pipe, even when considering a higher stiffness plastic pipe like SN4. This discrepancy is primarily attributed to the substantial difference in weight, particularly for larger pipe sizes. For instance, a concrete pipe with an internal diameter of 2100 mm weighs approximately 3 tonnes per linear meter, whereas an HDPE pipe of the same size, even with increased stiffness, weighs less than 300 kg per linear meter. Even when considering the highest reported values of embodied carbon for plastic pipes from the literature, the overall emissions for HDPE pipes remain lower than those of equivalent concrete pipes. Furthermore, for larger concrete pipe sizes, the value is likely to be higher if a figure closer to 0.25 $kgCO_2e/kg$ is applied. These findings align with previous research [12], which conducted a similar comparison for pipe sizes ranging from 600 mm to 1800 mm.

It is also essential to highlight that for plastic pipes with very high stiffness classifications, specifically those rated SN8 and above, the embodied carbon values per linear meter will be comparable to those of concrete pipes especially in the very large sizes. This convergence occurs due to the increased material density and weight associated with higher-stiffness plastic pipes, which subsequently leads to a higher carbon footprint. However, for pipe

diameters of 2000 mm and above, the majority of plastic pipes utilised in construction and infrastructure projects typically do not exceed the SN4 stiffness classification. As a result, the comparative analysis presented above remains an accurate representation of the emissions associated with both plastic and concrete for the cradle-to-gate phase.

Transportation (Gate to Site)

This section examines the carbon emissions associated with the transportation of both concrete and high-density polyethylene (HDPE) pipes from the manufacturing facility to the construction site, measured in kilograms of CO_2 equivalent ($kgCO_2e$). A previous study [10], utilising Defra's 2011 conversion coefficient [20], determined that concrete pipes exhibit a significantly higher carbon footprint than HDPE pipes in terms of $kgCO_2e$, particularly as either the transportation distance or pipeline length increases. In both scenarios, the carbon footprint of concrete pipes was found to rise approximately an order of magnitude higher than that of HDPE pipes. This substantial disparity in carbon emissions can be attributed to the greater weight of concrete pipes compared to HDPE pipes, leading to a significantly higher $kgCO_2e$ per kilometer.

This study aims to assess the carbon emissions associated with both materials, measured in kilograms of CO_2 equivalent per linear meter of pipe per kilometer. Additionally, it provides further comments regarding transportation-related emissions between the two materials.

To determine the emissions per linear meter of pipe, the study assumes the use of a fully loaded six-axle articulated lorry for one-way transportation. The return journey is excluded from the analysis, based on the assumption that the lorry will return empty, resulting in equivalent emissions for both materials.

It is important to acknowledge that full-capacity transportation, measured in terms of linear meters of pipe, may not always be achievable. However, in large-scale infrastructure projects that involve extensive quantities of pipe, particularly when using large-diameter pipes, a fully loaded transport scenario is considered a representative assumption. For the comparison of plastic pipes, the study examines the variant with higher stiffness, which is also the heavier option, to ensure a consistent basis for evaluation.

The comparison will be conducted using the Greenhouse Gas Protocol emissions calculator [21], which employs the latest emission factors for the UK. Emissions calculations are determined based on the mode of transport, vehicle type (HGV – Articulated 3.5-33 tonnes – Diesel), load weight (maximum lorry capacity measured in linear meters of pipes), and a distance of 1 kilometer. For comparison purposes between the two materials, the results are expressed per linear meter of pipe.

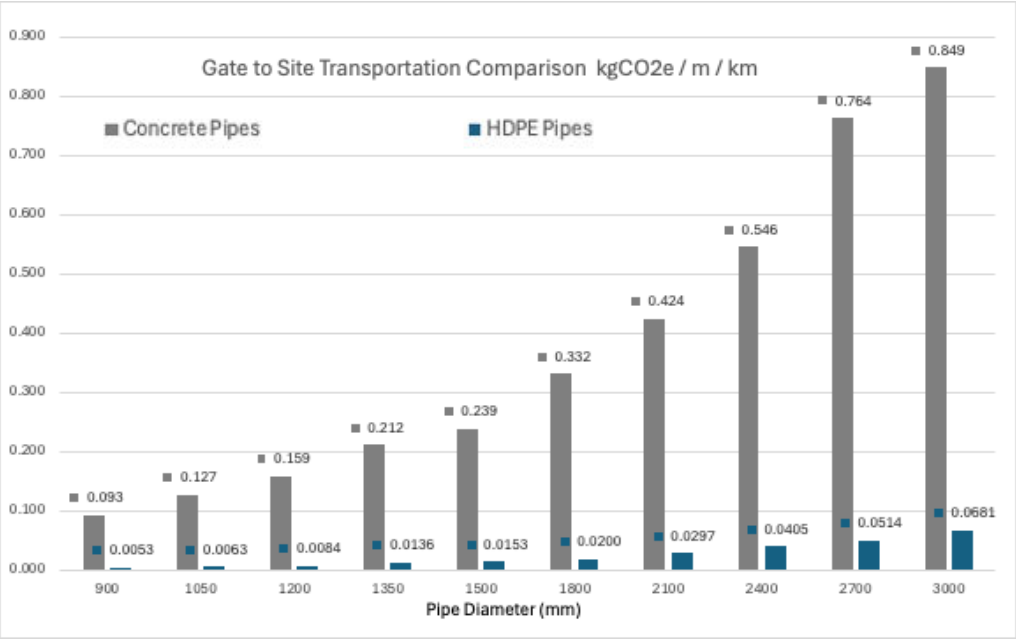


Figure 4: Comparison of carbon emissions per linear meter of pipe per km (Concrete vs HDPE).

As shown in the comparison above, there is a notable difference in transportation-related emissions between the two materials, aligning with findings from previous studies. This disparity is primarily attributed to the weight difference between concrete and plastic pipes, as well as the substantial variation in the number of linear meters of pipe that can be transported per load.

For large pipe sizes, there is a significant difference in transportation and handling between large-diameter concrete and HDPE pipes. Concrete pipes are typically produced in 2.5m lengths, with a 2100mm internal diameter concrete pipe weighing around 3500 kg. As a result, a lorry can transport approximately 9 linear meters of concrete pipes of the size before reaching its maximum weight capacity. In contrast, HDPE pipes of the same size can be transported in 14m lengths or longer, with the total load weight remaining around 3500 kg.

The primary limitation in transporting HDPE pipes is usually the dimensions of the lorry trailer. In some cases, with specialised loads, large-diameter HDPE pipes exceeding 20 meters can be transported in a single length. Additionally, different pipe diameters can be efficiently 'nested' within one another, maximizing the number of units that can be transported per load. The comparison of carbon footprints in terms of transportation shows that large diameter HDPE pipes result in significantly lower emissions, even when they need to be transported over much longer distances.

General Comments

The results of this study suggest that large diameter HDPE pipes are potentially are a more carbon efficient product than concrete pipes. The present study examined the carbon footprint in terms of production and transportation on site. On average, the embodied carbon of a concrete pipe at production stage is about 20% higher than that of an equivalent plastic pipe, even when considering a higher stiffness plastic pipe like SN4.The production stage is the most carbon intensive stage for both materials especially in comparison with the transportation phase. In both stages the large diameter HDPE pipes have less embodied carbon despite the fact that the embodied carbon per kilogram in concrete pipe production is notably lower than that of HDPE pipes.

As outlined in the initial stages of this study, the installation phase has been excluded from analysis due to the complex and bespoke nature of the factors involved, which are not easily quantified. It is well-established that the installation of HDPE pipes necessitates a higher degree of precision and care compared to other materials, particularly with regard to the correct placement of backfill material around the pipes. This consideration is equally important for large concrete pipes; however, it is even more critical for HDPE pipes due to their material properties and structural characteristics.

In contrast to concrete pipes, which are typically limited to a maximum length of 2.5 meters per section, large plastic pipes, such as HDPE, can be delivered in significantly longer lengths. This provides a distinct advantage, reducing the number of joints required during installation. Furthermore, the ease with which bespoke components can be fabricated for HDPE pipes enhances the potential for a streamlined installation process, thus resulting in reduced

installation time and, consequently, a reduction in carbon emissions associated with this phase of construction.

Although the installation phase is not considered in this analysis, a critical factor, particularly relevant when both pipe materials are used in gravity sewer applications, is their comparative hydraulic performance. For concrete pipes, Manning's n value is typical 0.012 or greater. In contrast, large-diameter structured wall HDPE pipes have a tested Manning's n value range of 0.009. Many countries adopt a design value of 0.010 for HDPE pipes to allow for minor long-term degradation, while also recognising the material's superior resistance to corrosion and abrasion. Even under conservative assumptions, HDPE pipes offer approximately 30% greater flow capacity than comparably sized concrete pipes in gravity sewer applications. Consequently, smaller diameter HDPE pipes can often be used in place of larger concrete ones. This substitution can significantly reduce the overall carbon footprint not only from cradle to gate but also during the installation phase by requiring less excavation and backfill material.

Moreover, the large diameter HDPE pipes are in alignment with the principles of Design for Manufacture and Assembly (DfMA). This approach encourages the production of prefabricated components in controlled factory settings, which are then delivered to the site ready for installation. This method not only minimises installation time but also offers significant health and safety benefits while contributing to sustainability by reducing the overall carbon footprint associated with the construction process. Although the concrete pipe industry has made substantial strides in adopting the DfMA philosophy, the inherent heaviness of concrete pipes presents a challenge in achieving the same level of versatility and efficiency as that offered by plastic pipe alternatives. Another critical aspect to consider when evaluating the carbon footprint of large-diameter pipelines is that the entire system must be assessed, which typically includes not only the straight pipeline sections but also the associated bends and customised manhole components. It is essential to recognise that the overall environmental impact of the pipeline system, including these auxiliary elements, plays a significant role in the final carbon footprint.

In conclusion, it can be inferred that large diameter HDPE pipes have considerable potential to support the construction industry's efforts to reduce carbon emissions in line with emerging environmental targets.

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