ARUP

Buildings & Infrastructure Priority Actions for Sustainability

Embodied Carbon

Stone

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This document is a snapshot in time of industry research, opinion, and knowledge. The information is subject to change as industry progresses and new information comes to light. This document is to be periodically reviewed and any comments or suggestions are welcomed via jo.spencer@arup.com and the BIPAS team. BIPAS is a multi-disciplinary group of engineers within Arup, funded via Arup's internal investment programme. We carry out research and create resources relating to sustainability, primarily for use within Arup but shared externally when it is appropriate. Our objective is to address those areas that engineers engage with on a daily basis, to enable them to address sustainability in an informed and effective manner.

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Contents

Introduction

With the building and construction industry accounting for 40% of annual CO_2 emissions, decarbonising the buildings sector is imperative. In the search for lower carbon materials, natural materials are gaining popularity due to their potential for reduced global warming potential (GWP). Though a natural material, stone used in construction is non-renewable and should be treated as a scarce resource and designed with this in mind.

To conduct carbon calculations for stone used in buildings and infrastructure, consideration should always be made for the application, durability and extension of life. As designers, we can exert influence via our designs and specifications by working collaboratively with contractors, clients, and architects. To do this, we need to understand the carbon emissions associated with stone, the design intent and the available options.

Using less material as an industry is fundamental to reducing emissions. Since production processes alone cannot eliminate them, we must make informed and timely material choices. Other than carbon intensity, stone choices are typically impacted by:

- Cost
- Aesthetics and appearance
- Availability
- Durability and expected life
- Ease of installation
- Maintenance requirements
- Weight (impact on slabs, structural frame and foundations)
- Safety (slip resistance, tactility, impact resistance)

Stone in context

Natural stones are defined and denominated according to EN 12670 and EN 12440. This requires a petrographic examination according to EN 12407. Natural stone is classified according commercial and scientific terms. The commercial names are usually applied in trade and often differ from the scientific terms. The scientific classification reported below provides useful general information on the technical properties, processing types and uses of the different natural stones [1].

- **Igneous rock** *e.g. granite, basalt*
- **Sedimentary** *e.g. limestone, sandstone, travertine*
- **Metamorphic** *e.g. marble, quartzite, slate*

Natural stone products are used for:

- Facades
- Paving (setts, kerbs and slabs)
- Lining
- Flooring
- Roofing
- Masonry units
- Solid works (sills, columns, vanity and kitchen tops, etc)
- Structural stone elements (See Structural Stone)

Except for solid works and structural stone elements, these products fall under the scope of the European Construction Products Regulation 305/2011, recently repealed by Regulation (EU) 2024/3110, which mandates CE marking. In UK, excluding Northern Ireland, products are regulated by The Construction Products Regulations as amended in 2019 and 2020.

This document provides information regarding lifecycle stages of stone, design considerations and opportunities, and limitation of current understanding of sustainability of stone. It is not an exhaustive list however, provides indication of carbon considerations of stone and their impacts.

Data explored in this report is based on the analysis of 40 Environmental Product Declarations (EPDs) from European, Chinese and North American stone companies.

Lifecycle

The stages referred to in this document align with the life cycle assessment set out in ISO 14040, whereby Stage A is ‘up-front’, Stage B is ‘in-use’, Stage C is ‘end-of-life’ and Stage D is ‘beyond life-cycle’, as seen in Figure 1.

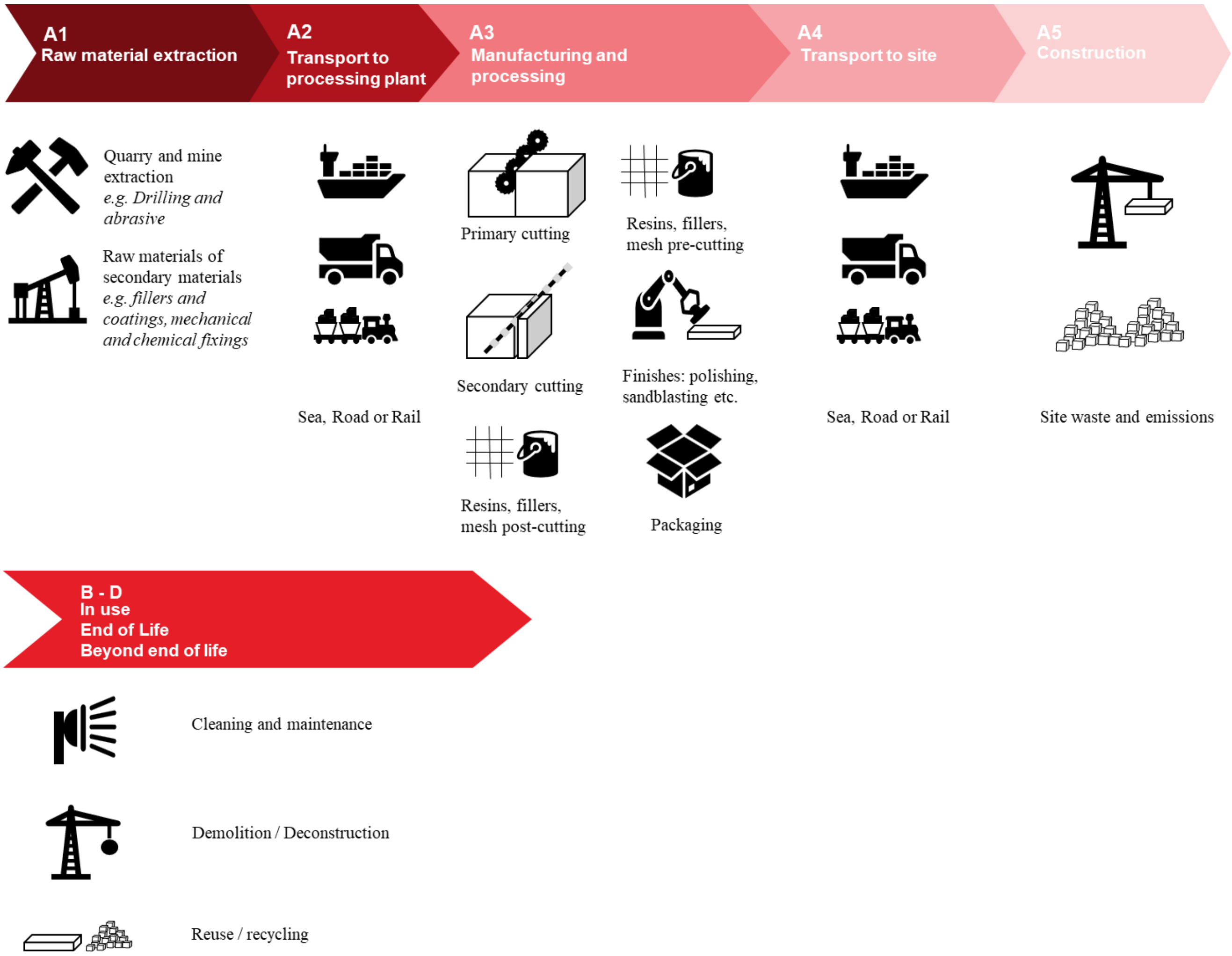

Figure 1

Life cycle stages for stone products

To provide an estimate of average carbon associated with the A1-A5 stages, data from 40 EPDs was collected and converted to $kgCO_2e/m^3$. Only a quarter of the EPDs surveyed included partial or full data for modules A4 and A5. Due to high variability, these results were excluded. From the data, typically A1 and A3 account for majority of the embodied carbon of stone. The transport modules, Module A2 and A4 (not shown), were found to be highly variable and can significantly increase the embodied carbon of a stone depending on the manufacturing logistics and site.

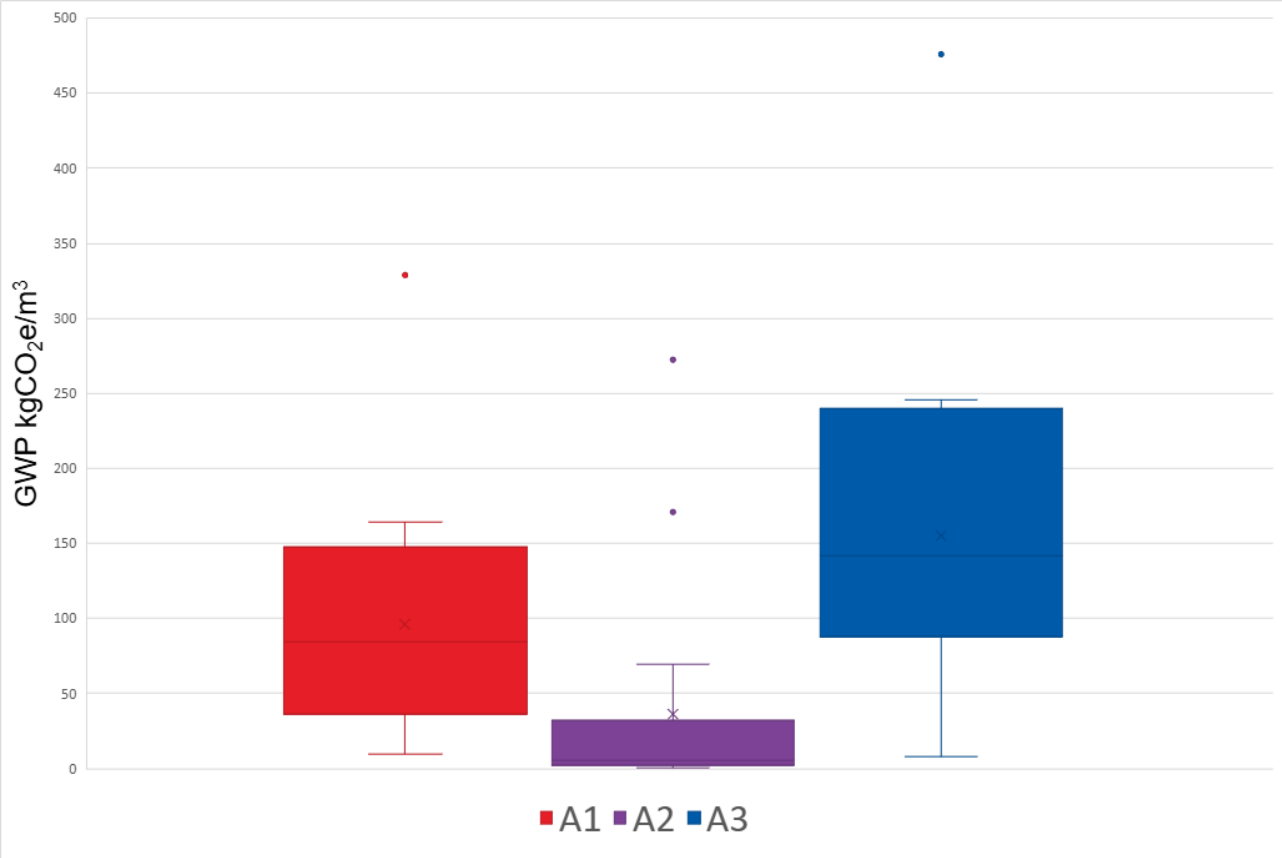

Figure 2

A1-A3 GWP per m^3 of stone products according to Arup research with vertical error bars indicating the range of data with dots representing individual data outliers.

As seen in Figure 2 there was a large range within the data, indicated by the long error bars and outliers. The range of values could be attributed to a series of factors, including:

- Different product types such as raw stone blocks to full stone slab systems,
- Different stone type such as granite and limestones etc.,
- Non-standardised calculation methodologies

Currently there are no Product Category Rules (PCR) for stone EPDs [2]. It was important to ensure that the data collected is reflected accurately so it can be compared. For example, although stone is a natural material, it is not renewable and therefore references to biogenic carbon to the stone itself were excluded [3].

Additionally, the majority of EPDs also did not include a conversion rate, which is calculated by density, thickness and m^2. Commercial trade names frequently misclassify stone varieties. Therefore, identifying the actual geological type is the only way to make technical comparisons for a given application.

A number of EPDs had also been agglomerated and averaged for a variety of product and stone types. This may provide a high-level understanding of the embodied carbon of stone, however, should not be relied upon as an accurate absolute value. Although the data was limited, several factors were considered to impact the embodied carbon, including:

- Stone type: igneous, metamorphic and sedimentary,
- Location and extraction processes
- Dimensions and formatting including finish of the stone product.

These are explored qualitatively in the sections below.

Stage A

A1 – Raw material extraction

Module A1 includes the carbon emissions associated with extracting and manufacturing raw materials. Stone is extracted from mines and quarries. There are different reasons as to why a mine or a quarry is chosen to extract stones. Mines have a lower impact on the visual quality of the landscape, but due to limited working space require more specialised equipment, lighting and ventilation systems. These are typically run on electricity and can add to the energy required. The selection of different extraction methods will be dependent on stone type and the specific characteristics of the mine or quarry.

The two main methods of stone extraction are the following:

1. Drilling: typically using jackhammers, drill rigs, wagon drills**,** involves creating holes in the stone using rotary or percussive drills, which is often the first step in quarrying. This is typically used for granite or for marble/limestone in dry areas.
2. Abrasive: used for cutting large blocks of stone efficiently with minimal waste. There are two main methods:
   - Diamond wire saw, used for both marble/limestone and granite
   - Chain saw, diamond belt saw, disk cutter, used for marble/limestone

Drilling methods rely on heavy machinery, powered by diesel or electricity, while abrasive technologies are typically electric and use less energy. For example, modern diamond wire saws now use inverters. Inverters help regulate the speed and power of the motor to match the cutting load in real time to reduce unnecessary power consumption.

In addition to the above, excavators, wheel loaders, generators, and air compressors are commonly used, and are mostly diesel-powered but with potential for future electrification. Some compressors and hydraulic drills are already electric or have lower in energy consumption.

It should be noted that all methods, depending on the quarry characteristics, can produce a significant amount of dust and waste material that may require additional processing.

Stone type will also affect the carbon emission associated with raw material extraction. Harder stones, such as granite, will usually require processes which will typically increase the embodied carbon associated with Modules A1 and A3. On the other hand, granite tends to be more homogenous than limestone and marble, reducing the processing waste.

There will be a carbon impact associated with the raw materials of other products such as fillers, coatings and fixings that are required during different stages of the stone extraction and processing, these are discussed qualitatively in Section "EPD system boundaries limitations".

A2 & A4 – Transport of materials to the processing plant and finished products to the site

Module A2 accounts for the carbon emissions associated with transport from the quarry to the processing plant / stone yard and throughout the manufacturing process. This includes the block and any intermediary stone slabs for further processing into finished stone products. Module A4 accounts for the emissions associated with transport of the finished stone product from the processing plant to the construction site.

The transport emissions are highly variable and dependent on the product type and proximity of the processing plant. For example, simple products may be processed at a single processing plant near the quarry or supply location, whilst complexed products may be done at multiple processing locations.

To minimise carbon emissions associated with transport, stones that are locally quarried should be selected for designs. However, given rock formations are different in all regions, local sourcing only allows for limited options of simple stone products. The stone market is therefore reliant on its global movement.

Global stone movement

Supply chain transparency is important not only for responsible resourcing but also for embodied carbon calculations. The most recent global stone trading reports (2022, 2023) have been used to provide a high-level overview of the stone market and global movements [5, 6]. This highlights the scale of transport emissions associated with the production, processing, and installation of stone products. Limitations of the data include:

- It does not include where stone is processed within the same country it is quarried.
- It includes stone in all applications - not specific to the built environment

Table 1 provides the stage associated with global stone trade movement and the module where it is typically accounted for, noting the limitations noted above.

Table 1

Description of Life Cycle Analysis (LCA) module and associated stages within the global trade movement.

Module associated with transport emissions	Stage associated with global stone trade movement
Module A2*	Raw stone exporters
	Raw stone importers
Module A4	Finished product exporters
	Finished product importers
Depending on the system boundary, additional transport associated with intermediate processing steps may be included in Module A2. This is more likely for products with multiple processing stages (e.g., architectural stone with mouldings) and less relevant for simpler products such as paving slabs.	

Figure 3 show the top 10 major stone producers by country and Figure 4 shows the top five importers and exporters of stone at various stages of processing by country and quantity.

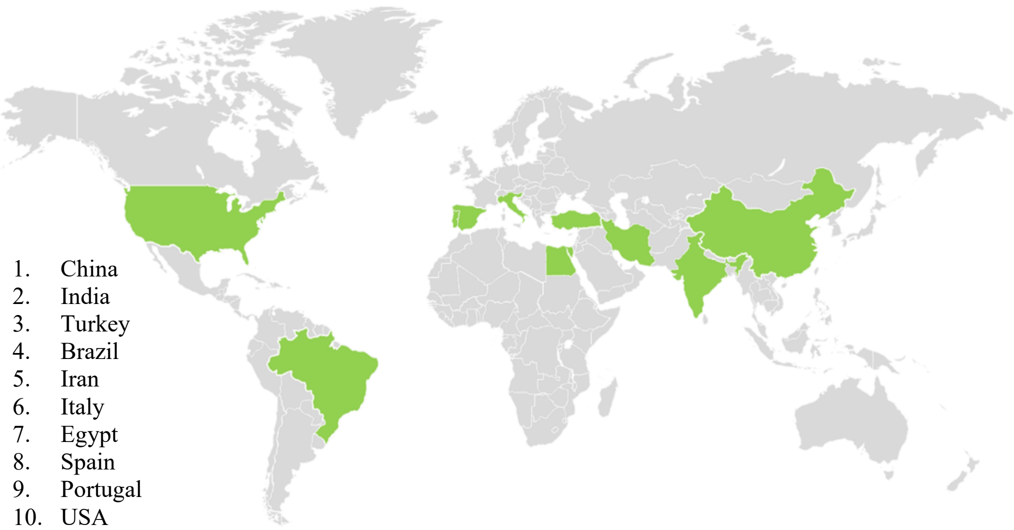

Figure 3

Location of top 10 major producers of Stone in 2022 [5]

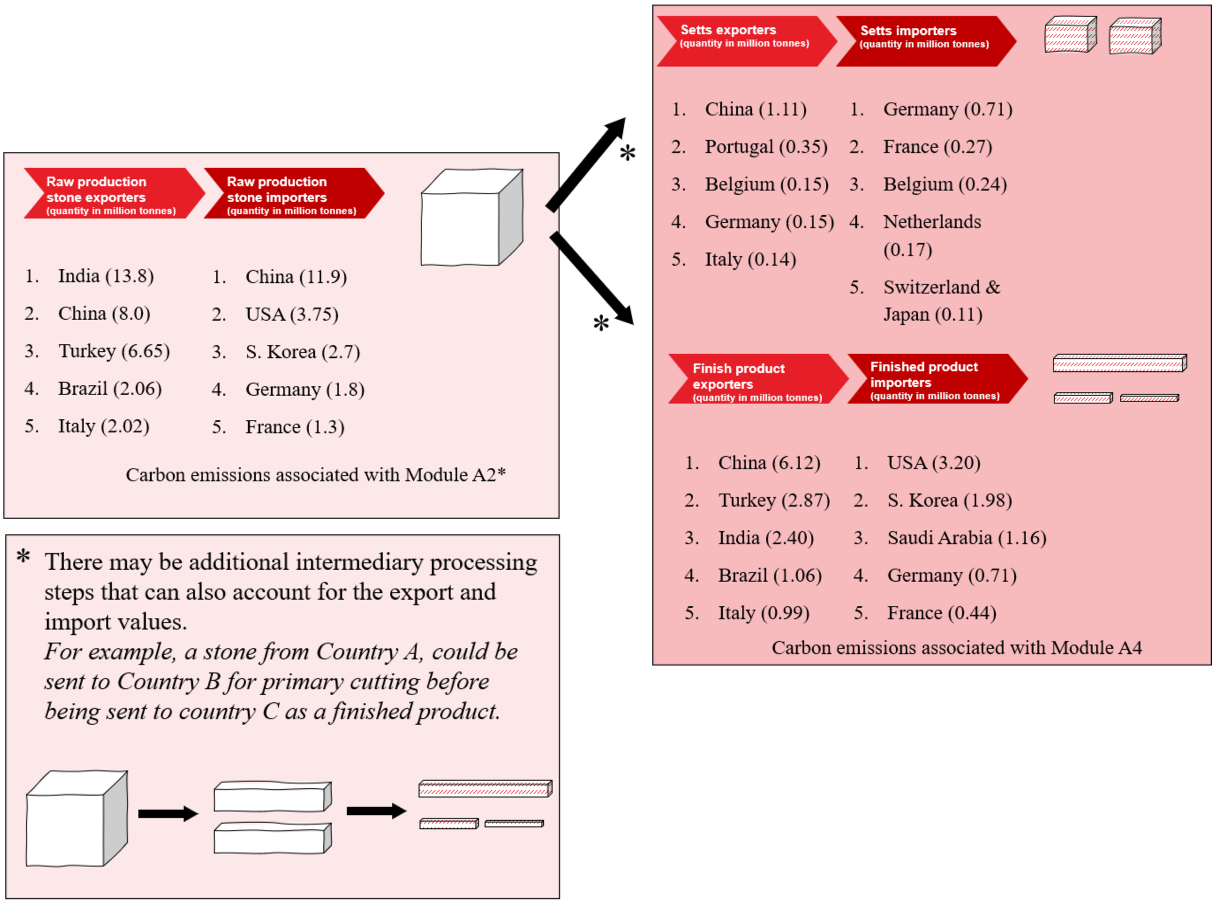

Figure 4

The top 5 exporters and importers for different stone products from raw material extraction. (Raw material extraction (2022) [5], Subsequent trading steps (2020) [6]. Quantities provided in the bracketry is in terms of quantities in million tonnes **[5, 6]**.

From Figure 3 and Figure **4**, China, India, Turkey and Brazil are both major producers and major exporters of raw stone. Of these, only China is also a major importer of raw stone. This suggests China possesses significant processing capacity, allowing it to aggregate raw supply from other regions to leverage lower processing costs. The data also indicates that different applications may have different transport emissions. For example, European countries play a more important role in the import and export of setts which may reduce the transport emissions to a more regional footprint.

Global stone supply chains frequently decouple extraction from processing, meaning raw blocks are not always finished near the quarry. While transport modes vary by distance (typically road or rail), separating these stages significantly increases carbon emissions. This is due to the inefficient transport of raw material, of which a proportion of the stone transported will become waste. Supply chain transparency is essential to accurately calculate the lifecycle carbon impact, particularly for stone marketed as 'local' but processed abroad. Table 2 can be used to help estimate the carbon associated with transporting material depending on the distance.

Table 2

Transportation CO_2e values [4]

Location of processing plant compared to the site	Carbon Emissions $kgCO_{2e}/kg$	Assumption
Local < 50km	0.005	Transported 50km by road
National < 300km	0.032	Transported 300km by road
Regional < 1500km	0.161	Transported 1500km by road
Global > 1500km	0.183	Transported mostly (10,000km) by sea and then 200km by road

A3 – Manufacturing

Module A3 includes the carbon emissions of the processing of raw materials extracted in the quarries or mines. This can be split into two main parts: primary and secondary cutting, and stone finishing. The fabrication of composite systems, such as stone laminates on aluminium honeycomb or glass, is not included in this document but will increase the embodied carbon.

Primary and secondary cutting

Primary cutting typically involves the initial reduction of large stone blocks into slabs or strips. This process involves the use of heavy machinery such as gang-saws, block-cutters and diamond multi-wire saw machines that are energy intensive. Some innovations have been introduced to reduce energy consumption. For example, replacing granite gang-saws with diamond multi-wire saw machines reduces energy consumption and produces cutting waste free of iron particle contamination. The granite gang-saws traditionally require a mixture of water, lime and metallic grit for cutting, which makes it difficult to re-use the sludge obtained from the process.

Secondary cutting involves further reducing the size of the stone slabs/strips into standardized products (like tiles) or cut-to-size products. This stage typically employs cutting lines, bridge saws and CNC machining centres. This step ensures that the stone pieces are of the desired dimensions and quality for their intended use. For simple products like tiles, setts, paving, secondary cutting is often done at the same place as the primary cutting. More complex products, such as facades and feature work, are likely to be done elsewhere.

Finishing

Different finishing techniques for stone impact its embodied carbon due to the varying energy requirements and material inputs involved.

Polishing: involves extensive grinding and buffing, which consumes a considerable amount of power and abrasives. Polishing is a common finish for internal applications but less so in external application post 1980s.

Honing: considered a pre-polishing phase, and is achieved on the same polishing lines, using different abrasives. Optimisation processes for reducing energy consumption and the risk of stone breakages have also been introduced. According to the type of stone, different degrees of honing (grit) can be obtained.

Sandblasting and other rough finishes, like bush-hammering: achieved using the same polishing lines with different tools. These processes may be more energy intensive than polishing and honing, but at the same time much less intensive than the traditional processes involving the use of compressed air and abrasive minerals.

Flaming: a technique used to create a rough texture, which involves applying high-temperature flames to the stone surface. Depending on the temperatures required (typically higher for granite), a high energy consumption and associated carbon emissions may be required due to the use of gas over electricity.

Fillers and coatings used to seal or enhance the stone appearance or properties can add to the embodied carbon due to the production and application of these substances. These products can be applied manually or automatically in the so called “resin lines”. These substances are usually not clearly declared or accounted for in current EPDs or Life Cycle Analysis LCAs.

As seen in Figure 2, A3 can vary significantly, which can be attributed to a range of factors including stone dimensions and thicknesses, stone type, application and visual criteria.

For example, thin stone elements (10-12 mm tiles and < 20 mm slabs) may have a higher embodied carbon per m^3 due to the precision required for cutting, tighter tolerances, and increased waste during processing. Their higher surface area-to-volume ratio likely increases the amount of finishing processes or secondary materials per m^2 or weight in tonnes. However, this may be balanced by resource efficiency and reduced need for additional fixings due to the stone's lighter weight.

Additionally, for a cut-to-size project a design that optimises a mix of stone sizes can help to reduce the waste coming from the secondary cutting and increase productivity due to improved flexibility.

Packaging

There are often packaging and protection materials required for the transport of stone. However, the majority of these are wood and cardboard materials and the impact is less significant. Wood and cardboard used as packaging to safely deliver the stone to the site is then transported to be either landfilled or recycled.

Other materials, such as polystyrene, are also used for the transportation of finished products, especially for interiors. These materials are expected to have a much greater carbon impact due to the higher embodied carbon and limited end of life scenario which is typically landfilled.

EPD system boundaries limitations

The non-standardised approach of EPD system boundaries for stone can lead to large variations. Within Stage A this can be seen by the lack of definition of product type from raw blocks to finished systems and the inclusion or exclusion of the relevant fillers, coatings and fixings.

For stone products in construction, the use of fillers, coatings and fixing system, is typical and can vary in quantity and stage of the lifecycle depending on stone type and application. For example, in interior applications the use of fillers and coatings are commonly applied during the processing process and therefore should be included in Stage A. Post-applied fillers and coatings are also common, however may be accounted for outside of the stone EPD system boundaries, but should be included in the lifecycle assessment. For external applications, the use of fillers and coatings are less common, but may still apply.

Further research is needed to assess the embodied carbon impact of fillers, coatings and fixings. These are expected to increase the embodied carbon of stone, but may also improve its performance and durability thereby potentially increasing service life and reuse potential. Further descriptions of fillers, coatings and fixings are provided below, with other lifecycle assessment considerations provided in the “Watch-Its” section.

Fillers and coatings

The stone industry now commonly uses both fillers and coatings, especially for coloured limestones and marbles. In some cases, direct application of fillers at the quarry is necessary to consolidate fractured zones for the extraction of stone blocks. Fillers are also applied to rough slabs and stone blocks after extraction and before the primary cutting, to eliminate or reduce small imperfections or micro-cracks. These products can help to improve visual appearance and durability of the stone product, and therefore can help to achieve longer service life. Fillers are typically polymer or cementitious based, with the selection of material dependent on the stone type and application. Coatings are typically polymer based. It is assumed that polymer-based fillers and coatings, in particular epoxy resins, will be more energy intensive than cementitious based fillers, that may incorporate higher recycled content or supplementary cementitious materials to reduce the carbon footprint.

Fixing systems

The type of fixing systems used for stone materials in the built environment, primarily used in facades, can typically be split into handset stone, mechanical, adhesive, or a combination of the latter two. Fixing systems are primarily chosen based on the application, ease of installation and visual aesthetic. It should be noted that as stone thickness increases, the system required will need to accommodate the increase in weight, often resulting in thicker mechanical fixings and a thicker layer of adhesive.

Mechanical

Cladding will commonly use mechanical fixings for external applications with or without adhesive. These include load-bearing and restraining fixings and are typically made from stainless steel or aluminium. These will have a significant embodied carbon, but will allow for durability of the building compared to an adhesive only system. When used separately without adhesive, this may also be easier to dismantle for reuse. This does not apply to stone on precast systems, which is discussed further in the “Route to Net Zero: Reuse” section.

Adhesive

Flooring, tiling and some types of paving are usually fixed with adhesives. Adhesives are characteristically epoxy, polymer or cementitious based including mortars. Though products vary, epoxy typically has the highest embodied carbon, with polymer and cementitious have lower embodied carbon . Adhesive types are selected primarily based on the application, type of support, stone properties with particular reference to dimensional stability, sensitivity to staining, and size of the stone elements.

A5 – Site construction

Module A5 includes carbon emissions of construction related activities associated with placing stone on site. This includes the emissions from the equipment used for installation, and the emissions associated with the waste material. Traditional methods of stone construction where pieces are sized to be installed manually will be much slower, but require less heavy installation machinery. Larger stone sections such as stone on precast, or unitised stone panels for façade systems of dimension and post-tensioned stone for structural applications, are more likely to be manufactured off site and installed faster with crane machinery.

A5 will be dependent on the different fixing methods and the different approaches used for different applications.

Figure 5

Example of stone-faced precast façade being craned into place [8]

Figure 6

Example of a panelised stone system being craned into place [9]

Figure 7

Example of dowel restraint fixings in handset stone (installed) [9]

Waste

The volume of site waste and the associated carbon emissions, varies depending on the processes used by the contractor. The global waste value associated with installation is approximately 5%, but this can be increased significantly on a project-by-project basis [10]. For example, large format stone sizes and stringent visual range criteria can lead to significant off-cuts and rejected material which is typically crushed and sold as aggregate. This can also happen if the visual range is not properly defined.

Stage B

Based on their design features and components, stone products have a service life of at least 50 years, and often 100 years is possible [10]. The service life of stone products is dependent on the stone characteristics including density, water absorption and mineral composition, climate exposure, installation quality and maintenance. For building elements with a longer service life (e.g. 60 years for façades), a suitable stone should be able to provide a service life for the entire life of the building.

Stage B has a small contribution to the material's embodied carbon, with minimal maintenance. Stone can be repaired using fillers and protected with coatings which may contribute to embodied carbon.

However, depending on the installation conditions, application and final finishing, maintenance needs are limited to cleaning routines. Notably, coatings can protect the stone for a period of about 5-10 years depending on the stone and climate but should never be used on a stone that is not suitable for the intended application.

It is important to use the right cleaning techniques, suitable products, and a regular but not excessive cleaning schedule, for example cleaning is expected between 10 – 25 years. More frequent cleaning operations usually lead to the stone becoming dirty more quickly. This is especially true when using abrasive tools or harsh chemicals which can damage the protective patina on the stone, making the surface more porous and prone to absorbing dirt, contaminants and moisture.

Stage C

Stage C includes the emissions associated with demolishing and removing stone components from a building. At the end of its useful life, the cladding is removed and transported to be either landfilled or recycled. Emissions in this stage may depend on the format of the stone used and how easily it can be dismantled. For example, handset stone facades may be easier but slower to dismantle than stone on precast.

Impacts of stone removal from the site will also depend on its format – if the building is demolished, or deconstructed. Handset stone can easily be re-used so may be transported to a stone masonry yard for refurbishment. Stone on precast, currently, can be only crushed. Globally, most of the stone in the built environment gets crushed for landfill, fill materials and secondary aggregates. Global figures on the waste and disposal of stone are not readily available and are expected to be highly variable from country to country as well as from region to region. Many different factors contribute to these variations, such as local laws and regulations for landfilling of demolition waste and the access to virgin aggregates.

Often there are incentives or penalties and therefore there may be increased interest in recycling stone as aggregate, rather than letting the material go to landfill.

Stage D

Circular economy

To maximize material lifespan, stone should be reused at its largest size first. For example, using it as large-format full slabs, before downsizing into smaller blocks and finally crushing for aggregate. Designing for deconstruction with stone needs to be considered at the outset of a project. Some fixing methods are considered preferable to others for the potential stone reuse. For handset stone, lime mortars can provide a feasible disassembly route similar to bricks. However, stone adhesively bonded to a backing is more challenging to separate. Stone using mechanical fixings can also be designed for deconstruction. For example in stone slab rainscreens, undercut anchors are hidden on the rear face of the panel, eliminating the need to drill or cut into the stone edge. In contrast, kerf slots are cut on the panel edge to introduce a fixing device. The undercut anchors make it possible to remove the stone without damaging it and to re-use in other applications.

Recycled aggregate

Recovered stone can be recycled as aggregate in products such as concrete, terrazzo or fill, but the quantities may be limited by local regulations and physical properties, especially for structural applications. It is important to only specify recycled aggregates when there is a local source available, otherwise transportation emissions may outweigh the intended carbon benefits [18]. Additionally, depending on the type of recycled or secondary aggregates, there may be increased water demand and a need to increase the cement content of the concrete to achieve the specified characteristic strength, with a consequential increase in CO_2e.

Currently in the UK, reuse of stone from cladding and lining for terrazzo is limited to local terrazzo manufacturers, but only if there is already a client for this new product.

Design Tips

There is no global solution to eliminate the embodied carbon of stone used in construction, but there are several different approaches for reducing these emissions on our projects. As designers we have a huge impact, and it is our responsibility to recognise and support parts of the supply chain that are looking to make technological advancements to improve the emissions of the stone industry.

Efficiency in design

As designers, we can lower our carbon impact by:

Using Less
Aim to have maximum use of the stone block and utilisation of the stone product. This can be achieved by correct sizing, where the panel size should be chosen on the average size of the stone block, preferably specifying more than one size. Designing panels with flexibility for both the visual criteria and the use of offcuts. In addition to maximising utilisation of the stone for its service life, choosing the appropriate stone. Using less can have the biggest cost and carbon savings on a project.

Reusing and refurbishing
Where possible, reusing stone elements in-situ can have significant cost, programme and carbon benefits. Where stone elements cannot be reused, circular economy principles can be implemented to maximise carbon benefits [13].

Specifying and sourcing stone more effectively
Specify and sourcing appropriate stone and finish for the intended application.

- For example, a flamed finish is not suitable for materials without quartz, such as limestone, as the high temperatures can stress other minerals and cause cracking. Additionally, for paving applications, a flamed limestone is prone to wear and will not withstand frequent use. The visual range criteria for the stone should be clearly defined together with the physical and mechanical properties.
- The current availability should be checked together with previous built references. Stringent visual criteria limit the amount of the stone block that can be used on the project, potentially increasing waste. This includes reconstituted stone, terrazzo and precast elements.

Benchmarking stone
Establishing carbon benchmarks for stone types and their finishes is important to classify stone by embodied carbon. There is ongoing work around this - however, this will require cross-industry support to standardise the measuring, reporting and benchmarking of emissions produced by different stone types.

Design for the future
If future changes are anticipated, trying to delay the need for any replacement/major refurbishment can have significant long term carbon reduction [14]. Also, circular economy principles should be incorporated into the design and details for easy disassembly and re-use at end of life. We should also be designing to make maintenance and repair easier.

Structural Stone

The modern widescale adoption of structural stone and its use cases are still being understood and not explored fully in this guide. A short summary of its potential is provided below.

Stone has historically been used in a structural load-bearing role. During the 20th century, stone gave way to more economical materials like steel, concrete, and glass that could better accommodate rapid, large-scale construction. Now, architects and engineers are revisiting stone as a sustainable structural material. The processing involved in stone construction is minimal compared to other structural materials. The processing involved in structural stone is also much less than that for façade stone, as no finishing and fewer cuts are required. Given that stone is not used for aesthetic purposes, fewer pieces will be rejected for falling out of range, therefore also reducing the amount of waste at the quarry compared to façade stone. Although certainly not applicable to all structures, if the stone is properly selected for the role, consideration given to its anisotropic and variable properties, and if the stone is sourced and manufactured locally, the embodied carbon can be minimal.

It should be noted that there are different methods of using stone in structural load bearing applications; masonry stone, massive stone and post-tensioning. The first two are limited to compression-dominated structures and generally require minimal additional materials. The latter, post-tensioned stone, does rely on steel cables for tensile resistance which offsets its environmental advantages. The difference in embodied carbon per structural component, or per strength of component, between these structural load-bearing stone methods and stone on precast concrete backing/stone fixed onto structural concrete/steel with metal fixings, needs to be determined.

Route to Net Zero

The development of industry-wide decarbonisation best practices and routes to Net Zero is still ongoing. The most developed literature is from the Natural Stone Institute who have developed an American National Standard, ANSI 373 Sustainable Production of Natural Dimension Stone, which provides a series of metrics for sustainability [15, 16]. The Stone Federation (Great Britain) have developed a Stone Sustainability Statement and the Ethical Stone Register which provides statements to encourage ethical and sustainable practices [17].

Considerations for quarries and fabricators include:

- ***Site management:*** Mitigation of hazards keeping both staff and visitors safe such as minimizing water usage, controlling dust and noise, and management of rainwater.
- ***Excess process materials:*** Utilisation of 'waste' offcut stone as possible. For example, larger offcuts can be used for smaller products, veneers and mosaics, smaller offcuts crushed as aggregates, dust/fines used in mortar or concrete.
- ***Solid waste:*** Tracking non-liquid waste to limit the use of single-use products inclusive of internal consumer waste and recycling points.
- ***Chemicals:*** Identifying and eliminating potentially hazardous substances from facilities. For example, using water-based, low emission adhesives, sealers and cleaning products.
- ***Land reclamation and adaptive reuse:*** Quarries can have significant impacts on both the landscape and the surrounding nature. Quarrying or processing activities require land use change, from natural habitats to industrial grounds which plant and animal species cannot inhabit. Ensuring sensible practices with minimal impact, is important.

  Quarries, particular outside the UK and Europe, using indiscriminate explosives to extract stone have drastic impacts on the landscape and are to be avoided. As well as their impacts on the landscape, explosives may cause microcracks in the stone that could render it unsuitable for certain uses.

  Stone is a finite resource and many quarries are already exhausted. Although there is sufficient resource for decades to come, the way in which stone is extracted should consider quarrying efficiency, as faster consumption will require more quarries and mines to be built. This is largely overlooked in many projects, when there is a desire for the 'perfect' slab, with much of the rest of a block being wasted. During the design stages, wastage can be minimised by specifying the right stone, size and finish, recommending the most suitable use of stone in the design as well as supporting the quarry in finding the best practices and technologies.

  Responsible consumption and production should be specified in accordance with relevant guidance documents (how is the stone processed, selected, designed and installed). To promote quarrying companies going through the process of obtaining the required documents, EPDs or LCAs should be requested on every project.
- ***Innovation:*** Routes for the decarbonisation of stone heavily rely on the decarbonisation of energy for processes such as extraction, manufacturing, and transport and the use of carbon capture and storage. Without the investment and rapid development of these technologies, the routes to net zero for stone may never be realised.
- ***Water usage***: This is significant during cutting and finishing processes and should be recycled, with some companies achieving over 95%. Filter presses to remove water from the slurry should also be incentivised to avoid slurry bring left in an open field near the processing plant.
- ***Energy***: The use of more modern processing techniques that use electricity will typically be lower in embodied carbon due to the embodied carbon of components like chemicals and fuel. As the grid decarbonises this will further reduce carbon emissions associated with A1 – A3. For example, many stone companies are now using energy from renewable sources (like high efficiency photovoltaic

panels) and have introduced innovation (like inverter technology) and internal optimisation processes to reduce significant embodied carbon.

- ***Social Governance and Human Health and Safety:*** Health and safety in natural stone quarries and processing plants is often far behind where it should be, particularly so for countries where transparency, traceability and accountability are lacking. In Europe there are several regulations to ensure the safety and health of workers in the workplaces.

  The risks of using stone made with unsafe practices should be mitigated through correct specification. BS8902: 2009 'Responsible sourcing sector certification schemes for construction products.' This provides some guidance on the basic specification requirements including:

  - safe and healthy workplace environments
  - no child labour
  - acceptable wages
  - appropriate working hours as defined in SA8000 (2008)

  Quarries, mines or stone factories and yards can demonstrate conformance by audit certificates / correspondence detailing the methods of dealing with the items listed above, or through evidence; (Company documentation such as an EMS or H&S manual/paperwork and guidance to staff, etc).

  In addition to the supply chain, health and safety considerations of producing the stone also apply to the use phase and the specification of stone as a material for a particular application. There are many examples where stone has been used for an application and has subsequently failed as it has not been specified correctly, and the source of the stone has not been investigated such that either the stone or the stone properties are not what was expected.

Specifiers and designers can influence sustainability, not only through design choices, but also by selecting companies that prioritise responsible sourcing, understand and promote appropriate material use, and selecting materials that minimise transportation impacts from production through to installation.

- ***Responsible sourcing:*** Choosing suppliers with a clear understanding of their up and down-stream supply chains, transparency on their extraction and manufacturing processes, awareness of the standardisation framework for stone, and implementation of the required testing programmes to achieve the required certifications, will help with the accountability of implementing sustainability, ethical sourcing, environmental, and carbon reduction policies.

- ***Stone selection and utilisation:*** Choosing local stones and technically appropriate stones that are underutilised. For example, many stones are only used for a low-value product such as aggregates currently due to aesthetic considerations.

- ***Minimising transport:*** To reduce the embodied emissions of stone construction, stone should be sourced as locally as possible (if suitable for the intended application), with adequate quarrying and manufacturing technologies that limit the environmental impact. Off-site manufacture may have multiple benefits including a potential decrease in carbon emissions (due to less wastage and transport) and can be considered in the design stages.

- ***Re-use:*** Several of the EPDs reviewed in creating this document included LCA end of life scenarios assuming re-use/recycling rather than landfill. There is a need to define reuse and recycling. Reuse is the use of existing materials or components (stone) in a new application either on the current site (Onsite reuse) or another site (Offsite reuse) in their existing state, without undergoing any significant reprocessing. Recycling is the process whereby materials are collected and remanufactured into alternative raw materials which produce new products of the same or lower value with similar or different material characteristics. There are also different levels of reuse maturity even within stone products. For example, paving and setts are commonly reused whilst stone façade cladding is typically crushed for recycling.

  A common end-of-life offering for scrapped stone is to crush it and mix it with resin or cement, turning it into terrazzo. The classification of recycling or downcycling depends on the processing and applications compared to the original stone panel. There is a carbon impact associated with the other materials and processing of this material. The end-of-life scenarios for these materials also need to be considered to minimise the loss of materials and carbon during the subsequent cycles. The comparative carbon impact of recycling stone into aggregates for different applications, such as concrete and terrazzo, is unknown.

Similarly, the current reuse of stone also has a hierarchy in terms of carbon and the ability to continuously be reused in a closed loop system. A common re-use strategy is to incorporate a pre-cast concrete backing onto the stone; this allows for previously thick stone slabs to be cut into thinner sections with limited program implications. However, due to the fixing types most used in these systems (dowel pins inclined in opposite directions), the continued reuse of these hybrid panels is not possible. The composite nature of the product also hinders the reuse and recycling capabilities. Therefore, this only creates a semi-linear process and cannot be classed as a closed loop system. Note that precast and prefabricated components offer improvements in production efficiencies, helping to reduce both carbon and production costs. However, precast concrete often has more carbon intensive mixes or relies on constrained resources, therefore a careful assessment of the carbon implications is required when using these materials.

Alternatively, the reuse of stone without a precast concrete backing is possible and preferable. This is dependent on a variety of factors, including stone thickness and fixing type. The dismantling of stone for this type of reuse is often slower due to the care needed to maintain the stone and remove fixings. However, this offers a fully closed loop/minimal loss of material during subsequent cycles of reuse. There is a need to develop details and fixing systems that allow for continuous disassembly and reuse.

A new EU Construction Products Regulation (CPR) has been published to cover the reuse of materials and the route to provide sufficient data for CE marking.

Watch-Its

Declared unit

Issue: There are currently no Product Category Rules for the preparation of EPDs for stone products in construction. This can make it difficult to compare EPDs, including the declared unit.

Watch out for: The use of kg or m^2, without a conversion factor using density and thickness which can help to compare carbon values.

Naming convention

Issue: The commercial name of stones may not be the same as the petrographic name which would give some indications on the density, strength and durability of the stone

Watch out for: A stone may be called 'marble' for example, but this might not correspond to its geological formation. Different stone typologies may have different technical properties, processing requirements, compatible coatings, fillers and fixing systems for the application.

Fillers and coating

Issue: Most stone use in construction will require fillers and coatings, especially for floor applications. Especially if the stone itself is low embodied carbon, the incorporation of these substances can significantly impact the overall embodied carbon of the stone.

Watch out for: Fillers and coatings can help improve the durability and appearance of the stone, however can increase the embodied carbon. Without data available, a factor should be included to adjust the embodied carbon of the stone system.

Fixing type

Issue: Most stone used in construction will require either a mechanical, adhesive or both fixing systems. Especially if the stone itself is low embodied carbon, the incorporation of these substances can significantly impact the overall embodied carbon of the stone.

Watch out for: Without data available, a factor should be included to adjust the embodied carbon of the stone system.

Lack of transparency in data sources

Issue: Some manufacturers may not fully disclose the sources of their data or the methodologies used to calculate carbon footprints.

Watch out for: Claims that are not backed by third-party certifications or do not provide clear information about the data sources.

Inconsistent boundaries in Life Cycle Assessments

Issue: Different studies may define the life cycle boundaries differently, including or excluding certain stages (e.g. raw material extraction, manufacturing, transportation, installation, use phase, and end-of-life).

Watch out for: Data that does not clearly specify the stages included in the LCA, leading to incomplete or incomparable results.

Outdated or incomplete data

Issue: Carbon impact data may be based on outdated manufacturing processes or materials that do not reflect current practices.

Watch out for: Reliance on older studies or data that has not been updated to account for technological advancements or shifts in industry practices.

Geographical variability

Issue: Carbon impact can vary widely depending on the location of material extraction, manufacturing, and disposal, as different regions have different energy mixes, transportation methods, and waste management practices.

Watch Out For: Data that does not consider geographical differences or assumes uniform carbon impacts across different regions.

Greenwashing

Issue: Companies may exaggerate the environmental benefits of their products or use misleading terms like "eco-friendly" without substantial evidence.

Watch Out For: Marketing claims that are not substantiated by verifiable data or third-party certifications like Environmental Product Declarations (EPDs).

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