REGIONAL DATA EVALUATION FOR LIFE CYCLE ASSESSMENT OF CONCRETES IN HUNGARY

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Symbols and abbreviations	
CDW	Construction and Demolition Waste
DMC	Domestic Material Consumption
EU	European Union
KSH = CSO	Central Statistics Office
LCA	Life Cycle Assessment
NA	Natural Aggregate
NAC	Natural Aggregate Concrete
QGIS	Quantum GIS (programme)
RA	Recycled Aggregate
RAC	Recycled Aggregate Concrete
SCM	Supplementary Cementitious Material
WPP	Waste Perlite Powder

1. Introduction

The construction industry is one of Europe's largest sectors, providing almost 18 million direct jobs and contributing to about 9% of the EU's GDP (‘European Commision’ 2023). Furthermore, it uses a large amount of natural resources, which leads to natural depletion. The production of construction materials releases large quantities of greenhouse gases and generates a considerable amount of waste, which is not controlled or recycled.

A lot of discussion has been going on regarding sustainability, sustainable materials, and sustainable technologies, but it is still unclear for many how to label some a product or a technology as sustainable. One possible solution is to use LCA, which can prove that certain materials or technologies are sustainable through the environmental impact as a quantitative measure. This methodology works with multifunctional and specific databases. Many public datasets are available, and users can improve them with specific data. One example is Ecoinvent, a global life cycle inventory database developed for a wide range of products. When it comes to concrete, investigation on environmental impact has been based on a range of ingredients of natural (e.g., sand, gravel), artificial (e.g., expanded clay) and recycled (e.g., recycled CDW) origin.

In order to quantify and adapt LCA, it is necessary to have a good understanding of the LCA processes taking place. Previous studies found that environmental impact assessments of concrete are highly affected by transportation distances (Dias et al. 2021). Raw materials are typically transported overland by truck. The shorter routes contain higher error sources due to the overland routes' meandering. This variation is incorporated in the sensitivity analysis of transport impacts on environmental assessment. Using a more accurate distance for a known location and resource source improves the accuracy of the analysis (McLellan et al. 2011). Hence, this research focuses on transportation distance data adaptation for concrete production based on the Hungarian market, which can be used as an input for LCA. The following sections will introduce and describe the present context of the concrete manufacturing process (i.e., section 1.1) and the management of construction and demolition waste (i.e., section 1.2).

1.1 Concrete production

Concrete, defined as an artificial stone, is the most widely used building material. It can cover a variety of attributes such as coloured, translucent, high-strength, quick-setting, etc. Shortly, a very diverse building material. The global consumption rate is approaching 25 gigatonnes (Gt) per year, corresponding to over 3.8 t of use per person annually (Petek Gursel et al. 2014). The concrete's main components are cement, aggregate and water. In a ready-mixing plant, fresh concrete is produced by mixing these raw materials. In addition, certain properties of concrete are improved with other materials, such as air-entrained agents for increasing frost resistance or fibre reinforcement for limiting crack propagation. Overall, the amount of concrete raw materials depends on the desired properties of the concrete to be produced. After the mixing, the concrete is transported to the construction site, in most cases by truck (Figure 1). Fresh concrete can easily be shaped, and most concrete is poured in place on the construction site, although using pre-fabricated members is also available (Balázs György 1994).

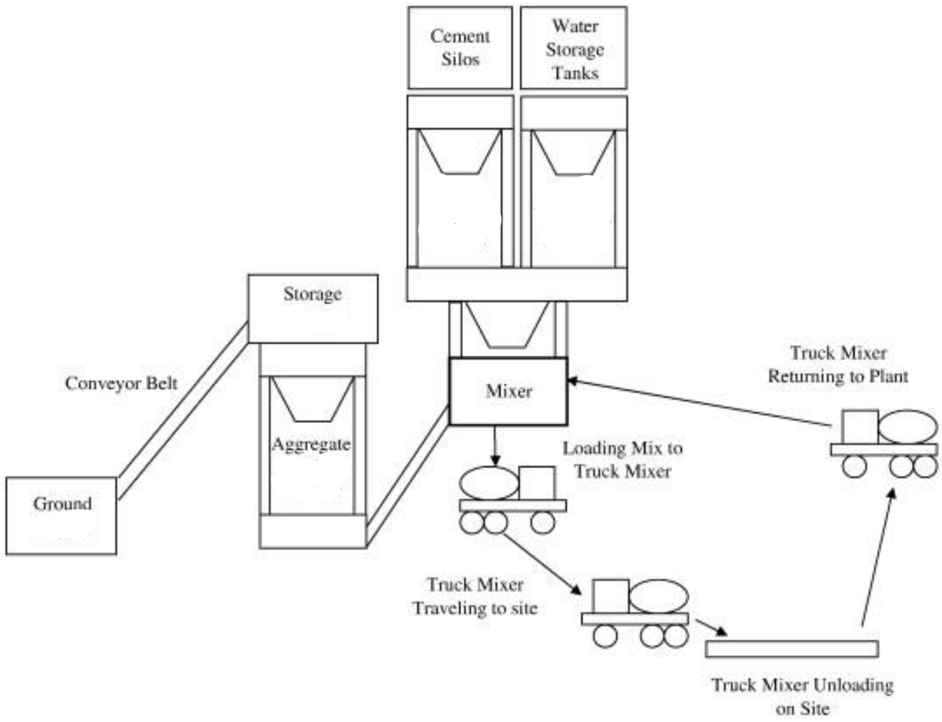

Figure 1 Ready mix concrete plant representation (Park et al. 2011)

1.1.1 Aggregates

The construction industry is one of Europe's largest consumers of natural resources. Large quantities of these materials currently end up in landfills without any form of recovery or re-use. Approximately 70% of concrete is made up of aggregates. Recycled aggregates (RAs) from CDW, which could differ based on the virgin material (e.g., concrete, brick), could reduce the use of natural aggregates (NAs). In 2019, 27.395 (million) m^3 of NAs were extracted from quarries and sand mines in Hungary, based on the report of the Hungarian Mining and Geological Service (Magyar Bányászati és Földtani Szolgálat 2020).

Concrete aggregate's life cycle generally has four main steps: exploration, extraction, processing, and transportation. The process begins with the site selection for the exploration and then continues with the aggregates mining. NAs are usually extracted from natural deposits, like quarries or sandpits. The critical point generating the extensive environmental burden of NAs is the fact that mines are finite and that after their exhaustion, the areas need to be recultivated and further cared for (Estanqueiro et al. 2018).

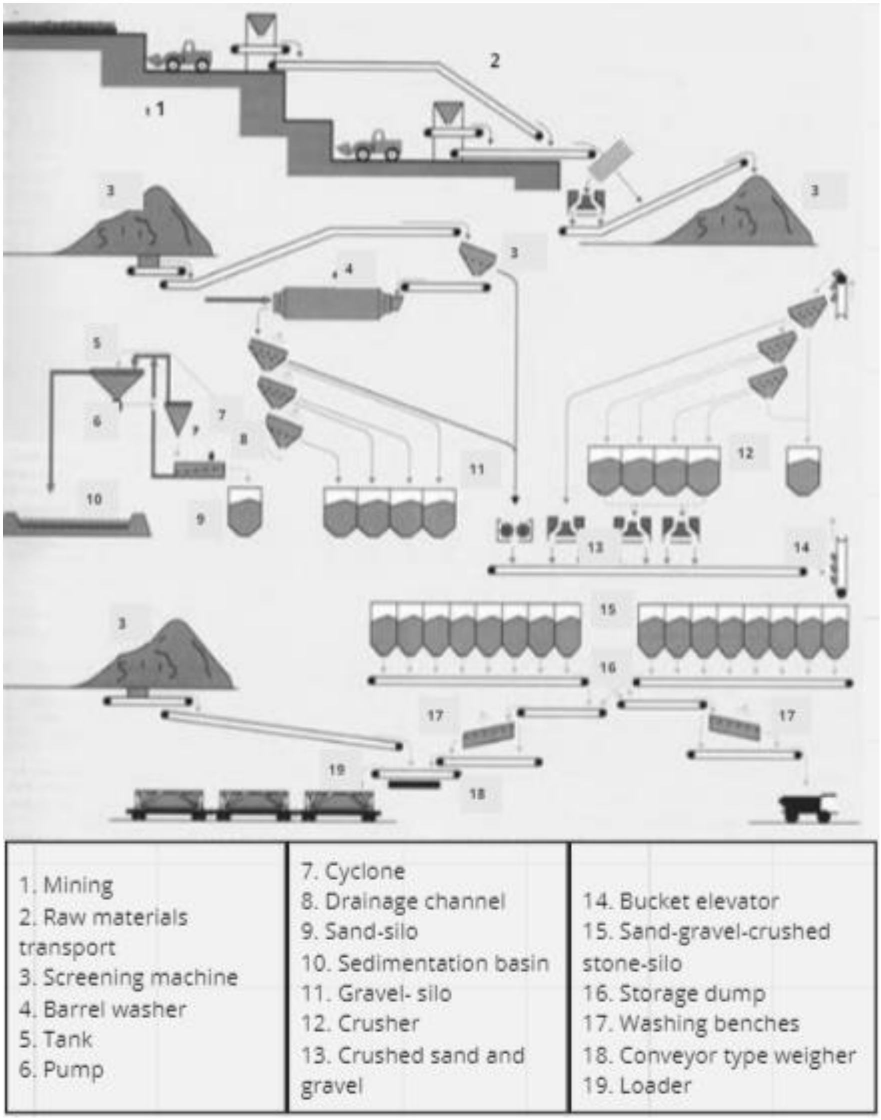

Figure 2 Sand and gravel mining process (Kellenberger et al. 2007)

On the other hand, an alternative available on the market for decades now is RAs, either originating from the reprocessing of materials from mines or quarries or CDW. CDW treatment plants can be divided into two types: (1) fixed treatment plants that cannot be moved and (2) mobile treatment plants that can be moved to the demolition sites or any other location. Some companies have both types of plants (Colangelo, Petrillo, and Farina 2021). Both types of plants have advantages and disadvantages. Fixed plants have more space, and therefore better classification of CDW can be obtained, leading to the possible better quality of products. On the other hand, the materials must be transported there, but even so, experience shows that energy consumption is lower. Mobile plants are easy to move and relocate to the construction site but have shape limitations, fewer grading options and generally less space. They have a simple structure that can be easily transported by road or even rolled to the site on its own wheels. They are not very complicated structures, while fixed plants are more complex. However, for mobile plants, transportation distance to the site can be influential on its environmental burden (Estanqueiro et al. 2018)

Furthermore, previous studies demonstrated that concrete containing RAs performs well regarding mechanical and durability properties, and it can be used as a structural material (Xiao et al. 2012; Pacheco et al. 2015). However, there is still limited adoption of recycled aggregate concrete (RAC), mainly attributed to higher porosity due to the virgin concrete. In the rest of the paper, RA and RAC would mainly refer to recycled concrete aggregate and recycled concrete aggregate concrete, respectively, unless specified differently. The advantages and disadvantages of the wider application of RAC are presented in Table 1.

Advantages	**Disadvantages**
• Reduction of the waste amount being landfilled. • Saving non-renewable mineral resources. • Reduction of environmental impacts due to improved regional waste management, mining processing techniques and equipment. • Cost reduction in the context of reduced energy consumption for construction.	• RAC contains crushed concrete, which influences the mechanical properties depending on the composition of the original concrete. • RA contains hydrated cement paste adhered to the surface of the virgin aggregate, which entails a greater porosity than the NA and a consequent greater absorption of water. • Depending on the original concrete, the RA can contain different contaminants, such as sulphates, carbonates, and organic materials, which can negatively affect the overall environment and the concrete properties too.

Table 1 Advantages and disadvantages associated with the use of recycled aggregates (Colangelo, Petrillo, and Farina 2021)

1.1.2 Cementitious materials

Cementitious materials can be divided into two types: hydraulic cement and supplementary cementitious materials (SCMs). Cementitious materials constitute around 10÷15% of concrete by volume. During the hydration process, they act as a binder for the aggregates. Currently, SCM is widely used in concrete in blended types of cement or added separately in the concrete mixer. Widely used examples of SCM are fly ash or blast-furnace slag, which are used as a partial substitute of cement. In the construction industry, cement production is one of the main industrial emitters of greenhouse gases, especially carbon dioxide (CO_2) (Lothenbach, Scrivener, and Hooton 2011).

The typical cement production process is presented in Figure 3. Cement is produced by firing of 75-80% limestone and 20-25% clay. The limestone and clay are transported from the quarry to the factory, crushed, mixed and homogenised. They are then stored in large quantities in suitable halls. After being preheated in a heat exchanger tower, the grist is burnt to clinker in a rotary kiln at a temperature of around 1450 °C. The clinker is cooled, and additives are added in the cement grinding mill, using steel balls to finely grind. Using environmentally friendly technology, dust is separated from the gases leaving the kiln and the mill. The cement is then sold in bags or barrels and transported to the processing site (Balázs György 1994). On the other hand, the production of SCMs does not include the clinkering process. So, utilisation of SCM would typically result in reduced CO_2 footprint of cementitious materials (Lothenbach, Scrivener, and Hooton 2011).

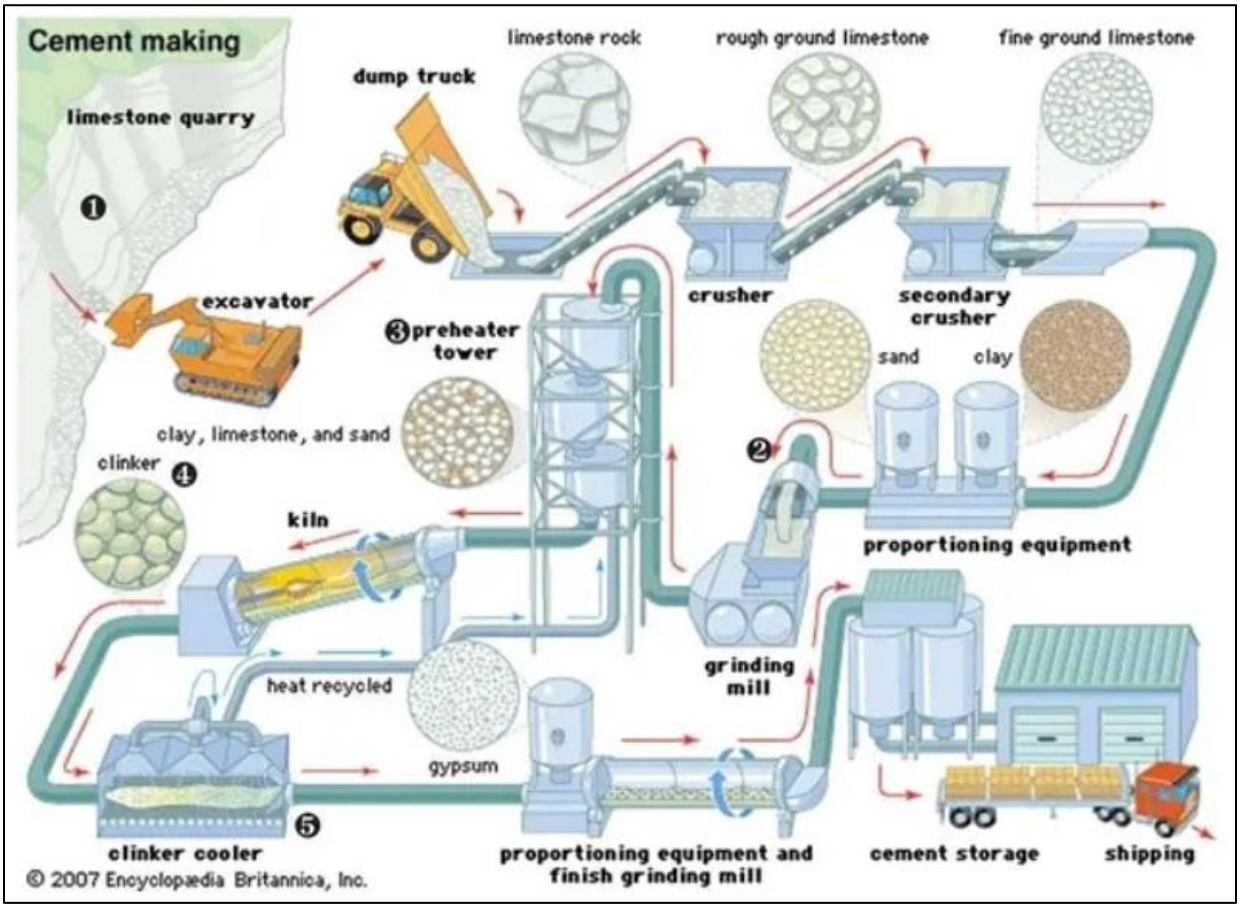

Figure 3 Cement production process ('The Constructor, Building Ideas' 2023)

1.2 Construction and demolition waste in Hungary

CDW can typically include soils, concrete, bricks, glass, wood, plasterboard, metals, and plastics. It usually contains large amounts of inert minerals and smaller amounts of other components. The specific composition of CDW cannot be determined in percentage terms because it can vary between sites, regions and countries, especially because there are differences between countries in the waste definition and methods of CDW management. Some of the materials, such as bricks, can be recovered from the demolition sites and re-used directly in construction, but other materials, such as concrete, must undergo a physical or thermal process like crushing, sorting, screening, grinding and recycling. CDW management also includes stages such as collection, transportation and storage (Manfredi and Pant 2011).

One of the possible solutions is recycling of CDW for their further use as raw materials in new concrete used in construction. However, recycled CDW materials are often more expensive when compared to conventional raw materials and their use in the construction industry is not fully understood or accepted. In Hungary, the Landfill Tax introduced in 2013 greatly contributed to the utilisation of CDW. There are a number of standards that have been developed in terms of utilising CDW in certain applications. Specific guidelines and technical information for correct use are available in Hungary in the 45/2004. (VII.26)BM-KvVM regulation. This regulation contains detailed rules for the management of CDW (Deloitte 2015).

This section also seeks to gather all available data and information about CDW generation, exports/imports, and treatment in Hungary. A large amount of waste is produced on construction and building sites. In 2020, 8297 thousand tons of CDW were generated in Hungary, according to the Central Statistical Office (Központi Statisztikai Hivatal 2022a). The pollutant emissions of the construction industry are very high. In addition, the incorrect disposal of waste causes significant environmental impacts; for example, soil and water contamination and ecosystems are polluted. Unfortunately, illegal disposal of waste is also a serious problem. In Hungary, 328 000 m^3 of waste were disposed of illegally, based on the Hungarian Government's 2020 survey (Elekházy 2022). Landfills are composed of soil and groundwater layers, where leakage of contaminants might affect public health. About 70% of CDW must be recycled or re-used by 2020 based on European Union (EU) regulation 2008/98/EC. In Table 2, data on CDW generated in Hungary annually between 2017-2021 is presented together with the typical waste treatment scenarios.

	2017	**2018**	**2019**	**2020**	**2021**
CDW generated (thousand t)	6 942	7 240	8 158	9 543	9 947
Landfilled CDW (thousand t)	1 237	1 107	1 147	896	1 108
Landfilled %	17.82	15.29	14.06	9.39	11.14
Material recovery (thousand t)	5 694	6 133	7 011	8 646	8 838
Material recovery %	82.02	84.71	85.94	90.60	88.85
Energy recovery (thousand t)	10	0	0	0	1
Energy recovery ‰	1.44	0	0	0	0.10

Table 2 Annual CDW management (Central Statistical Office 2021)

One of the ongoing EU's goals is to achieve a circular economy, where products are in use longer, and materials are recycled to manufacture new products. A step towards a circular economy in the construction industry is recycling. The "waste hierarchy" covers the following order: prevention, reuse, recycling, recovery, and disposal as the least desirable option (Deloitte 2015). Although recycling is in the third place in this hierarchy, it is an effective methodology in the cases when the first two are not applicable.

For comparison of the data on circular materials use in Hungary and other EU countries, three neighbouring countries (i.e., Romania, Slovakia, Slovenia) and three developed EU countries (i.e., the Netherlands, Germany, and France) data is presented in Figure 4. The indicator assesses the proportion of recycled materials and materials returned to the economy, which saves the extraction of primary raw materials in the total material consumption. A higher recycling rate implies a greater substitution of primary raw materials with secondary materials, ultimately reducing the environmental impact of primary material extraction. Circular material use, often referred to as circularity rate, is defined as the ratio of materials used in a circular manner to the overall material consumption; this ratio is given in the vertical axis of Figure 4. The overall material consumption is determined by adding the aggregate domestic material consumption (DMC) to the circular use of materials. DMC is outlined in an economy-wide material flow record. The circular use of materials is estimated based on the amount of waste recycled in domestic recovery facilities, subtracting imported waste slated for recovery and adding exported waste designated for recovery abroad. The imports and exports of waste intended for recycling, meaning the volume of waste brought in and sent out for recovery, are estimated using European statistics on international trade in goods (Eurostat 2023a). The Netherlands has a far superior recycling performance. Hungary has had figures between 6 and 7 since 2013. The value for Hungary is indicated by the horizontal blue axis on the graph. Even compared to the neighbouring countries, Hungary’s circularity rate is just higher than Romania’s. This shows an unflattering position of Hungary in circular economy adoption and introducing of circular material solutions in one of the most influential industries (i.e., the construction industry), seems as an approach which could contribute to more beneficial trends in future. However, for that to be achieved, considering not just the technical properties of the developed solutions is necessary but also their environmental impact for wider application, which is addressed partly in this research.

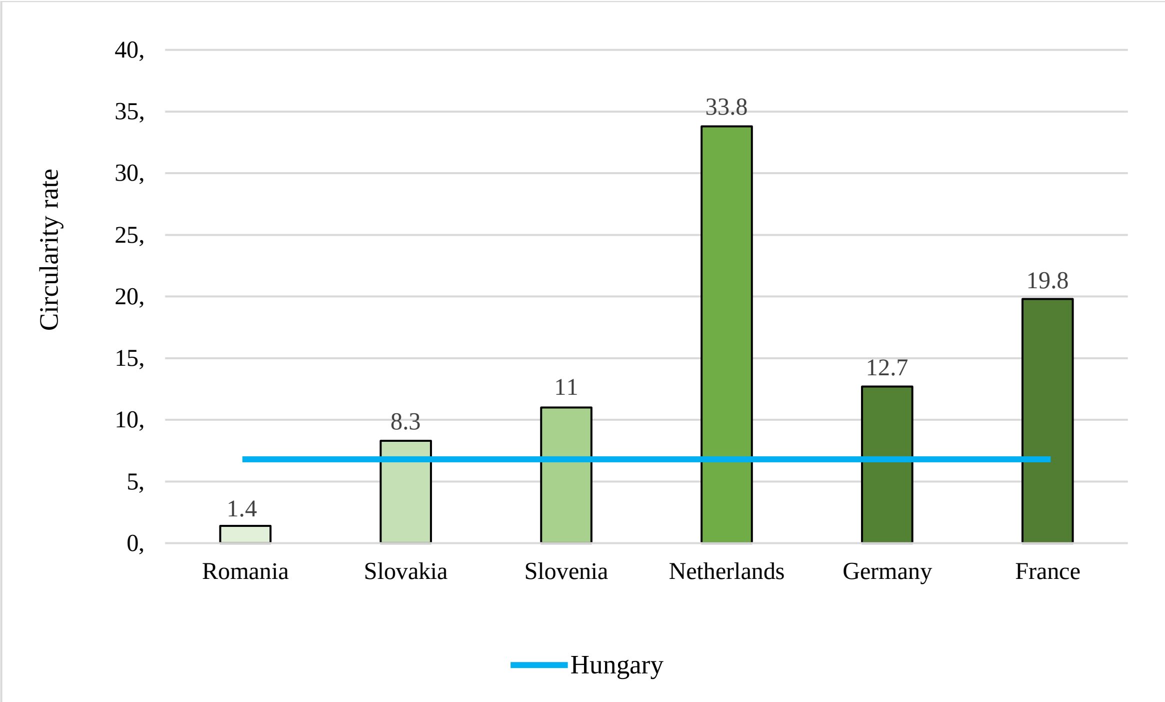

Figure 4 Circular material use rate in 2021 (Eurostat 2023a)

Furthermore, recycling rates of raw materials used at the end of life are shown in Figure 5. Hereby term material refers to a wide range of recyclable materials, not only CDW, such as glass, metals, plastics, etc. Figure 5 shows the percentage of the materials (e.g., gypsum, limestone, aggregates, metallic elements, iron, aluminium, copper, zinc) that are re-used at the end of their life cycle. This data is for the whole EU, so it cannot give a comprehensive picture of the situation in Hungary, but it is conclusive that the most commonly recycled element is lead. Of the materials found in construction waste, gypsum and limestone have a relatively low re-use rate of 1%, as do aggregates, which include crushed stone, sand and other materials, with a total re-use rate of 9% (Eurostat 2023a).

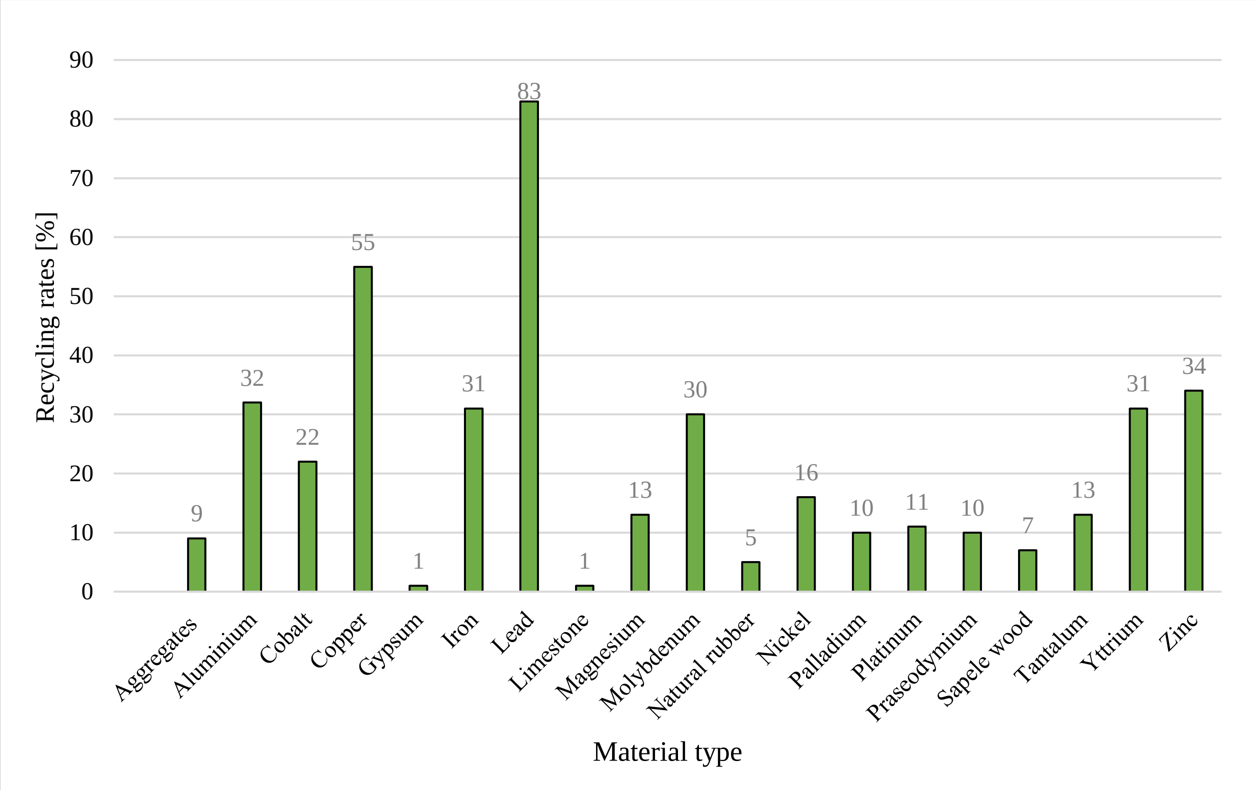

Figure 5 Recycling rates of raw materials used at the end of life (Eurostat 2023b)

2 Research methodology

2.1 Data collection

At first, data was collected on transportation distances for the production of conventional concrete, including cement and natural quartz aggregate, as the most widely used aggregate type for concrete in Hungary. After that, transportation distances for less environmentally intensive raw materials for concrete are examined, including RA, waste perlite and recycled concrete powder as SCMs. Figure 6 shows the graphical representation of the raw materials for conventional and green concretes.

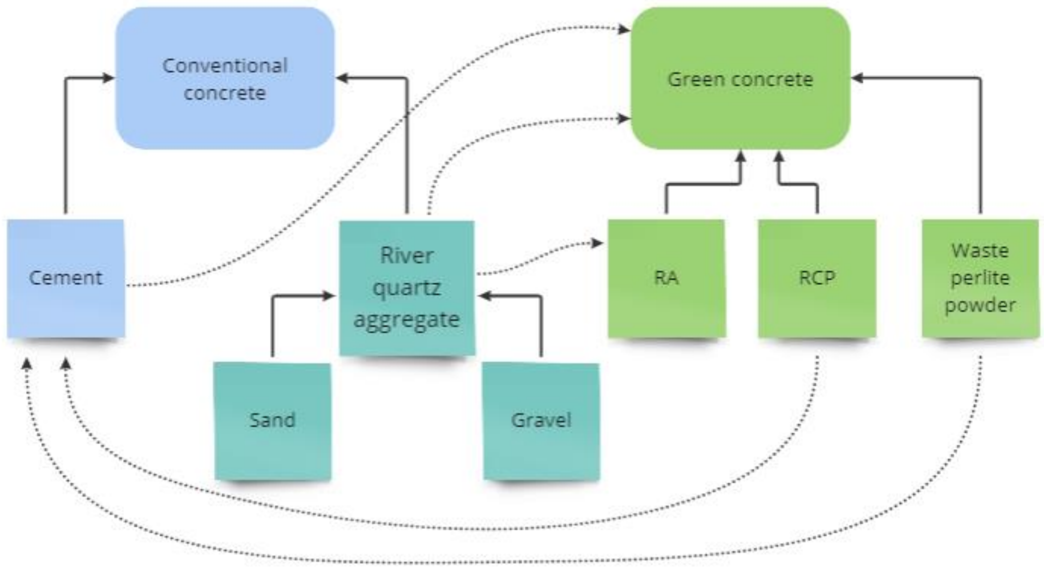

Figure 6 The links between raw materials

However, the limitations of this study are hereby listed:

1. The number of concrete plants in the country is difficult to estimate; no surveys have been carried out, and no relevant public data on concrete production are available yet.
2. Mobile concrete plants are increasingly being installed next to larger construction sites, which makes it even more difficult to estimate the number of concrete plants accurately.
3. The research has started to manually determine the number of plants on various construction websites and Google Maps, but this could be recognised as not fully representative of accurate data.

For conventional concrete, data collection on raw materials was based on the following steps:

1. **Cement**

   Cement plants' locations are available on the company websites. The cement plants usually have descriptions of their production and transportation processes. Annual certificates on air pollutant emissions (e.g., HCl, HF, NO_x, SO_2) from cement kilns are also available on their website (DDC 2022).

2. **Aggregate**

   The location of the quartz aggregate mines is taken from the statements published by the Hungarian Mining Association and the Hungarian Mining and Geological Survey and from the location of the pits available on Google Maps.

In the case of alternative raw materials (i.e., RA, waste perlite and recycled concrete powders) following steps are conducted for data collection:

1. **RA and recycled concrete powder (RCP)**

   Locations for recycling plants were based on available data on Google Maps. Recycling companies were searched and verified using the database on https://xir.hu/ and Google Maps. Since a database on recycling plants' locations does not exist, this process generated an extensive dataset, noting the fact that there is a possibility of missing a negligible number of locations.
2. **Waste perlite powder (WPP)**

   WPP is a waste generated through perlite production. Hence, the locations necessary are actually for perlite mines and production companies. The number and locations o perlite mines are extracted from Google Maps.

2.2 Location check process

Two different approaches were developed for map development of raw materials. The first one was concerning location data of the quartz aggregate based on a map published by the Hungarian Mining Association, hereafter referred to as Map1 only (Magyar Bányászati és Földtani Szolgálat 2022a) and The Hungarian Mining and Geological Survey has an online available map, hereafter referred to as online map only. This online map was available on the following website: https://map.mbfsz.gov.hu/asvanyvagyon_kataszter/ Map1 is shown on the right side of Figure 7, while the online map is shown on the left side of Figure 7.

Map1 shows all the mining data at once, so that in addition to quartz aggregate mines, for example, clay mines or peats were also present. The online map helped to select these other non-quart aggregate mines separately. By clicking on each point in the online map, information is provided about the mine's raw material, owner, area and other data. The quartz aggregate mines are marked with a brown colour in both maps in Figure 7 (Magyar Bányászati és Földtani Szolgálat 2022b). In this research, data was used just on river quartz aggregate, gravel and sand.

So, it was necessary to match the information provided by the online map with the Map1 and select the necessary quartz aggregates mines. This checking process is shown in Figure 7.

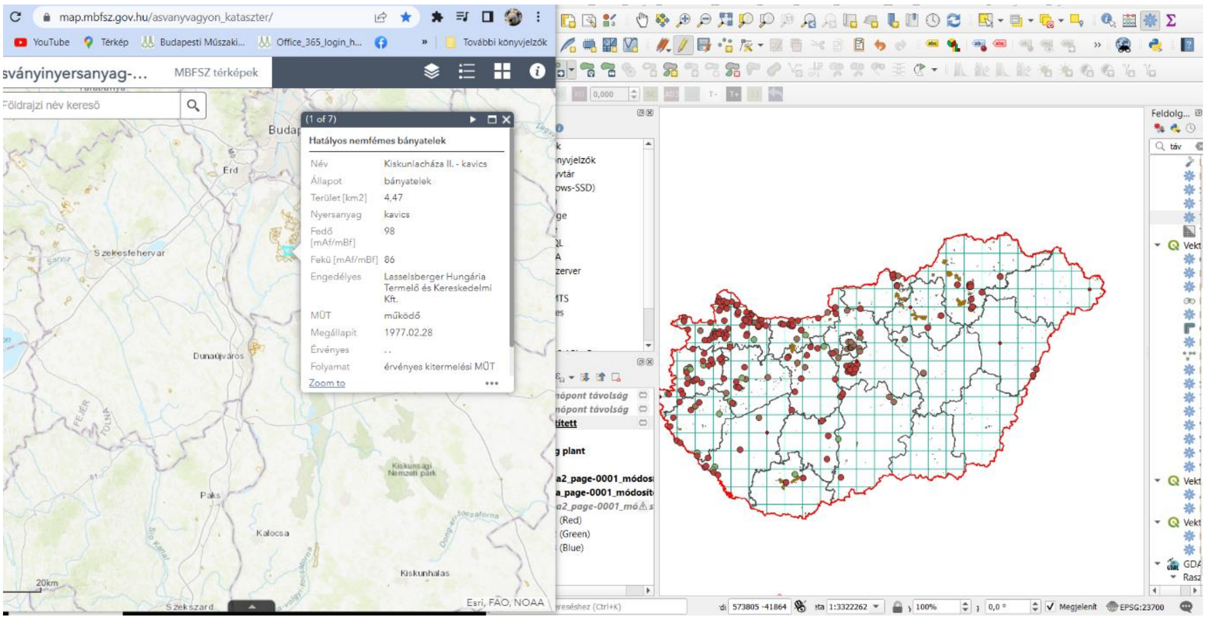

Figure 7 Location check process for quartz aggregate mines

The second approach was based on the changes in the geographic coordinates to the EOV coordinate system ones. The other necessary locations for concrete factories, perlite mines, and recycling sites were based on geographic coordinates from Google Maps because it only allows to get these kinds of coordinates. These could be converted to a uniform projection system before starting the measurement. The Map1 is using another so-called EOV coordinate system. EOV is a single national projection for Hungary. It defines the shape of the Earth as a rotating ellipsoid and covers the entire area of the country in a cylindrical projection. The orientation of the coordinate axes is northeast, so positive X and Y points are at north and east, respectively. For Hungary, the X coordinate is always less than 400 000 m, and the Y coordinate is always greater than 400 000 m. However, all selected points and the distance measurements should be in the same projection system because this way, the measurements are less error-prone. A 20×20 km grid covers Map1. This grid is used to place the map in a uniform projection system. It was most convenient to use EOV coordinates because each line of the grid fell on integer coordinates divisible by 20 000. All coordinates were searched on the following website: http://pf-prg.hu/.

On the website, the grid was used to identify points of interest with integer coordinates. The uniform projection system was generated by QuantumGIS (QGIS). This is an open-source and free geographic information system. Then Map1 was loaded into QGIS, and the coordinates of the points identified on the website were entered. The software can place the whole map in the EOV coordinate system based on the given points with high accuracy. This process is called georeferencing.

2.3 Transportation distance measurement

The software used for determining transportation distances was also QGIS. As a first step, cities with the most intensive industrial activities (i.e., Budapest, Debrecen, Győr, Miskolc, Pécs, Szeged, Szombathely) were selected as representatives of different regions of the country, as shown in Figure 8 (Központi Statisztikai Hivatal 2022b).

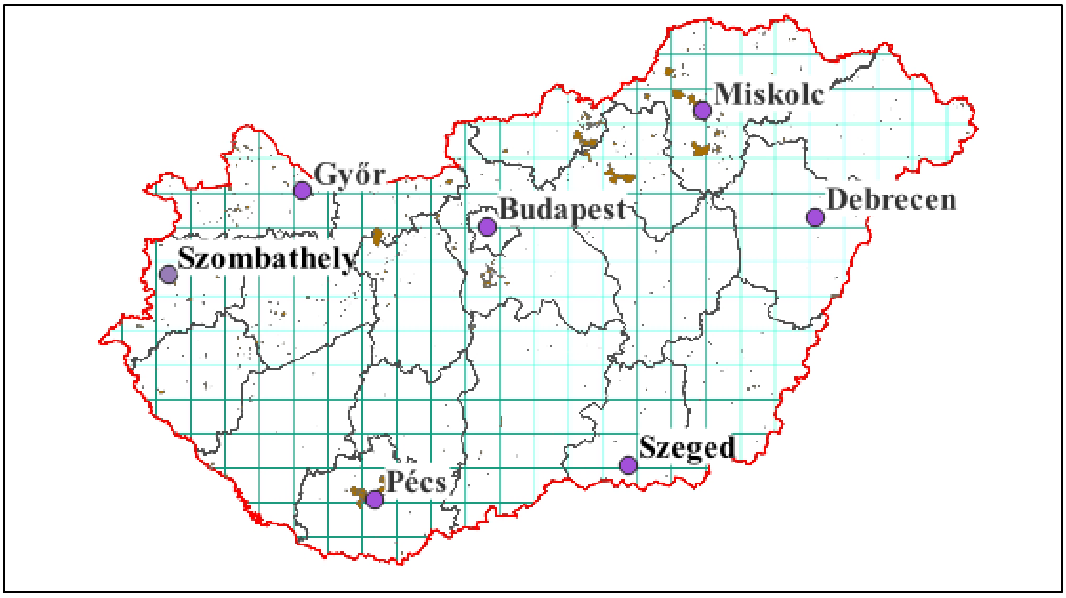

Figure 8 Selected cities

Additionally, in Figure 9 example of distance measurement is given based on the location of quartz aggregate quarries. This was performed using a built-in function of QGIS, which gives the distance between these points as the airline. The measured distances are indicated by a coloured line. Then, the distances were gathered in one data table. The minimum and maximum distances are determined, and the average distances are calculated using an Excel spreadsheet. The detailed results for each raw material investigated are presented in the next section (i.e., section 3).

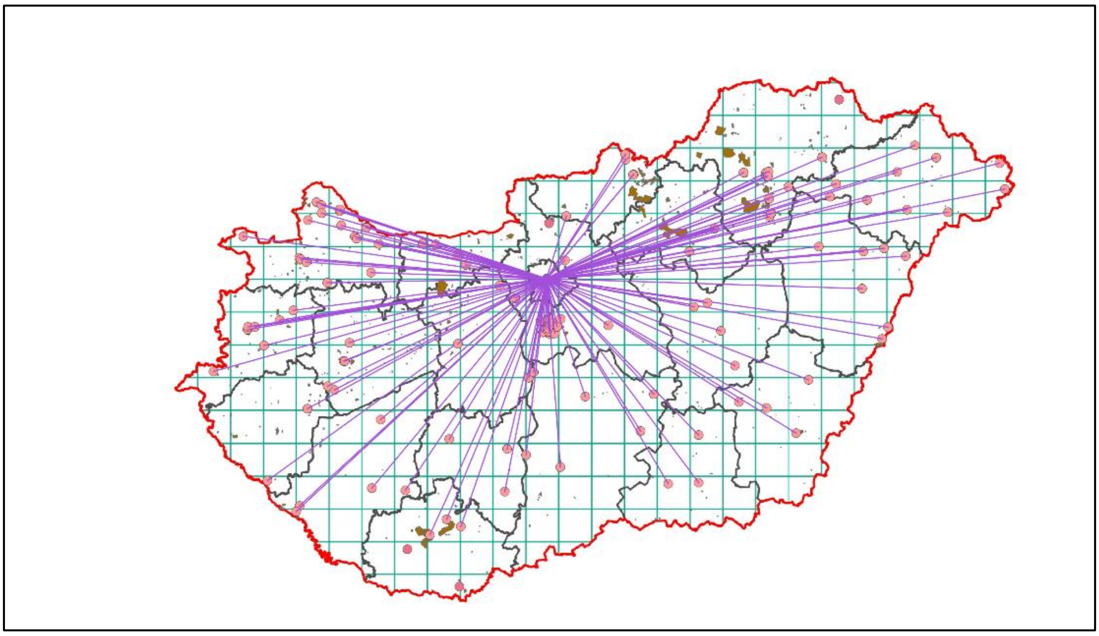

Figure 9 Distances measuring process

3 Results and discussion

Figure 10 map showing all investigated points, including cities considered, as well as quartz aggregate mines, perlite mine, cement plants, mobile and fixed recycling plants are presented. As presented, the quartz aggregate is the raw material with the most data points, having mines widespread throughout the country. Moreover, the number of cement plants is limited to two distinct regions, near the capital city and in the southwest of the country. The data on the recycling plants is the most complex due to the variety in types leading a probable disappearances in the handling of the CDW and management. Finally, waste perlite powder, as waste generated during the production of perlite, is associated with the least complex evaluation of transportation distances due to the limited number of mines.

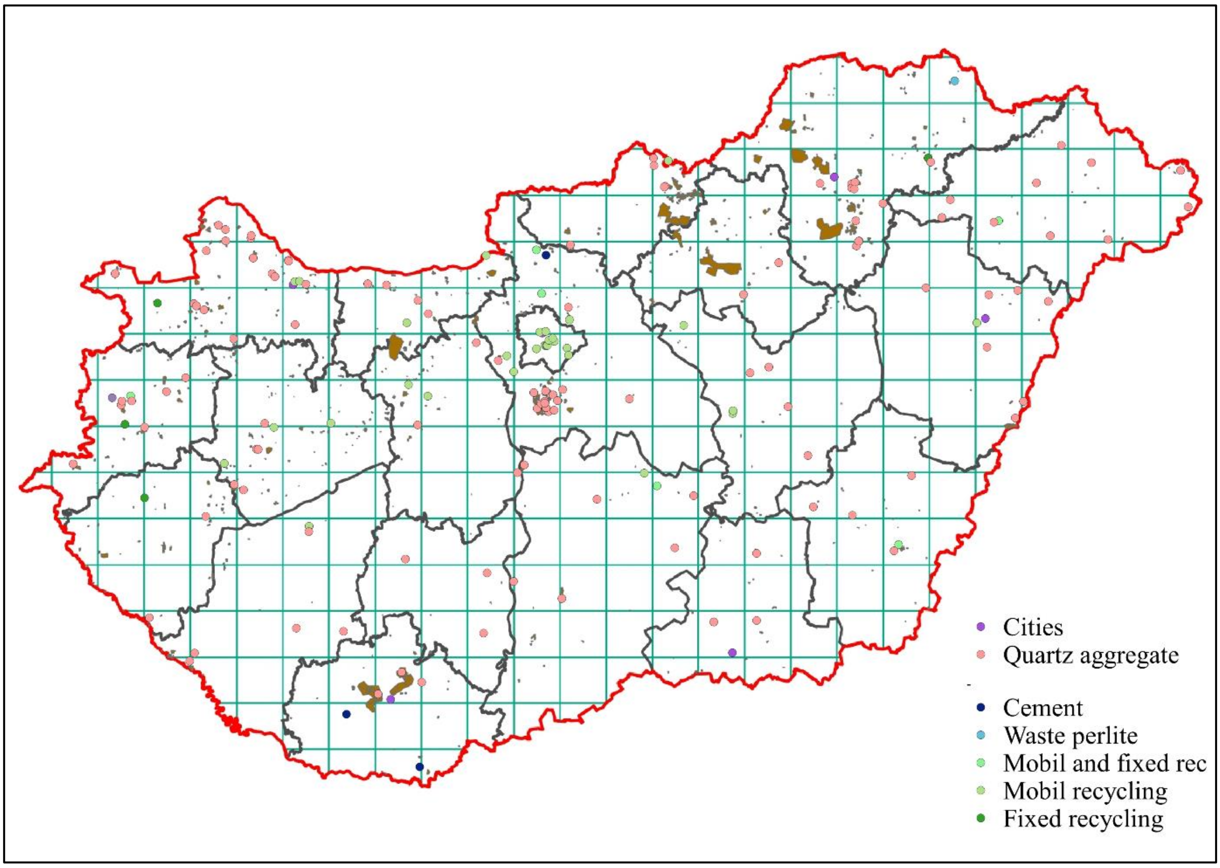

Figure 10 Summary of points

3.1 Aggregate

3.1.1 Quartz aggregate

A total of 117 quartz aggregate quarries are marked on the map (Figure 10). The quarries are scattered throughout the whole of Hungary, especially in Pest County and the northern part of the country. Overall, fewer quarries are located in the southern and especially southeastern part of the country. In Table 3, the minimum and maximum distances are presented and the calculated average distance. When data on minimum distances is considered, Győr seems to have the shortest distance to the quartz aggregate quarries, while Budapest is the longest. However, this trend is not followed for average and distances, where Budapest seems to have the most beneficial distances associated. This could be mainly due to the fact that the capital city is in a central location, and the majority of the construction activities are concentrated in it, directing the whole supply chain towards Budapest.

Győr is the city with the most mines within the shortest distance for a simple geological reason. During the Miocene period, which spanned from 9 to 25 million years ago, certain areas of the North Central Highlands were covered by a sea. In the late stages of the Tertiary period, during the Pliocene (2.5 to 9 million years ago), a significant portion of Hungary began to emerge as dry land, particularly around the mountainous regions. However, much of the country was still covered by the relatively shallow Pannonian Sea, with depths ranging from 10 to 100 meters, containing slightly saline water. Due to intermittent, gradual subsidence, thick layers of sand and clay accumulated in this sea. By the end of the Pliocene, the entire country's surface gradually started to rise. The Pannonian Sea receded, and in its place, in the subsiding basins (Great Hungarian Plain, Little Hungarian Plain), interconnected freshwater lake systems formed, where ancient rivers deposited their sediment and alluvium. These quartz aggregates (gravel, sand) are what we mine today.

The favourable accumulation of quartz aggregate is owed to the fact that during the Pliocene and Pleistocene periods, rivers originating in the surrounding mountainous areas primarily deposited their sediment, consisting mostly of gravel and sand, in the Carpathian Basin. Hungary's geographical position thus favoured the accumulation of quartz aggregate. Since its formation, the Carpathian Basin has continuously possessed an important sediment-collecting characteristic due to the ongoing erosion of the elevated rock material from the surrounding mountain ranges. Notable deposits are associated both with present-day and ancient riverbeds in Hungary. The main areas for quartz aggregate mining are situated around the Danube, Sajó, and Rába rivers ('Földtani Közlöny (Geological Bulletin)' 1973).

Significant quartz aggregate occurrences, due to the above-mentioned alluvial deposition, are found in the northern part of the Danube and the Rába valley, the Danube below Budapest, the area around Délegyháza and the Sajó River. These areas are marked in brown in Figure 11. Győr proximity to both the Danube and the Rába rivers is the reason for the large number of mines in the area. Miskolc is located near the Sajó River, which is also the reason for the small minimum distance.

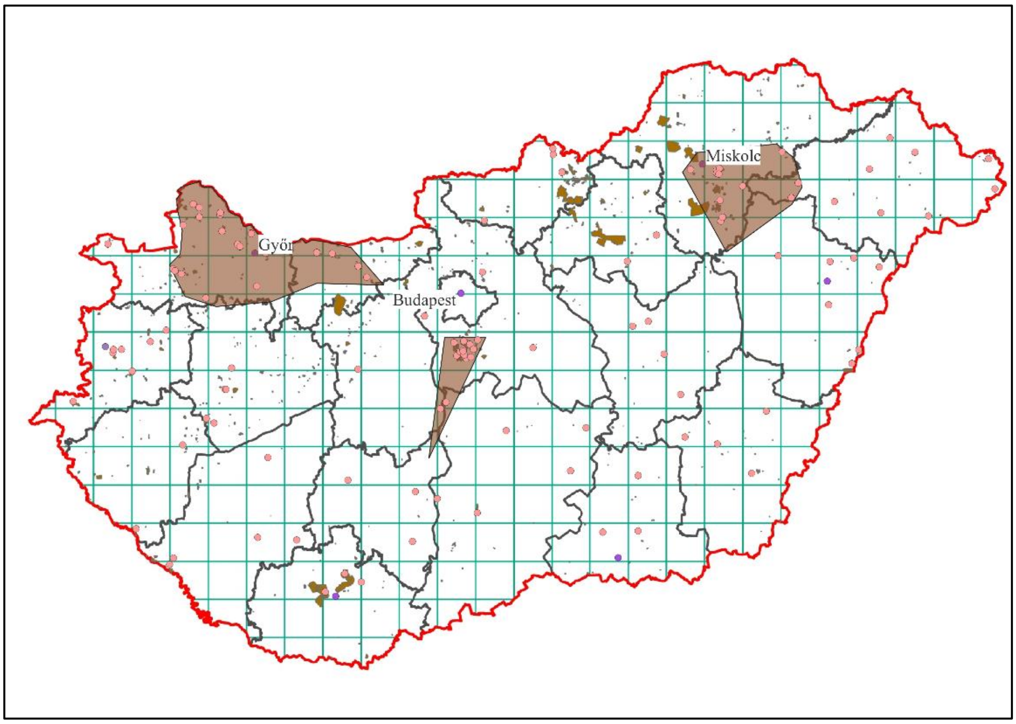

Figure 11 Significant quartz aggregate occurrences

	Quartz aggregate quarry distance [km]						
	Budapest	Debrecen	Győr	Miskolc	Pécs	Szeged	Szombathely
Minimum	15.88	10.39	5.56	6.79	5.93	15.59	4.47
Average	131.02	203.6	161.81	179.05	197.87	190.7	210.31
Maximum	285.18	399.97	388.99	352.71	411.68	313.75	473.16
Average of nearest 5	23.11	19.71	9.09	8.64	23.85	39.86	12.13
Average of nearest 10	26.14	31.81	17.10	17.92	45.51	59.95	28.87

Table 3 Minimum, maximum and average distance between quartz aggregate quarries and considered cities

It is important to note that the concrete plants will presumably supply aggregates from the nearest quarries. Therefore, the average distance of the 5 and 10 nearest mines to the selected cities is also shown in Table 3. Pécs and Szeged are in the worst situation.

Moreover, a frequency table has been prepared (Table 4) to compare the distance intervals of the most mines to each city. Between 0-100 kilometres, distances were classified in intervals of 20 kilometres, and distances greater than 100 kilometres were not classified separately. Approximately half of the mines are more than 100 km away due to Budapest's central location. A comparison of the tables shows that the average distance does not always fall within the most frequent distance interval. Hence, using average values could be problematic regarding the representativeness of the real market state. Table 4 also shows that mines are located closest to Budapest, Győr and Miskolc, with 15 mines within a 20 km radius of Budapest, 10 for Miskolc and 13 for Győr. Within a 60 km radius, Szombathely has a larger number of mines (13) due to its location in the Little Hungarian Plain region, close to both the Danube and the Rába. It can be seen that Pécs is a unique case with this exceptionally small minimum value, as most mines are 100 km away. Very few mines are located near Szeged, most of them are 100 km away.

Distance [km]	***Number of quartz aggregate quarries***						
	Budapest	Debrecen	Győr	Miskolc	Pécs	Szeged	Szombathely
0-20	1	3	6	5	3	2	4
20-40	14	3	7	5	1	0	3
40-60	5	5	8	4	2	2	5
60-80	5	10	6	7	3	4	7
80-100	8	10	9	8	4	4	13
>100	84	86	81	88	104	105	85

Table 4 NA quarries distance frequency table

3.1.2 Recycled aggregate

In Hungary, there are few fixed recycling plants. On the contrary, mobile crushing and grinding machine handling and installation companies are numerous throughout the country. However, it is hard to tell which companies are actually focused on the reuse and recycling of the products back into the economic cycle as a raw material and which are just crushing CDW. Indiscriminately collected building rubble can also be used, for example, as a road base. This is a typical example of "downcycling" or "problem shifting". This does not actually reduce the environmental burden but simply transfers it to another life cycle. Most plants processing building rubble are located around Budapest, in Pest County and in the north-western regions. In the rest of the country, there was limited data availability, so there may be more plants than indicated.

A total of 41 waste treatment plants were marked on the map (Figure 10). The plants are scattered all over the country, especially in Pest County and around Budapest. They are mostly mobile plants. This is probably due to the intensive industrial activity in Budapest. Data from the southern part of the country are scarce. Table 5 presents the minimum and maximum distances and the calculated average distance. There are a total of 4 fixed plants in the country, one each near Debrecen, Győr, Miskolc and Szombathely. Out of these, one plant is certainly fully specialised in CDW recycling, located in Bodrogkeresztúr in the northeast of the country, closest to Miskolc. This is the reason for the variation in the minimum distances and the significantly large maximum and average distances. Most major cities are located near mobile recycling treatment plants, while the total number of mixed treatment plants is 6.

	Distance [km]						
	Budapest	Debrecen	Győr	Miskolc	Pécs	Szeged	Szombathely
	Fixed recycling plants						
Minimum	167.14	73.84	59.24	41.44	137.78	230.49	12.76
Maximum	186.46	375.37	280.36	329.42	330.39	291.38	368.24
Average	180.51	295.01	136.7	248.55	208.25	266.53	118.01
	Mobile recycling plants						
Minimum	1.18	4.11	1.49	72.18	82.94	86.68	56.27
Maximum	188.24	335.48	296.59	291.8	301.74	248.5	375.87
Average	53.61	204.67	112.65	164.35	170.41	170.25	180.03
	Mixed (i.e., fixed and mobile) recycling plants						
Minimum	17.15	42.73	85.26	73.67	147.85	79.32	8.06
Maximum	203.49	371.61	306.77	319.07	335.1	283.3	391.44
Average	116.54	178	178.6	162.98	213.03	173.09	228.47
	All 3 varieties (i.e., fixed, mobile and mixed) recycling plants						
Average of 5 nearest	3.48	68.39	35.59	73.45	118.22	92.07	33.62
Average of 10 nearest	4.79	106.47	54.97	98.85	131.21	121.08	62.57

Table 5 Minimum, maximum and average distance between CDW treatment plants and cities

Moreover, a frequency table has been prepared (Table 6) to compare the distance intervals of all kinds of CDW treatment plants in each city. Between 0-200 kilometres, distances were classified in intervals of 20 kilometres, and distances greater than 200 kilometres were not classified separately. Most plants are expected to be located around Budapest. Most plants are expected to be located around Budapest. There are no plants within 60 km of Pécs and Szeged, which could be problematic for addressing the quartz aggregate material supply issue identified in the previous section (i.e., section 3.1.1)

Distance [km]	Number of recycling plants						
	Budapest	Debrecen	Győr	Miskolc	Pécs	Szeged	Szombathely
0-20	15	1	2	0	0	0	2
20-40	2	0	0	0	0	0	0
40-60	3	1	2	1	0	0	3
60-80	3	1	4	2	0	1	1
80-100	5	0	5	2	1	2	3
100-120	2	3	15	2	0	2	1
120-140	2	1	3	5	6	0	3
140-160	1	2	0	13	4	12	0
160-180	2	1	3	3	15	7	3
180-200	5	15	3	2	8	3	14
>200	1	16	4	11	7	14	11

Table 6 All CDW treatment plants distance frequency table

3.2 Cementitious materials

3.2.1 Cement

Table 7. shows the cement raw materials delivery method between the limestone mines and the cement plants. There are currently three cement plants in Hungary, one located in Vác, very close to the capital (i.e., less than 50 kilometres away). For this cement plant, the raw materials are mined on the nearby Naszály hill (Figure). In the limestone quarry, the blasted stones are crushed into smaller sizes and transported by a conveyor belt, to which another conveyor belt connects the clay so the raw materials arrive at the cement plant as a mixture.

Quarry	Transportation mean →	Cement plant
Beremend, Nagyharsány	trucks	Beremend
Naszály-hill	conveyorbelt	Vác
Bükkösd	railway	Királyegyháza

Table 7 Cement's raw materials transportation

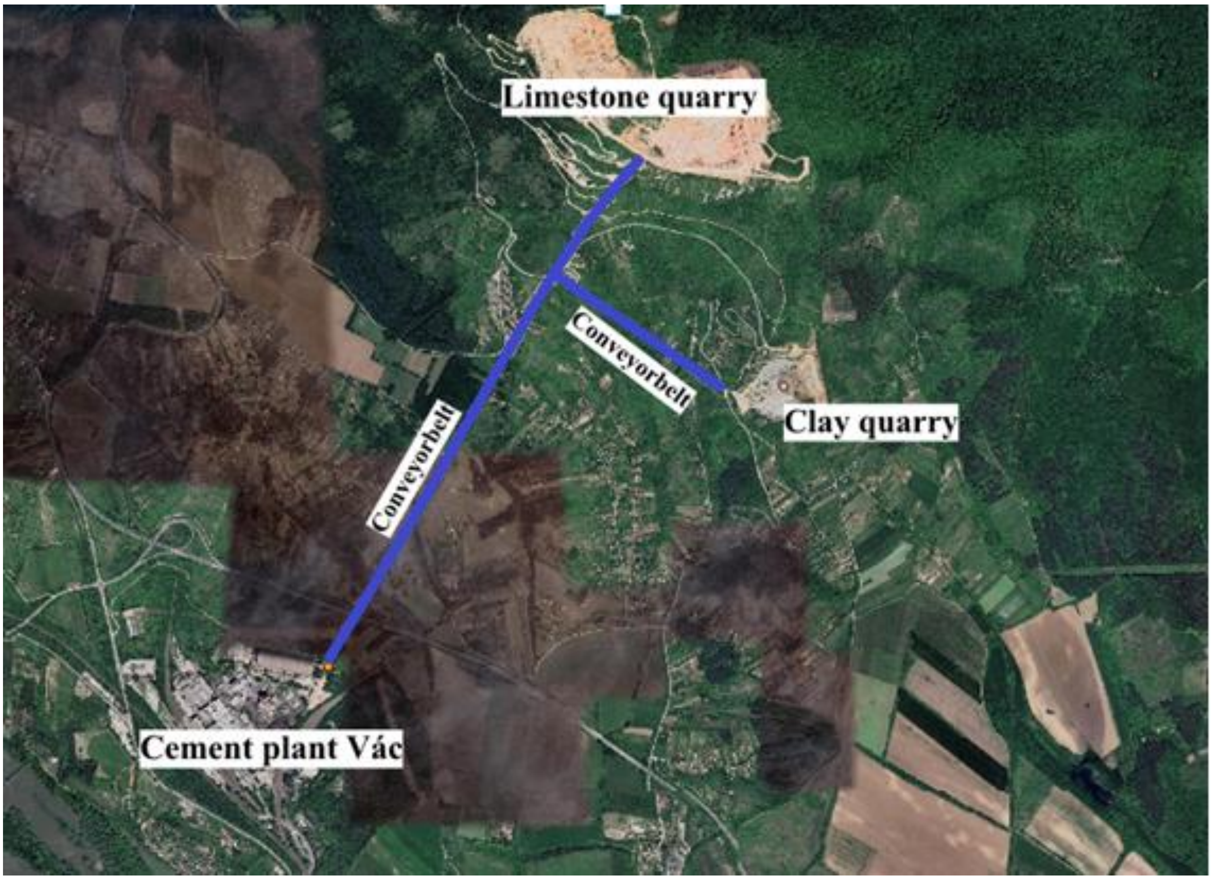

Figure 12 The raw materials' path for Vác's cement plant

The other two plants (i.e., Beremend and Királyegyháza) are located in the southwest of the country, in Baranya County (closest to Pécs). The process of cement production in Beremend (Figure 12.) is similar to that in Vác. The raw materials are transported mainly by trucks. There are mines on either side of the plant, about 5 kilometres away, one within Beremend and the other in a village called Nagyharsány (DDC 2022). On the other hand, at the cement plant in Királyegyháza, raw materials are transported by rail from a mine in the village of Bükkösd, a distance of about 15 kilometres (Gyula 2016). The path of raw materials used in the Királyegyháza cement plant is shown in Figure 14

	Distance from the cement plant [km]						
	Budapest	Debrecen	Győr	Miskolc	Pécs	Szeged	Szombathely
Minimum	33,81	192,21	110,27	129,31	20,2	144,12	170,57
Maximum	138,24	276,76	171,27	251,97	85,3	167,84	192,14
Average	195,28	325,46	216	314,29	203,87	190,22	208,1

Table 8 Minimum, maximum and average distance between cement plants and cities

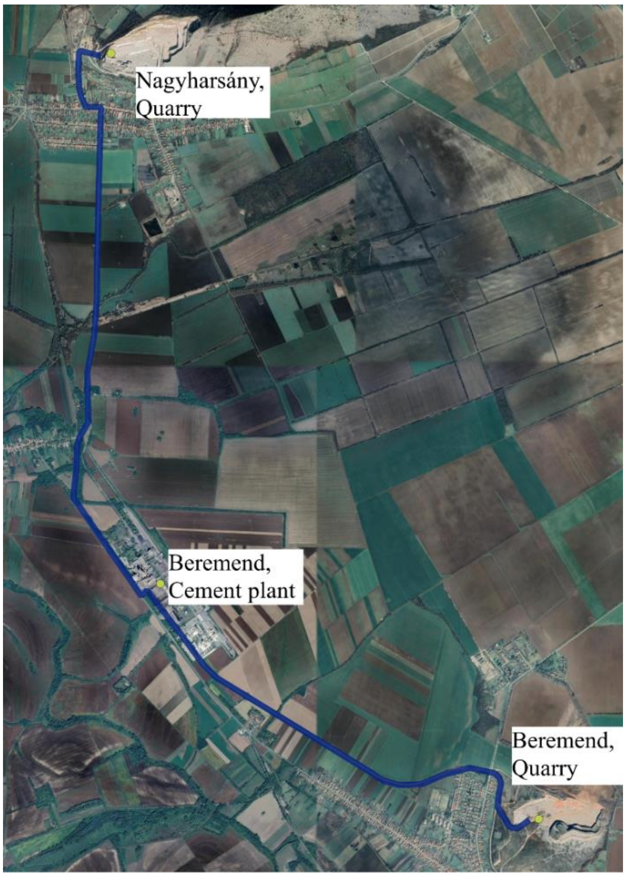

Figure 13 The raw materials' path for Beremend's cement plant

Figure 14 The raw materials' path for Királyegyháza's cement plant

3.2.2 Waste perlite powder

Waste perlite powder (WPP) originating from the production of perlite is a possible SCM due to its amorphous silica content and availability in Hungary. There exists one mine, but it satisfies the demand in Hungary and exports large quantities abroad. It is located in the northeastern part of the country, in the Zemplén Mountain, the mountain called Gyöngykőhegy. The processing plant is located right next to the mine. The extracted perlite is moved with machinery. With the exception of Miskolc, it is located at a distance of more than 100 km from the other large cities surveyed (Table). In terms of its distance from the cement plants where WPP can be used, its north-eastern location means that two out of three cement plants (Beremend, Királyegyháza) are located between 370-380 km.

Distance from the perlite plant [km]						
Budapest	Debrecen	Győr	Miskolc	Pécs	Szeged	Szombathely
209.3	103.79	299.73	66.71	362.52	265.78	389.75
Distance from the perlite plant to cement plant [km]						
	Vác		Beremend		Királyegyháza	
Pálháza	192.47		376.87		380.32	

Table 9 Distances from the perlite plant to the considered cities and cement plants in Hungary

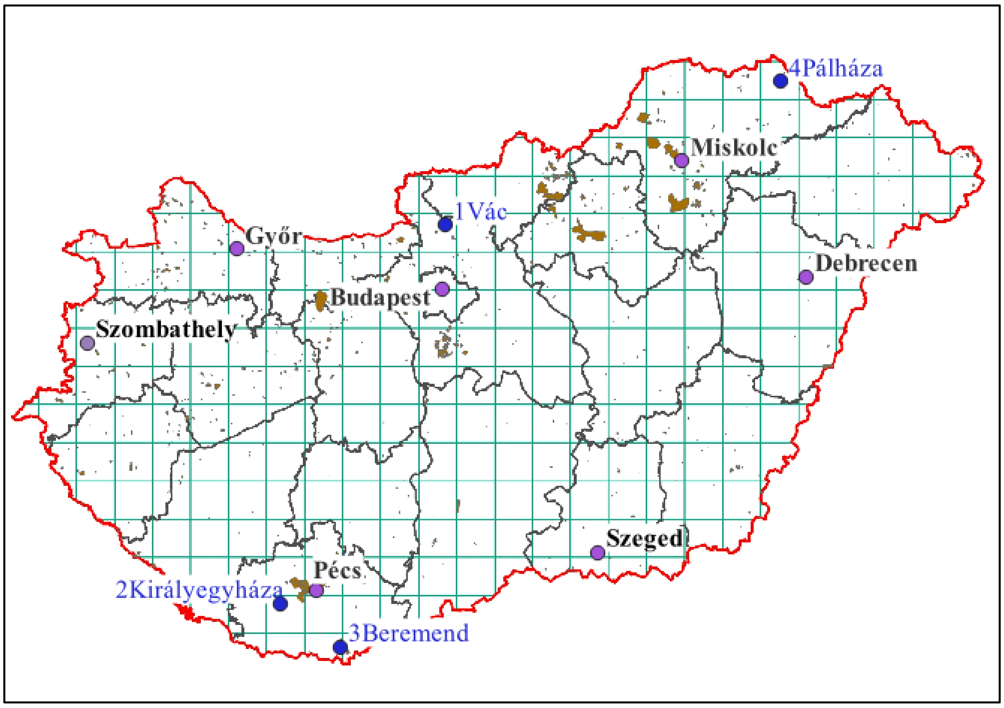

Figure 15 Location of cement plants and perlite quarry, marked with blue points

A total of 3 cement plants and a perlite plant are marked on the map. (Figure 14.) It can be seen that the distances between the plants and the selected cities are very different. In Table 8. the minimum and maximum distances are presented, and the calculated average distance.

The only town within a short distance of Beremend and Királyegyháza is Pécs (20.2km) because they are located in the southwestern part of the country. While Vác is located roughly in the middle of the northern part of the country, so with the exception of Budapest, it is similarly far from the selected northern cities (around 180 km away).

3.2.3 Recycled concrete powder

Recycled concrete powder (RCP) is similar to WPP in both its production and use. It is generated through the recycling of aggregate without environmental burden. It has an environmental impact just regarding transportation distances, which is also similar to WPP. Also generated in mobile or fixed recycling CDW treatment plants, so transportation distances are discussed in section 3.1.2.

3.2.4 Discussion based on previous research

One of the studies on Portuguese data demonstrates that the utilisation of RA in concrete production offers environmental advantages over NA, specifically in terms of land use and respiratory inorganics. Moreover, coarse recycled aggregates may exhibit superior environmental performance compared to natural ones, provided that fine recycled aggregates are also incorporated in concrete production rather than being disposed of in landfills. It's important to note that these findings are highly sensitive to transportation distances (Estanqueiro et al. 2018). However, the Portuguese study mainly focused on NA replacement by RA, while in our research, the cement replacement is also taken into account by locally available waste materials.

The LCA results indicate that the overall environmental impacts are primarily dependent on the transportation distances and types used in the process. It is crucial to emphasise that the environmental sustainability of the utilised RA is realised only when recycling facilities are located in close proximity to the concrete plants. However, there are significant benefits in terms of waste reduction and minimising natural resource depletion. RAC benefits from the increasing scarcity and distance of NA sources from areas where most construction projects are located. On the other hand, recycling facilities are generally located near larger urban areas (mostly for economic reasons) (Marinković et al. 2010).

Transportation accounts for a minimum of 4-14% of the comprehensive environmental impact of concrete, but there is a significant difference when using NA and RA. Aggregates are high-volume, low-value commodities and constitute the heaviest components of concrete. Therefore, considerable attention must be paid to evaluating their environmental impact, considering the types of transportation methods and distances used in the process (Zhang et al. 2019).

While keeping all other factors constant, it is only by altering the transportation distance of the aggregate that we can determine the "limit" for the NA transportation distance. This limit signifies that for natural aggregate transportation distances below it, the environmental impact of RAC is greater than that of natural aggregate concrete, regardless of the recycled aggregate transportation distance. The value of this "limit" depends on the environmental impact under consideration (Marinković et al. 2010).

In both natural aggregate concrete and RAC, cement production is the largest contributor to all impact categories. This is due to the substantial CO_2 emissions during the calcination process in clinker production, as well as the use of fossil fuels. The contributions from the aggregate and concrete production phases are very small, while the transportation phase falls somewhere between cement production and aggregate and concrete production phases, depending on the transportation scenario (Marinković et al. 2010).

4 Conclusions

In terms of natural aggregates, the supply chain does not seem to be consistent between major cities in Hungary. This phenomenon could provide an opportunity to higher utilisation of recycled concrete aggregate (RA) in the regions where scarcity of close mines seems to be the case (e.g., Pécs, Szeged). However, it is important to consider the critical distances within which there is no advantage of using RA. The RA supply chain must be optimized in order to minimise the environmental impact, which vary greatly among different modes of transportation.

In Hungary, trucks are the most used means of transporting concrete raw materials. These vehicles are very flexible and widespread in the transport sector, as they can be loaded and unloaded in many places using different techniques. They also allow for most delivery schedules. Taking advantage of the proximity of aggregate mines to rivers, the extracted quartz aggregate could also be transported by ship, resulting in fewer environmental impacts. However, transportation by ship would mainly not be applicable to RA, which could also be a disadvantage of their utilisation in the regions where this is viable for natural aggregate.

Another possible way to reduce the environmental impact is to install recycling plants indirectly next to ready-to-mix concrete plants. In this way, inadequate concrete mixes and waste materials could be reused immediately.

In terms of cementitious materials, the location of cement plants is limited to two regions, the capital region, and the south-western part of the country. Thus, in the eastern and south-eastern part of the country (e.g., Debrecen, Szeged), the use of alternative cementitious materials is more attractive. In Hejőcsaba near Miskolc there was earlier a cement plant which was renovated but is out of order now. The Hungarian government plan to start a new cement plant in these years. This could be done by restarting the existing and renovated plant at Hejőcsaba. With this factory and the location of the perlite plant, it is possible to integrate waste perlite powders into the supply chain of the north-eastern part of the country.

As the environmental impacts of these waste materials depend only on the distances transported, they can be considered and taken into account throughout the country. A rotary kiln is also used in the production of alumina, so the alumina factory in Ajka could be converted or made suitable for cement production. The use of waste from alumina production would thus be favoured. Secondary raw materials used in cement production, such as blast furnace slag and fly ash, have become scarce with the closure of coal-fired power plants. In Hungary, the only coal-fired power plant still in operation is in Visonta, in the Mátra Mountains, and it is also due to be closed down. Imports of fly ash and blast furnace slag are already taking place from Kassa and Serbia.

Moreover, some cement factories have railway connections for their raw material supply. Budapest, due to its central location and high industrial activity, serves as a hub for all railway lines. This means that the finished cement products could be transported here by train, not only faster but also with lower CO2 emissions and thus, a smaller environmental impact. Nevertheless, carbon intensive cement production has significantly higher burden than the environmental impacts associated with cement transportation. Since waste perlite and recycled concrete powder are waste materials, environmental burden is just associated with their transportation providing an attractive sustainable solution in concrete industry of Hungary.

However, in order to perform an accurate analysis, life cycle assessment of each process could require a mass or economic allocation, where environmental impacts are distributed between different products. The study can be extended to other unconventional concrete components (i.e., either aggregate or cementitious materials) available on the Hungarian market. Examples include the stable composition of fly ash from biomass-fired power plants and the finest dust from glass waste processing. The use of by-products and wastes from production is also more beneficial to the market economically.

In order to provide more environmental benefits of recycled aggregate concrete in Hungary it is expected that all ingredients of the concrete recycling process (i.e., coarse and fine aggregate, recycled concrete powder) should be utilised in order to reduce the environmental burden. When waste perlite powder is considered, it could be an appealing supplementary cementitious material in recycled aggregate concrete due to its pozzolanic activity and possible low environmental burden. For more precise conclusions on optimum mixes from environmental perspective, the quantification of possible environmental benefits through life cycle assessment will be future step of the research taking into account transportation data on the raw materials gathered in this study.

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