LIFE CYCLE ASSESSMENT OF CONSTRUCTION DEMOLITION WASTE-BASED GEOPOLYMER BINDER WITHIN THE FRAMEWORK OF SUSTAINABILITY

SÜRDÜRÜLEBİLİRLİK ÇERÇEVESİNDE İNŞAAT VE YIKIM ATIĞI ESASLI JEOPOLİMER BAĞLAYICILARIN YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

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Submitted to
Graduate School of Science and Engineering of Hacettepe University
as a Partial Fullfillment to the Requirements for be Award of
the Degree of Master of Science in Civil Engineering

January 2023

ABSTRACT

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January 2023, 84 pages

In today's world, where the population is rapidly increasing and natural resources are decreasing accordingly, the concept of Life Cycle Assessment (LCA) is becoming increasingly important in the fight against climate change and global warming. According to International Organization for Standardization (ISO) 14040/44 standards, life cycle analysis is an environmental assessment method that brings a holistic perspective to the life cycle of products or services. It identifies the environmental aspects and potential impacts associated with a product, process or activity by identifying and quantifying the energy and materials used and the emissions and waste generated by all processes. In this way, LCA aims to reduce resource consumption, reduce environmental emissions and thus reduce their impacts. In this LCA study, cradle-to-gate system boundary was determined and SimaPro software and the Impact 2002+ method was used. Within this thesis's scope, geopolymer binders with lower environmental impacts were considered and life cycle analyses were carried out to develop environmentally friendly materials. The geopolymer binder systems were created using construction demolition waste (CDW), which has reached levels that cannot be ignored worldwide, thereby ensuring that CDW is controlled in the most environmentally appropriate way possible. In this study, in which construction demolition wastes such as hollow brick, red clay brick, roof tiles, concrete waste and glass waste were used, 2 types of geopolymer mortar mixtures, a completely CDW-based geopolymer mortar (CDW100) and supplementary cementitious materials (SCM) substituted geopolymer mortar (CDW80SCM20), were created and their environmental impacts were evaluated with LCA. Then, in order to observe the negative effects of cement on the environment, a cementitious mortar mix was also included in the system and compared with the geopolymer mortar mixes. According to the findings of impact assessments, CDW-based geopolymer mortars exhibited significantly lower environmental impacts except for aquatic eutrophication and ozone depletion. The advantages of geopolymer mortars in terms of environmental impacts made it possible to reduce the global warming effect by 48.1%, aquatic acidification by 22.1%, land occupation by 45.2% and non-renewable energy by 1.83%. However, aquatic eutrophication and ozone depletion were higher compared to ordinary Portland cement (OPC) mortar. Compared to CDW100, CDW80SCM20 showed a slightly higher impact in the environmental impact categories. The largest difference in this comparison is for land occupation and global warming with 30.8% and 16.9% respectively. These outputs revealed that the geopolymer system containing only CDW is more advantageous in terms of environmental impact, while the potential disadvantage caused by the use of SCM retains its advantage compared to OPC mortar (except for non-renewable energy).

Keywords: Life Cycle Assessment, Construction Demolition Waste, Geopolymer Binder, Impact Assessment

ÖZET

SÜRDÜRÜLEBİLİRLİK ÇERÇEVESİNDE İNŞAAT VE YIKIM ATIĞI ESASLI JEOPOLİMER BAĞLAYICILARIN YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

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Ocak 2023, 84 sayfa

Nüfusun hızla arttığı ve buna bağlı olarak doğal kaynakların azaldığı günümüzde, iklim değişikliği ve küresel ısınma ile mücadele kapsamında Yaşam Döngüsü Analizi (YDA) kavramı gitgide önem kazanmaktadır. Uluslararası Standardizasyon Örgütü (ISO) 14040/44 standartlarına göre yapılan yaşam döngüsü analizi, ürün veya hizmetlerin yaşam döngüsüne bütünsel bir bakış açısı getiren çevresel değerlendirme yöntemidir. Kullanılan enerji ve malzemeleri ve tüm süreçler kapsamında oluşan emisyon ve açığa çıkan atıkları belirleyip ölçerek bir ürün, süreç veya faaliyetle ilişkili çevresel boyutları ve potansiyel etkileri tanımlar. Bu sayede YDA, kaynak tüketiminin azaltılması, çevresel salımların (emisyonların) ve dolayısıyla etkilerinin azaltılmasını amaçlar. Yapılan YDA çalışmasında beşikten kapıya sistem sınırı belirlenmiş, SimaPro yazılımı ve Impact 2002+ metodu kullanılmıştır. Bu tez kapsamında çevre dostu malzemelerin geliştirilmesi adına daha düşük çevresel etkilere sahip jeopolimer bağlayıcılar ele alınarak yaşam döngüsü analizleri gerçekleştirilmiştir. Jeopolimer bağlayıcılı sistemler, dünya çapında göz ardı edilemeyecek seviyelere ulaşan inşaat yıkım atıkları (İYA) kullanılarak oluşturulmuş ve bu sayede İYA'nın çevresel bakımdan mümkün olan en uygun şekilde kontrol altına alınması da sağlanmıştır. Harman tuğla, delikli tuğla, çatı kiremiti, beton atığı ve cam atığı gibi inşaat yıkım atıklarının kullanıldığı bu çalışmada, tamamen İYA bazlı bir jeopolimer harç (CDW100) ve tamamlayıcı çimentolu malzemeler (SCM) ikameli jeopolimer harç (CDW80SCM20) olmak üzere 2 tip jeopolimer harç karışımı oluşturulmuş ve çevresel etkileri YDA ile değerlendirilmiştir. Daha sonra çimentonun çevre üzerindeki olumsuz etkilerini de gözlemleyebilmek için çimentolu harç karışımı da sisteme dahil edilmiş ve jeopolimer harç karışımları ile karşılaştırılmıştır. Elde edilen etki değerlendirmesi bulgularına göre, İYA bazlı jeopolimer harçların sucul ötrofikasyon ve ozon tabakasının incelmesi dışında önemli ölçüde daha düşük çevresel etkiler sergilediği görülmüştür. Jeopolimer harçların çevresel etkiler açısından sağladığı avantajlar, küresel ısınma etkisinin %48,1, sucul asitleşmenin %22,1, arazi işgalinin %45,2 ve yenilenemeyen enerjinin %1,83 oranında azaltılmasını mümkün kılmıştır. Ancak, sucul ötrofikasyon ve ozon tabakasının incelmesi sıradan Portland çimentosu (OPC) harcına kıyasla daha yüksek bulunmuştur. CDW100 ile karşılaştırıldığında, CDW80SCM20 çevresel etki kategorilerinde biraz daha yüksek etki göstermiştir. Bu karşılaştırmadaki en büyük fark, sırasıyla %30,8 ve %16,9 ile arazi işgali ve küresel ısınma içindir. Bu çıktılar, sadece İYA içeren jeopolimer sistemin çevresel etki açısından daha avantajlı olduğunu, SCM kullanımının neden olduğu potansiyel dezavantajın ise OPC harcına kıyasla avantajını koruduğunu (yenilenemeyen enerji hariç) ortaya koymuştur.

Anahtar kelimeler: Yaşam Döngüsü Analizi, Jeopolimer Bağlayıcılar, İnşaat Yıkım Atıkları, Etki Değerlendirmesi

ACKNOWLEDGEMENT

First of all, I would like to express my gratitude to my advisor Prof. Dr. Mustafa ŞAHMARAN for his invaluable advice, guidance and support during my thesis study. In addition to the privilege of being Mustafa ŞAHMARAN’s student, I would like to state that he is more like a father than an advisor with his approach towards me, always helping me with all my problems by being solution-oriented and constantly motivating me.

I would also like to thank my second advisor Seda SELÇUK, who guided me in my thesis studies and helped me by sharing her valuable knowledge with me.

Also, I have to give thanks to Prof. Dr. İlhami DEMİR, Assoc. Prof. Dr. Mustafa Kerem KOÇKAR, Assoc. Prof. Dr. Alper ALDEMİR and Assist. Prof. Dr.Hüseyin ULUGÖL for giving me the opportunity to defend my master’s thesis.

I would like to thank TÜBİTAK Department of Science Fellowships and Grant Programs (BİDEB) thanks to its support within the scope of the 2210-C Scholarship Program.

Finally, I would like to express my gratitude to my dear mother, my dear father and my lovely sister, who faced all the difficulties with me throughout the completion of my thesis and supported me at every stage of my life. In addition, I am grateful for my family's valuable teachings and for always believing in me.

ZEYNEP ÜNSAL
January 2023, Ankara

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SYMBOLS AND ABBREVIATIONS

Abbreviations

ASTM	American Society for Testing and Materials
BFS	Blast Furnace Slag
$Ca(OH)_2$	Calcium Hydroxide
CDW	Construction Demolition Waste
CW	Concrete Waste
DALY	Disability Adjusted Life Years
EPD	Environmental Product Declaration
EU	European Union
FA	Fly Ash
GGBFS	Ground Granulated Blast Furnace Slag
GW	Glass Waste
GWP	Global Warming Potential
HB	Hollow Brick
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NaOH	Sodium Hydroxide
OPC	Ordinary Portland Cement
PC	Portland Cement
PDF	Potentially Disappeared Fraction
RCA	Recycled Concrete Aggregate
RCB	Red Clay Brick
RT	Roof Tile
SCM	Supplementary Cementitious Materials
SETAC	Society of Environmental Toxicology and Chemistry
SF	Silica Fume
UK	United Kingdom
UNEP	United Nations Environment Program

US	United States
XRF	X-Ray Fluorescence

1. INTRODUCTION

The focus of societies on sustainability and the increase in demands in this direction, decreasing resources and the legalization of efforts to combat climate change in many countries make it inevitable for the construction industry to adopt a more innovative approach. Today, many businesses, especially industries, are trying to respond to increasing environmental awareness with more environmentally friendly materials, products, processes and services that consume less natural resources and energy, are more recyclable, more durable, lower carbon and generate less solid waste.

Increasing cement and concrete consumption in parallel with rapidly expanding urbanization leads to the use of more natural reserves worldwide. The production and consumption of cement and concrete constitute a significant burden on people's lives. This situation, which should be evaluated in terms of sustainability and cost, encourages the search for environmentally friendly alternative raw materials and production methods.

One of the most significant problems in the modern world, when demand is rising quickly and resources are few, is construction demolition waste (CDW). Approaches to resource and waste management used during building operations have a substantia influence on the environment. By recovering and recycling materials with economic value, nations may use their natural resources most efficiently and over the long term. CDW management, which aims to limit waste and mitigate harmful environmental effects, is one of the most significant environmental concerns in the construction industry.

Considering all these considerations, geopolymer mixtures were prepared using construction demolition waste as an alternative to Portland cement. Geopolymer binders can minimize environmental issues by satisfying the cement-based binder systems characteristics. By producing geopolymer binders belonging to the alkali-active materials group, the development of environmentally friendly building materials and long-term sustainability are aimed.

Life Cycle Assessment (LCA) according to ISO 14040 standards was applied to evaluate the environmental performance of the prepared geopolymer mortar mixtures. LCA is a systematic and efficient method for assessing a product's overall environmental impact across its entire life cycle.

The study's goal is to perform a thorough LCA analysis for geopolymer mortar mixes created using construction demolition waste (CDW) and assess their environmental impacts. For this purpose, 2 types of geopolymer mixtures were designed, one containing 100% construction demolition waste and one containing 80% construction demolition waste and 20% supplementary cementitious materials. While performing life cycle analysis; the procurement/purchase of the materials, transportation, the processes in the necessary devices in the laboratory to make them ready for use and the electrical energy consumptions were taken into account. In order to observe the negative impact of cement on the environment, a cement mortar mix was also included in the system. The environmental implications of each of these mortar mixes were assessed using the LCA approach, and they were evaluated to identify which elements and/or mix has the best environmental performance.

The LCA study was conducted using SimaPro 9.0.0.35 software. The system boundary was established as cradle-to-gate within the scope of the study. For all mortar mixtures, 1 m^3 was used as the functional unit. In this study, the Impact 2002+ impact assessment methodology was chosen, and the characterisation results were utilized to interpret the findings.

2. LITERATURE REVIEW

2.1. Life Cycle Assessment (LCA)

An approach called life cycle assessment (LCA) involves assessing each step of a system's life cycle in terms of how it will affect the environment. LCA is a system based on environmental awareness and environmental effects. The LCA structure is defined and explained by the International Organization for Standardization (ISO) 14040 and 14044 series. The LCA is defined as follows by ISO 14040: LCA examines the environmental aspects and possible environmental impacts of a product (such as the use of resources and effects of emissions on the environment) during its lifespan (such as from cradle to grave), from the procurement of the raw materials used for its manufacture, to its use, treatment, recycling, and ultimate disposal when its life is over [1].

The environmental considerations of all decisions made during the project development and implementation operations have become even more crucial in light of the recent growth in society's sensitivity to environmental concerns. Natural resource usage and the potential to contribute to global environmental problems have started to be taken into account frequently during the decision-making processes, in parallel with the rise in environmental awareness. This is due to advancements in technology and living standards, which go beyond the traditional parameters like project cost and societal benefit. Since the early 1990s, life cycle analysis (LCA), a technique, has been increasingly popular in complicated decision-making processes and is continuously being improved [2].

Life cycle analysis has several advantages throughout many fields. It gives transparency in the flow of energy and materials as well as opportunities for process efficiency by evaluating the manufacturing processes. In this way, the product's environmental performance may be expressed numerically. In addition, because of the enhancements made to all product processes, resources are used most effectively, which results in indirect cost savings. It is also possible to compare products among themselves. Table 2.1 shows the benefits of life cycle analysis in different areas.

Table 2. 1. Benefits of life cycle analysis

Benefit Area	**Benefits**
Business strategy	Competitive advantage
	Potential for improvement in product quality
	Improving risk management
	Developing public reputation
Market requirements	Increased market share
	New business opportunities
	Supply chain management
	Opportunity to participate in other concepts based on the product life cycle such as Environmental Product Declaration (EPD), carbon label, ecolabel
National and international legislation	Regulatory compliance and risk mitigation against criminal sanctions

As a result, with life cycle analysis;

- conservation of natural resources,
- prevention of environmental pollution,
- ensuring environmental equity,
- development of environmental laws and regulations,
- the development of environmental performance assessment in environmental management systems,
- ensuring the production of environmentally sensitive products,
- reducing overall environmental impacts and health risks resulting from product development and use is possible.

The LCA approach can detect and analyze environmental impacts at different life cycle phases, beginning with the purchase of raw materials used in the manufacturing of a product or service, encompassing all pertinent production, distribution, consumer usage, and disposal as waste once being used. Figure 2.1 illustrates common system inputs and outputs as well as potential LCA phases that might be considered in an LCA [3].

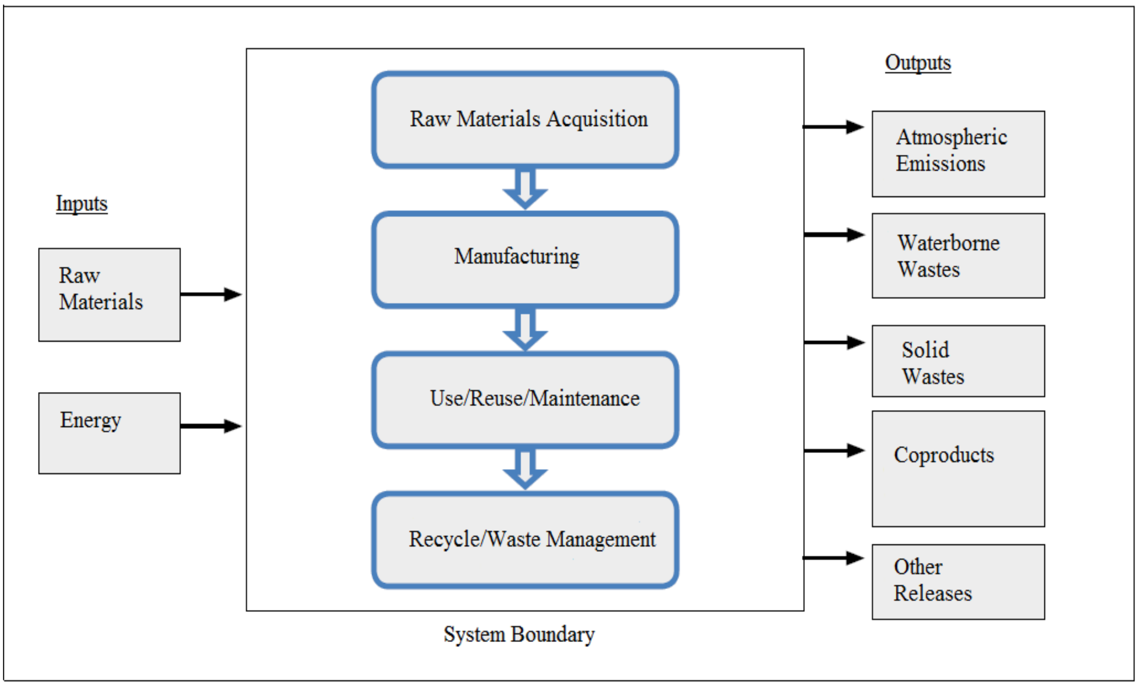


Figure 2. 1. Life cycle stages [3]

Three institutions have an important role in LCA at the international level; the United Nations Environment Program (UNEP), The Society of Environmental Toxicology and Chemistry (SETAC), and the International Organization for Standardization - ISO.

In 2002, the International Life Cycle Partnership, also known as the Life Cycle Initiative, was published by the SETAC and the UNEP. The initiative's main goal was to create practices that adhered to a predetermined framework and to enhance the supporting technologies. Because ISO never standardized LCA techniques in detail and because they are all subject to alternative interpretations concerning system boundaries, allocation methods, etc., the decade from 2000 to 2010 saw a divergence of methodologies. Nevertheless, it was around this time that the first Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) concepts were put out. Environmental, financial, and social factors of LCA sustainability evaluations have grown in significance during the past ten years [2].

ISO has published a series of guidelines for the standardization of procedures and methods. These guidelines are given in Table 2.2 [4].

Table 2. 2. ISO guideline series

ISO 14040 (2006): Environmental Management-Life Cycle Assessment-Principles and Framework
ISO 14041 (1998): Environmental Management-Life Cycle Assessment-Goal and scope definition and inventory analysis -not in use
ISO 14042 (2000) – Environmental Management-Life Cycle Assessment -Life cycle impact assessment– not in use
ISO 14043 (2000) -Environmental Management-Life Cycle Assessment-Life cycle interpretation– not in use
ISO 14044 (2006) –Environmental Management-Life Cycle Assessment-Requirements and guidelines
ISO 14047 (2003) –Environmental Management-Life Cycle Assessment- Examples of application of ISO 14042- revised by ISO 14047:2012
ISO 14047 (2012)–Environmental Management-Life Cycle Assessment- Illustrative examples on how to apply ISO 14044 to impact assessment situations
ISO 14048 (2002) –Environmental Management-Life Cycle Assessment-Data documentation format
ISO 14049 (2012) –Environmental Management-Life Cycle Assessment- Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis

As shown in Figure 2.2, according to ISO 14040, the life cycle evaluation of products is examined in four interrelated stages as Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation.

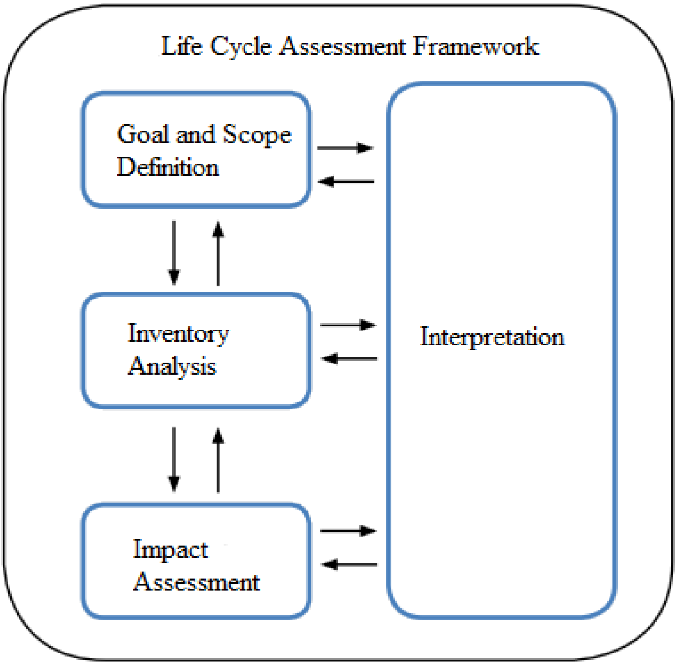


Figure 2. 2. LCA phases as defined by ISO 14040, 2006 [1]

The LCA methodology, which consists of four stages and is summarized as follows, is basically:

- Determining the goal and scope of the product/system to be studied
- Keeping an inventory of the water, energy, natural resources, and raw materials utilized to produce a good or service, as well as the emissions that result from that process
- Evaluation of possible environmental effects linked to these inputs and outputs, and
- It addresses the outcomes' systematic and comparative examination and presentation to decision-makers.

2.1.1. Goal and Scope Definition

The first stage of the LCA study, goal and scope definition, is the stage in which the purpose of the work to be done and the method for how to participate in the decision-making process of the environmental effects that will arise throughout the life cycle are determined. To ensure that the findings are relevant and applicable, it is important to make clear at this point the types of data that are thought to influence the decision-making process as well as how exact the results should be and how they should be interpreted and presented.

Goal and scope can be examined under some sub-headings such as functional unit and system boundaries:

- **Functional unit**- represents the quantity of the product's defined functions (performance attributes). The basic function of a functional unit is to perform as a reference for inputs and outputs. To ensure that LCA findings can be compared, this reference is necessary. In order to guarantee that these comparisons are conducted generally, it is crucial that LCA findings are comparable when comparing different systems. To carry out the desired function, such as the number of products needed to accomplish the function, creating the reference flow for each product system is essential [1].

- **System boundary**- outlines the system's basic unit processes. The inputs and outputs at the system boundary should represent the major flows in the ideal model of the product system [1]. Figure 2.3 shows system boundaries. There are several kinds of system boundaries, including as:

  a. Cradle-to-gate: From the gathering of raw resources to the factory gate.
  b. Cradle-to-grave: Starting with the extraction of raw materials and ending with the use and disposal of the finished product.
  c. Gate-to-Gate: A specific life cycle point to another specific life cycle point later on (for example, when crossing the fence line at an industrial plant to get raw materials) (e.g., when a finished product is given to a customer). It is an approach that deals with the lifecycle of a product or a single stage of the process [5].
  d. Cradle-to-cradle: From the cradle, it considers all processes while also taking recycling into account for the final disposal stage.

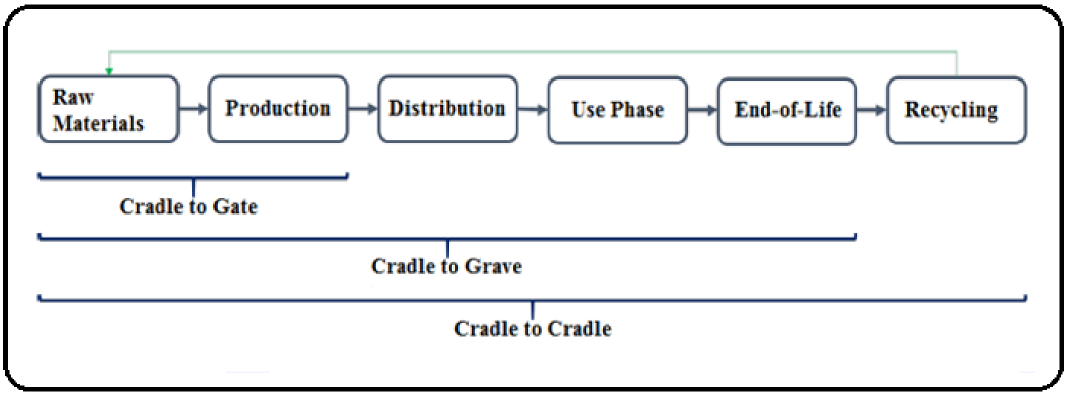


Figure 2. 3. LCA system boundaries

2.1.2. Life Cycle Inventory (LCI)

Life Cycle Inventory is a process that determines inputs and outputs such as raw material and energy needs, waterborne emissions, atmospheric emissions, environmental discharges, and wastes associated with the whole of a process, product, or activity's life cycle. Inventory analysis involves data collection, calculation, and allocation procedures according to ISO 14040,2006 [1]. These stages are summarised as follows:

<u>Data collection</u>: The following primary categories can be used to information about each unit process inside the system boundary: energy inputs, inputs from raw materials, auxiliary inputs, additional physical inputs, outputs, waste, emissions into the atmosphere, discharges into water and soil, and other variables [1]

<u>Data calculation</u>: Following the data collection, calculation processes are required to produce the outcomes of the inventories of the specified system for every unit process and the product system's designated functional unit that will be modelled. These calculation procedures involve validating the data gathered, connecting data to unit activities, and connecting data to the functional unit's reference flow [1]

<u>Allocating flows and releases:</u> Several industrial processes have a single outcome or are focused on the linearity of input and output of raw materials. In actuality, most industrial processes produce several products and reuse leftovers or intermediate goods as raw resources. When dealing with systems comprising numerous products and recycling systems, the necessity for allocation methods should be taken into account [1]

2.1.3. Life Cycle Impact Assessment (LCIA)

In the Life Cycle Impact Analysis (LCIA) phase, the effects of potential environmental emissions identified during LCI on human health, environment, and natural resource consumption are evaluated. Life cycle impact analysis establishes a link between the product/process and its possible environmental impacts.

According to ISO 14040, LCIA consists of mandatory and non-mandatory stages as shown in Figure 2.4. Accordingly, the mandatory stages for LCIA are explained as follows: impact category selection, classification and characterization. Other steps such as normalization, grouping, and weighting are left optional.

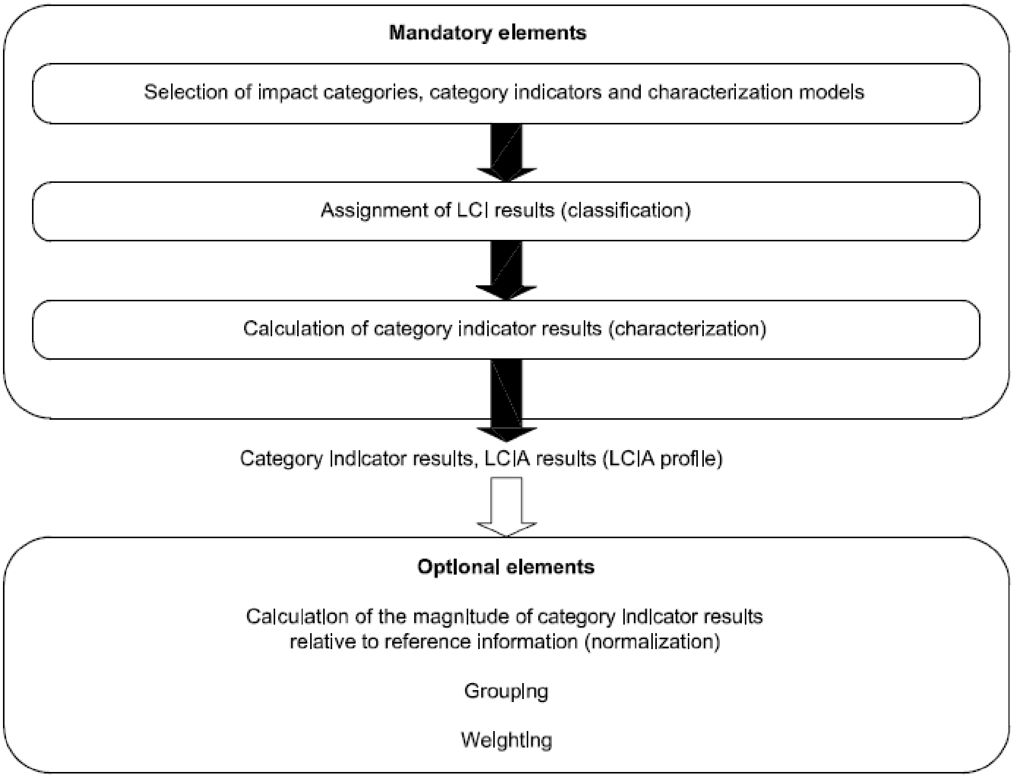


Figure 2. 4. Elements of LCIA phase [1]

Compulsory Elements:

- <u>Selection of impact categories</u>: The first stage of an LCIA is the selection of impact categories to be taken into account as part of the entire LCA. For an LCIA, impacts can be defined as the consequences that a system's input and output streams may have on human health, environmental emissions, plants, animals, or the future availability of natural resources. The impact categories often utilized in LCA studies are presented in Table 2.3 [3]

Table 2. 3. Impact categories commonly used in LCA studies [3]

Impact Category	**Examples of LCA Data(i.e classification)**	**Characterization Factor**	**Reference substance**	**Characterization Factor Description**
Global Warming	CO_2 NO_2 CH_4 CFCs HCFCs CH_3Br	Global Warming Potential	kg CO_2 eq	Converts LCI data to CO_2 equivalents
Stratospheric Ozone Depletion	CFCs HCFCs Halons CH_3Br	Ozone Depleting Potential	kg CFC-11 eq	Converts LCI data to CFC-11 equivalents
Acidification	SOx NOx HCl HF NH_4	Acidification Potential	kg SO_2 eq	Converts LCI data to H+ ion equivalents
Eutrophication	PO_4 NO NO_2 Nitrates NH_4	Eutrophication Potential	kg PO_4 eq	Converts LCI data to PO_4 equivalents
Photochemical Smog	Non-methane hydrocarbon (NMHC)	Photochemical Oxident Creation Potential	kg C_2H_6 eq	Converts LCI data to C_2H_6 equivalents
Terrestrial Toxicity	Toxic substances with a rodent-deathly concentration reported	LC_{50}	kg Triethylene glycol into soil eq	Converts LC50 data to equivalents; uses multimedia modelling, exposure pathways

Aquatic Toxicity	Toxic substances with recorded fish-lethal concentrations	LC_{50}	kg Triethylene glycol into water eq	Converts LC50 data to equivalents; uses multimedia modelling, exposure pathways
Human Health	Total releases to air, water, and soil.	LC_{50}	-	Converts LC50 data to equivalents; uses multimedia modelling, exposure pathways
Resource Depletion	Quantity of Minerals and fossil fuels used	Resource Depletion Potential	-	Converts LCI data to a ratio of resource usage to reserve resource utilization.
Land Use	Quantity disposed of in a landfill or other land modifications	Land Availability	m_2 organic arable land eq*y	Converts the volume of solid waste from its mass using an assumed density.
Water Use	Water used or consumed	Water Shortage Potential	-	Converts LCI data into a ratio of the amount of water used to the amount of resources remaining in reserve.

- Classification: All emissions are categorized according to their environmental impacts during the classification phase, which correlates each environmental feature identified during the inventory analysis phase with impact categories. The LCI data can be categorized into one impact category or into two or more impact categories simultaneously [3]. For instance, SO_2 can be classified according to its effects on acidification and human health [6]. Nitrogen oxides (NO_x) emissions, for example, can concurrently be related to eutrophication, acidification, and aquatic toxicity. The relationship between emissions and impact categories is given in Figure 2.5. In this figure, raw materials utilized (top) and pollutants released (bottom) during the course of a product's life cycle are shown to the left. The impact categories that these emissions fall under are listed to the right. The figure shows how several emissions can have the same impact while also having multiple effects from a single emission.

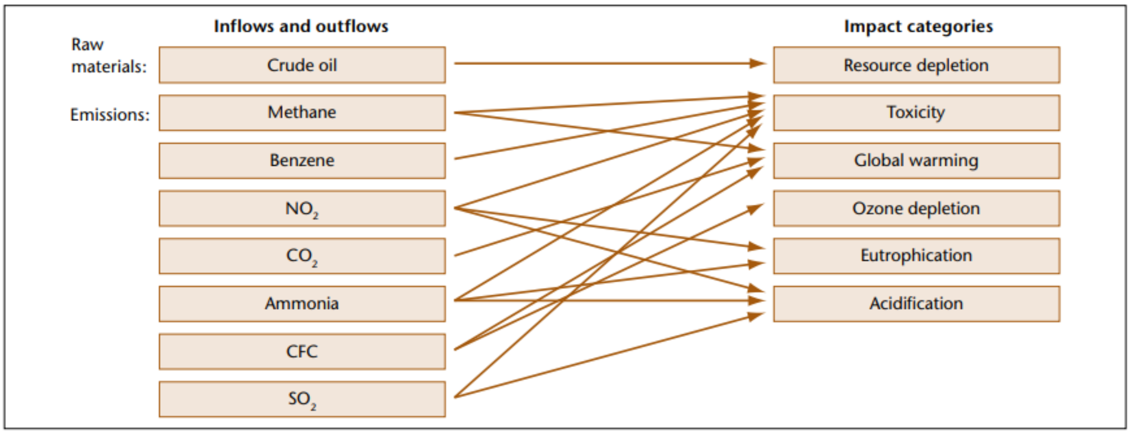


Figure 2. 5. Relations between emissions and impact categories [7]

- Charecterization: It can be done based on environmental models that allow us to compare different compounds linked to the same environmental problem. Equivalence factors are used to accomplish this. When compared to a selected reference substance, an equivalence factor shows how much more a certain component contributes to a problem. The formula used to calculate category indicators [8]:

  Category Indicator= Σ_s Factor of Characterization × Inventory of Emissions, where the chemical is indicated by subscript s.

  The example of global warming may help to clarify the computational process required to aggregate the data into one impact category. CO_2 is used as a reference in the case of global warming. A coefficient is assigned to each additional component that amplifies the greenhouse effect, indicating how much more or less the compound contributes to the impact overall. For instance, the equivalency factor for methane is 11, which indicates that 1 kilogram of methane has the same effect on the atmosphere as 11 kg of carbon dioxide. The outcome is given as an equivalent amount of CO_2 [7]

Optional Elements:

- Normalization: The results obtained after the characterization step cannot be compared as each is presented in different units (CO_2 eq., CFC-11eq, SO_2 eq. etc.). Therefore, values are converted to the same units for comparison.[7] In the normalization stage, each impact category findings are separated by a reference value and the most important possible impacts are emphasized in the weighting stage, and the most outstanding impacts are tried to be determined while presenting the product/service. [9], [10] The normalization process is performed using the following equation [8]:

  $$N_k=S_k /R_k$$

  Impact category is shown with k, normalized indicator with N, category indicator calculated at the characterization stage with S, and reference value with R.

- Grouping: To make it easier to understand the data for certain areas of interest, impact categories are categorized under one or more topics. Typically, the grouping comprises ranking or classification indicators and is organized in accordance with the indicators' properties (for example, emissions to water and air) or their location (for example; regional, local, and global).

- Weighting: The weighting step of an LCIA involves allocating weights or relative values to various impact categories, environmental issues, and relevance as a whole. The weighted value is multiplied by the scores for each environmental issue, all scores add up to form the total environmental index.

  Weighting is frequently used as linear weighting factors:

  $$EI= \Sigma V_k N_k \text{ or } EI= \Sigma V_k S_k$$

  where N is the normalized indication, S is the category indicator from the characterization phase, V_k is the weighting factor for impact category k, and EI is the overall environmental effect indicator [8]

  Due to the fact that it includes selecting social, political, and ethical values, weighing is still a controversial LCA component. The most challenging stage in LCA is weighting, particularly when using the midpoint technique.[6]

There are many impact assessment methodologies in the literature that differ from each other using different impact categories, characterization, normalization factors, and assessment methods [11]. The following lists these impact assessment methods:

- IMPACT 2002+
- CML
- ReCİPe
- BEES
- TRACI
- Cumulative Energy Demand (CED)
- IPCC
- Eco-Indicator 99
- EDIP/UMIP
- Ecological Footprint
- Ecological Scarcity
- Ecosystem Damage Potential

2.1.4. Interpretation

Interpretation is the final stage of LCA according to the ISO 14040 standard. The stage of interpretation of the assessment is expressed as the step in which the adverse effects of a product classified and defined in the impact assessment are interpreted for the purpose of reducing energy, raw material uses and environmental waste throughout its life cycle. The interpretation phase is intended to convey the LCA results in line with the goal and scope of the research in a clear, comprehensive, and consistent manner, as per the ISO 14040 standard. This phase includes two primary steps [12] :

1.Identification of significant issues; The outcomes of the LCI and LCIA phases are organized to identify important concerns. Significant issues should be resolved iteratively during the assessment process and in accordance with the description of the aim and scope. These issues can include:

- Inventory elements like energy use, significant material flows, waste and emissions, etc.
- Indicators of the impact category whose magnitude is of particular interest or concern.

- Essential contributions of life cycle phases, such as specific unit processes or groups of activities, to the findings of LCI or LCIA (e.g., transportation, energy production)

The outcomes can be shown in the form of tables, bar graphs, data lists, or other practical formats. They can be organized based on different operations (such as energy supply, transportation, and the extraction of raw materials), forms of environmental impact, or other criteria.

2.Evaluation: The evaluation's objective is to increase the study's dependability. The evaluation should be conducted using the following three techniques:

- Completeness check: Missing or partial data will be assessed during the completeness check to determine whether they are necessary to meet the objectives and limitations of the study. To fill in the gaps, missing data must be provided, computed, or the definition of purpose and scope might be changed.
- Sensitivity check: Sensitivity control refers to the monitoring of data, assumptions, allocation schemes, calculation schemes, etc. to assess the impact of uncertainties.
- Consistency check: The methods used are used to determine whether the study's purpose and scope are consistent with each other.

2.2. Environmental Impacts of Cement and Conventional Concrete

Cement and concrete are at the center of modern civilization with the advantages they provide by being convenient, easy, accessible, and economical for all construction applications in achieving a high standard of living. Concrete is produced in volumes exceeding 10 billion tons annually and is the second most utilized material in the globe following water [13]. However, the negative environmental effects of cement, which are required for the production of concrete, is a major issue that cannot be ignored. Approximately 8% of worldwide CO_2 emissions come from CO_2 released during the manufacturing of cement [14], [15]. One ton of Portland cement (PC) produced releases about 0.8 tonnes of CO_2 equivalent emissions and the total amount of CO_2 released is the sum of the emissions caused by burning fossil fuels during cement production and the calcination process carried out to form calcium oxide by removing carbon dioxide from calcium carbonate [16].

Numerous studies at the environmental scale have described the consequences of various cement producing technologies. According to recent studies, calcination plays a significant role in how cement manufacturing affects the environment [17], [18]. It demonstrates that only 20% of climate change's consequences are attributable to the techniques used to prepare raw materials and those used following calcination (grinding). 60% of the emissions during heating are caused directly by the chemical decarbonization of limestone, whereas 40% are caused by fuel combustion [19].

Water management and air pollution are the areas where the action is most urgently needed given the effects of cement production. It was determined to speed up action plans at the Copenhagen Climate Summit since it was widely acknowledged that the years 2020 and 2050 will be crucial turning points for climate change. According to data from recent research, the atmosphere's current concentration of carbon dioxide (CO_2) is close to 380 ppm [20],[21]. By the end of the century, it is predicted that the CO_2 concentration would surpass 800 ppm even when factors that directly influence CO_2 emissions, such as large trade volume, technical advancements, and social changes, are not taken into consideration [21]

Apart from CO_2 emissions, cement manufacturing facilities also emit carbon monoxide, nitrogen oxide, and sulfur dioxide, all of which have a demonstrably detrimental effects on the environment and human health. Numerous health issues and negative environmental consequences can be brought on by nitrogen oxide (NO_x), ground-level ozone, acid rain, global warming, deteriorating water quality, and visual impairments. High levels of sulfur dioxide (SO_2) can have a negative impact on the respiratory system and exacerbate pre-existing respiratory and cardiovascular conditions. Acid deposition, often known as acid rain, is mostly caused by SO_2. Carbon monoxide (CO) can harm health by reducing the quantity of oxygen that reaches the organs and tissues of the living body. Additionally, the cardiovascular and nervous systems may suffer harm. Smog, or ground-level ozone, which might worse respiratory conditions, is also aided by CO. [22]

As of 2019, with 55 integrated facilities and 22 grinding facilities, Turkey is ranked first in Europe and fourth overall for cement production [23] Turkey began producing cement in 1911 and imported cement up until the 1970s. Cement exports from Turkey started in 1978. With a 75-million-ton clinker production capacity as of 2018, Turkey is the largest cement manufacturer in Europe. Figure 2.6 illustrates the rates of cement and clinker production and associated CO_2 emissions.[24]

As can be seen from Figure 2.6, the amount of CO_2 emissions grew by 166% from 1990 to 2019. Except for 2001 and 2015, when there were some small declines, the cement industry in general has shown continuous growth. The construction sector and cement exports are the strongest drivers in the cement industry. In 2019, clinker production amounted to 57.800 kt (94% capacity utilization), resulting in CO_2 emissions of 30.423 kt [24]

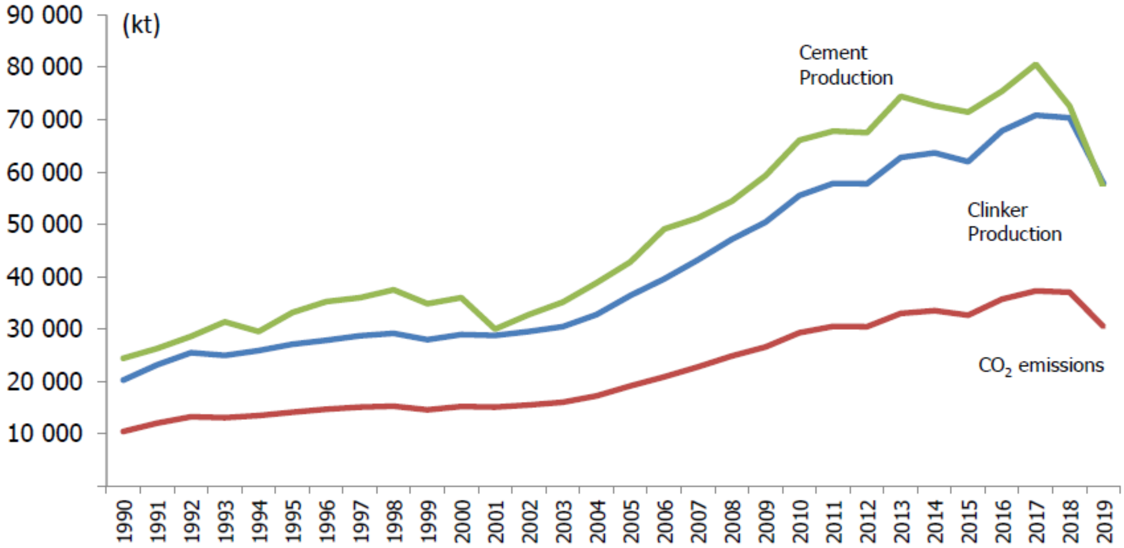


Figure 2. 6. Production rates of cement and clinker and associated CO_2 emissions [24]

In light of all these unfavourable circumstances, producing and consumption of cement and concrete pose a significant burden on people's lives. The need for control over cement production has become unavoidable due to the growing demand in the global market and the damaging environmental consequences it causes. Even though concrete is affordable, accessible, and has good performance qualities, the damage it causes to the environment is too significant to be disregarded. Analyzes like environmental life cycle assessments, which evaluate and optimize data on a product's environmental hazards at every stage of its service life to minimize the effects of the production process in question on the environment, are becoming more crucial for globally significant products like cement.

Given all these evaluations, it is undeniable that environmental awareness should be raised by drawing realistic conclusions about the harms that cement may create in the future and that other binders that are less damaging to the environment should take the place of cement. For long-term sustainability, it is essential to develop and create environmentally friendly construction materials.

2.3. Economic and Environmental Importance of Construction and Demolition Waste

The world's natural resources are depleting day by day as a result of increasing population and consumption. These resources will eventually run out if required precautions are not taken. Construction demolition waste is one topic that has gained a great deal of attention recently in our society when resources are few and demand is increasing rapidly.

The World Bank reported in 2012 that 1.3 billion tons of solid waste are produced annually by cities worldwide. By 2025, 2.2 billion tons per year are anticipated to be added to this level. Half of the annual solid waste produced worldwide is formed from construction materials [25].

More than 600 million tons of construction waste were produced in the United States (US) in 2018. The biggest portion (67.5%) was formed of CDW concrete, followed by asphalt concrete (17.8%). Of this, CDW wood products accounted for 6.8%, while all other items combined made up 7.9%. More than 90% of all CDW waste was generated by demolition, compared to less than 10% by construction [26].

Construction and demolition operations generate 850 million tons of CDW annually in Europe. Compared to other economic sectors, the building sector in the European Union (EU) generates the most waste, 35% of the total amount. [27]

In the United Kingdom (UK), construction demolition waste accounts for more than 50% of landfill volume, with an additional 70 million tons added each year [28]. In Australia, waste from construction activity represents 20-30% of the total waste deposited in Australian landfills [29]. Between 1993 and 2004, the annual production of CDW in Hong Kong doubled and was reported to be around 20 million tons [30]

Countries must eliminate waste and look into ways to recover and reuse materials with economic value if they want to use their natural resources effectively and over the long term. For this reason, construction demolition waste has become a problem that requires urgent solutions.

A concept like the life cycle of a structure could not previously be discussed. Due to this, when a structure reached the end of its productive economic lifetime, it was demolished, and the remaining waste was either idle or used as filler. It is also well-recognized that a variety of large-scale waste products are produced as a result of natural disasters. Natural disasters, in particular the waste produced by earthquakes, need the management, recycling, or elimination of excessive waste and the creation of emergency environments. Figure 2.7 shows that some of the post-earthquake demolition wastes are taken to landfills or some of them are dumped near natural resources such as lakes, etc., causing serious damage to the environment.

(a) **(b)**

Figure 2. 7. Improper storage of (a) demolition waste, (b) rubble heaps

2.4. Characteristics of Construction and Demolition Wastes

According to Figure 2.8, every activity associated with the construction industry is depicted as a cyclical process. From a sustainable standpoint, it is obvious that by striving for close to 100% recycling of CDW, the completion of this cycle may be accomplished. Construction and demolition waste from today is derived from building materials used 50–100 years ago. By emphasizing design and construction for future recycling or reuse convenience, developments could remain behind schedule even if a substantial percentage of this CDW may frequently be recycled [31].

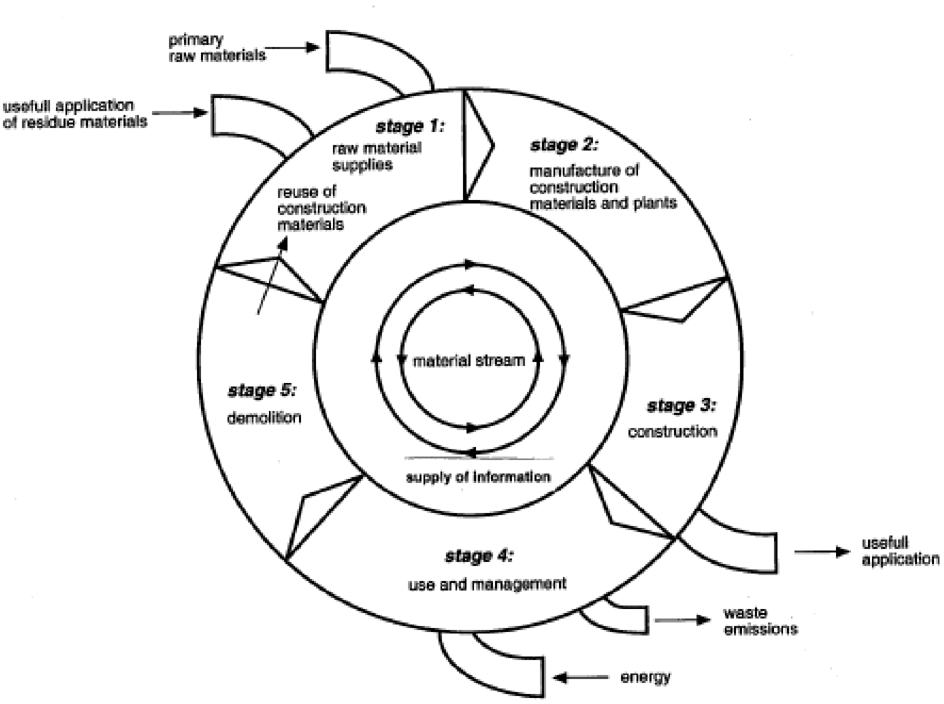


Figure 2. 8. The ideal,sustainable building cycle [31]

Since construction wastes involve complex and multidimensional problems (in terms of volume and pollution load) and have different characteristics, the problem should be approached and addressed in an integrated way. Demolition waste is not homogeneous. The composition of such wastes generated during the demolition of buildings depends on the contents of the building, the materials used in the building, its age, design style and size. The waste mass, called construction and demolition waste, includes a wide range of materials such as concrete, gravel, plaster, soil, sand, briquettes, slabs, and porcelain. These wastes can be categorized based on their source as shown in Table 2.4.

Table 2. 4. Sources of construction and demolition waste [32]

Categories	**Waste Types**
Road Construction and Maintenance Materials	Asphalt, concrete, cover soil
Excavation Materials	Soil, stone, gravel
Construction Demolition Waste	Concrete, mixed rubble, steel, brick, iron, timber
Building Renovation and Work Zone Materials	Wood, roofing materials, pipe, plastic, glass, metal, insulation materials

2.5. Geopolymer Binder Systems

The creation of low-CO_2 construction materials which is a substitute for ordinary Portland cement (OPC) is the geopolymer technology's primary use. Geopolymers have the capabilities to lessen environmental issues by meeting the characteristics of OPC- based binder systems. The term "geopolymer" was used by the French scientist and engineer Prof. Joseph Davidovits in the 1970s and geopolymer binders are produced as a synthetic alkali aluminosilicate material by activating amorphous aluminosilicates with alkalis [33][34].

Following a string of fire tragedies in Europe, this kind of substance was first created as an organic thermosetting polymer's fire-resistant replacement. It has been used in a variety of sectors as a thermal protective material, including protecting wooden constructions from heat. Afterwards, studies have concentrated on the suitability of these materials as building materials due to the excellent performance characteristics of geopolymers created due to the fly ash's alkali activation [35].

Even though the term "geopolymer" is typically used to explain the crystalline reaction products obtained from the reaction of alkalis with solid aluminosilicates, geopolymeric gels and composites are frequently used [36]; "alkali activated cement" [37], "geocement" [38], "low temperature aluminosilicate glass" [39], "inorganic polymer concrete" [40], "alkali bonded ceramic" [41], and "hydroceramics" [42]. A subset of the alkali-activated binders class known as geopolymers is made up of substances created by the activation of metallurgical slags with alkali, silicate, carbonate, or sulfate, which results in a substance that is mostly known as calcium silicate hydrate [43]. The bonding phase of a geopolymer is an alkali aluminosilicate gel with aluminium and silica attached to a three-dimensional tetrahedral gel structure with reasonably high resistance to water dissolution [44], [45]

Blast furnace slags, calcined clays, and fly ashes are the three most usual types of raw materials used as alkali activated materials in geopolymerization. As a supplementary material in systems based on Portland cement, each of them has undergone extensive research [46]–[48]. Figure 2.9 presents the typical SiO_2, Al_2O_3, and CaO concentrations of the three primary geopolymer binders (metakaolin, fly ash, and blast furnace slag).

Despite not being utilized as frequently as the other three, silica fume is used in geopolymeric systems and its content is also given in this Figure 2.9.

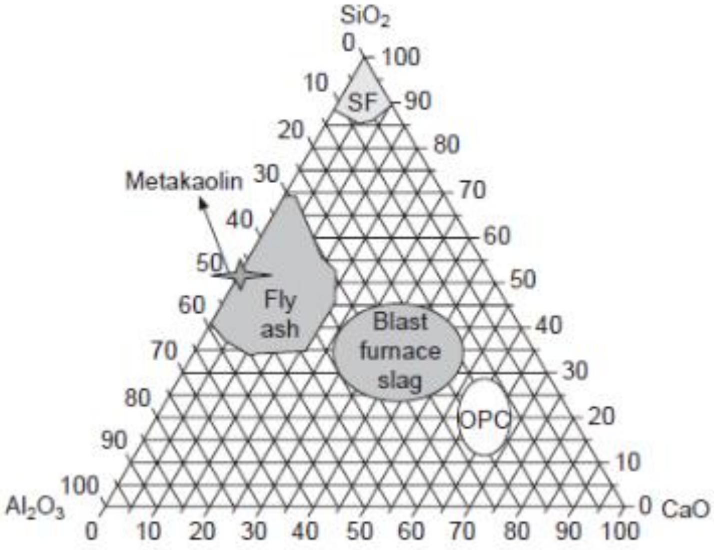


Figure 2. 9. Chemical composition of fly ash, metakaolin, blast furnace slag, portland cement, and silica fume

Geopolymers can have a variety of characteristics and strengths, including low shrinkage, high compressive strength, rapid or delayed curing (setting), acid resistance, fire resistance, and low thermal conductivity, based on the choice of materials and processing circumstances. With a suitable blend and processing design, geopolymers provide a flexible option to optimize different qualities and/or save costs for a particular application.

2.5.1. Utilization of CDW in Geopolymer Production

The increase in the amount of construction demolition waste has caused serious problems both globally and locally. In this context, construction demolition waste management is one of the most important environmental issues in the construction sector and it aims to reduce negative environmental impacts and minimize waste.

Thus, it has become more and more important in recent years to design and produce innovative industrial products using recycled materials. Geopolymer binders belonging to the group of alkali active materials are such new industrial products. Numerous studies have been undertaken recently to study the possibilities of utilizing industrial waste as a source of raw materials for the manufacturing of geopolymers. [49].

Robayo-Salazar et al. [50] investigated geopolymer composed of red clay brick (RCB) waste, concrete waste (CW) and glass waste (GW) activated with sodium hydroxide and liquid sodium silicate under different curing conditions. By controlling the production of alkaline activators by curing at ambient temperature, they demonstrated that it is possible to use RCB or CW as the primary elements of the geopolymer binder with strong mechanical properties.

Yang et al. [51] created a geopolymer concrete with recycled concrete aggregate (RCA) (40%) and natural aggregates mixtures. Metakaolin (5-25%) was added to the CW mixture powder to create the geopolymeric matrix. After 28 days of room-temperature curing, the resulting geopolymeric concrete had a compressive strength of approximately 40 MPa.

Allahverdi and Kani [52] used a mixture of Na_2O at 8% of the binder amount and Na_2SiO_3 with a silica modulus of 1.4 to activate a mixture of 60% concrete waste and 40% brick waste and achieved compressive strengths of 50 MPa as an outcome of their research.

Ahmari et al.[53] made a combination of 50% concrete waste and 50% fly ash, added sodium silicate and sodium hydroxide as alkaline activators, and obtained maximum strength results of 35 MPa.

Komnitsas and Zaharaki [54] stated that industrial wastes and construction demolition wastes such as fly ash, blast furnace slag, red mud are suitable for geopolymerization and it is possible to obtain compressive strengths up to 76 MPa with the use of appropriate alkali.

Yıldırım et al. [55] studied alkali-active binders developed by fully utilizing mixed CDW-based masonry materials as aluminosilicate binders. Waste roof tile (RT), red clay brick (RCB) and hollow brick (HB) were used in the matrix. This study’s key result is that it is possible to create waste using only a straightforward combination of these units in various ratios. With these mixes, compressive strength of up to 80 MPa was achieved.

With these results, it is clear that the use of construction demolition waste in geopolymer synthesis is currently of great interest in the management of such wastes. Especially thanks to these studies, the environmental impact of these wastes can be reduced by assessing these wastes. Furthermore, geopolymers are alternative binding agents to Portland cement with the potential to reduce CO_2 emissions and energy consumption.

2.5.2. Life Cycle Assessment Approach of CDW-Based Geopolymers

Many life cycle studies have been conducted on geopolymers created using construction demolition waste.

Habert et al. [56] conducted a detailed environmental assessment of geopolymer concrete production using the life cycle assessment methodology. This study also shows that geopolymer concrete production has a higher environmental impact than impact categories other than global warming, due to the heavy effects of sodium silicate solution production. However, it appears that geopolymer concrete has a similar impact on global warming to ordinary concrete when the production of fly ash and granulated blast furnace slag is taken into consideration during the life cycle evaluation.

Weil et al. [57] studied life cycle analysis of geopolymer and in addition to addressing the waste issue, the utilization of waste in geopolymer production might result in a decrease in the use of basic raw materials.

Salas et al. [58] stated that the production of sodium hydroxide, which is also used as a primary raw material in the production of sodium silicate, is the most important life cycle process for the environmental performance of geopolymer concrete. The study revealed that geopolymer concrete has a 64% lower Global Warming Potential (GWP) than conventional concrete..

Bajpai et al.[59] evaluated the environmental effects of geopolymer containing fly ash and silica fume. Life cycle assessment (LCA) of three geopolymer concrete mixes: fly ash geopolymer (with hydroxide and silicate of sodium); fly ash–silica fume blend geopolymer (with hydroxide and silicate of sodium); and fly ash–silica fume blend geopolymer (with sodium hydroxide) was carried out by comparing the environmental impacts with conventional cement concrete. Geopolymer concretes have lower global warming potential than conventional cement concretes. The lowest environmental impacts are due to fly ash-silica fume geopolymer concrete without sodium silicate as alkali activator. The use of fly ash-based silica fume geopolymer concrete resulted in cost savings of 10.87% to 17.77% per unit volume of this concrete.

Imtiaz et al. [60] analyzed the life cycle assessment of OPC concrete, recycled aggregate concrete, geopolymer concrete and recycled aggregate geopolymer concrete. According to the study, using geopolymer concrete instead of OPC concrete could reduce global warming potential by up to 53.7 percent. In addition to climate change, the use of geopolymer concrete means a reduction in acidification potential and photochemical oxidant formation in the impact categories. However, geopolymer concrete has increased the potential impacts of seawater ecotoxicity, freshwater water ecotoxicity, human toxicity, eutrophication potential, ozone depletion potential and terrestrial water ecotoxicity. The inclusion of alkaline activators such as sodium hydroxide and sodium silicate enhanced these effects.

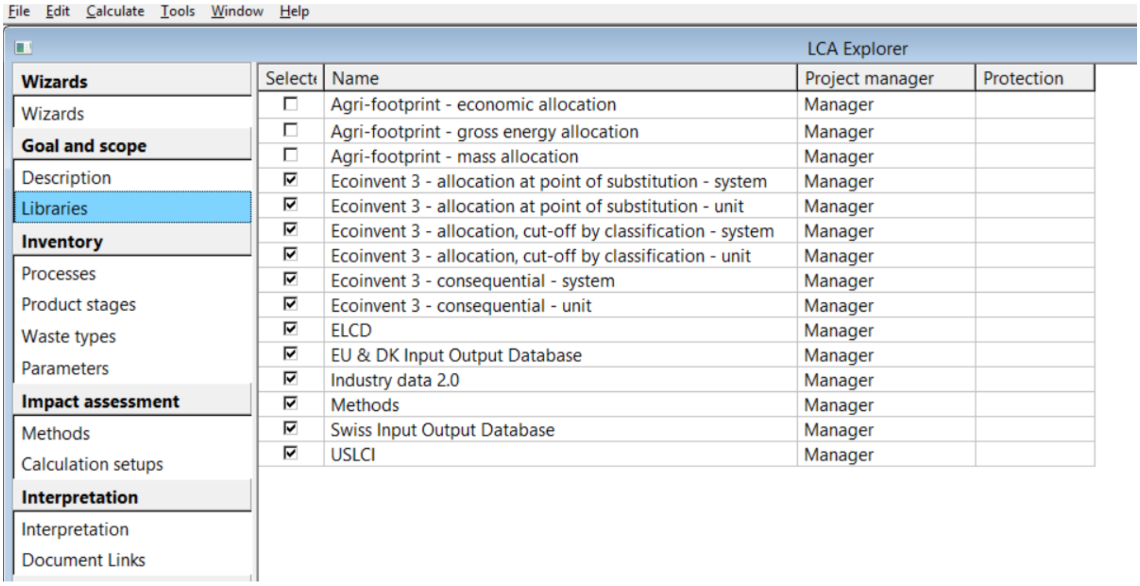
Colangelo et al. [61] investigated the environmental impact of concrete made with recycled aggregates and geopolymers. The study aims to propose a comparative LCA for concrete with recycled aggregates. SimaPro software was used to implement the life cycle assessment approach. A cradle-to-grave analysis was performed and the findings were analyzed based on Ecoinvent 3.3 and Impact 2002+ databases. The results showed that the environmentally optimal choice is concrete with 25% recycled aggregates. The production of sodium silicate and sodium hydroxide has a significant environmental impact, but geopolymer blends could be a viable option to limit global warming.

3. MATERIALS AND METHODOLOGY

3.1. LCA Software Used – Simapro 9.0.0.35

SimaPro version 9.0.0.35 was used as LCA software to analyze the environmental impacts of geopolymer mixtures according to ISO 14040/14044 requirements. Launched in 1990, SimaPro is an LCA software tool that collects, examines, and assesses sustainability information for products and services, developed by PRé Consultants and implemented in more than 80 countries [62].

SimaPro's background data is organized so that users may easily identify information that can be relevant to LCA. Libraries hold this information. SimaPro supports many LCI databases such as Ecoinvent, Agri-footprint, ELCD, USLCI, Swiss Input Output Database, which offer a huge quantity of information[63]. Figure 3.1 illustrates the selected databases from the SimaPro 9.0.0.35 library. All libraries were chosen, as shown in the figure, except for Agri-footprint, which is unique to agriculture. Despite all these choices, in this study the Ecoinvent 3 database was used since it occupies a larger area in the construction processes.



Select	Name	Project manager	Protection
☐	Agri-footprint - economic allocation	Manager	
☐	Agri-footprint - gross energy allocation	Manager	
☐	Agri-footprint - mass allocation	Manager	
☑	Ecoinvent 3 - allocation at point of substitution - system	Manager	
☑	Ecoinvent 3 - allocation at point of substitution - unit	Manager	
☑	Ecoinvent 3 - allocation, cut-off by classification - system	Manager	
☑	Ecoinvent 3 - allocation, cut-off by classification - unit	Manager	
☑	Ecoinvent 3 - consequential - system	Manager	
☑	Ecoinvent 3 - consequential - unit	Manager	
☑	ELCD	Manager	
☑	EU & DK Input Output Database	Manager	
☑	Industry data 2.0	Manager	
☑	Methods	Manager	
☑	Swiss Input Output Database	Manager	
☑	USLCI	Manager	

Figure 3. 1. Selected databases from SimaPro 9.0.0.35

The Ecoinvent association is a non-profit group that was established in the ETH (Swiss Federal Institute of Technology) domain in the late 1990s with the goal of creating a standard, forward-looking, uniform, and transparent database for Life Cycle Inventory (LCI) data that would be utilized in life cycle-based evaluations. The Ecoinvent project evolved into the Ecoinvent Association over the last 25 years, becoming a globally recognized partner in the administration of data for environmental evaluations as well as the publisher of the Ecoinvent database. Ecoinvent 1.01 was made available in 2003. The database has undergone several revisions, and Ecoinvent 3.0 was launched in 2013. Ecoinvent offers different datasets in many forms and invites data contributions from all around the world. The database of Ecoinvent has a wide range of processes. Numerous additional LCA programs access Ecoinvent or use its data, demonstrating the popularity of Ecoinvent [64].

The Ecoinvent has a specific location for each activity. Geographical locations are reported using globally recognized acronyms. For instance, the abbreviation of Switzerland is CH, Czechia is CZ, China is CN, Europe is RER, the United States is US, India is IN, Australia is AU, Global is GLO and Rest of World is RoW [65]. Because there are no available Turkish datasets, the RoW geography was used while entering the inputs into Simapro. RoW represents the global minus any local geographies for which a process is stored in the database. Assume that an activity is accessible in each of the following four regions: China (CN), India (IN), and Global (GLO). During the linking process, a replica of the global dataset is built as the RoW production. The production volume (PV) of the RoW activity is determined by subtracting the production volume of regional activities from the global volume: PV RoW = PV GLO – PV US – PV IN – PV CN [65]. Thus, RoW data was chosen in this study. Simapro also offers a variety of methods for evaluating impact assessment results. These methods are shown in Table 3.1.

Table 3. 1. LCIA Methods of SimaPro 9.0.0.35

Methods	
European	CML-IA baseline
	CML-IA non-baseline
	Ecological Scarcity 2013
	EDIP 2003
	EF Method
	Environmental Prices
	EPD (2018)
	EPS 2015d
	ILCD 2011 Midpoint+
	IMPACT 2002+
Global	ReCiPe 2016 (Endpoint and Midpoint)
North American	BEES+
	TRACI 2.1
Single Issue	Cumulative Energy Demand
	Ecosystem Damage Potential
	Greenhouse Gas Protocol
	IPCC 2013 GWP (100a and 20a)
	Selected LCI results
	USEtox 2
Superseded	BEES
	CML 1992
	CML 2 baseline 2000
	CML 2001
	Eco-indicator 95
	Eco-indicator 99
	Ecological footprint
	EDIP/UMIP 97

In this study, the LCIA method IMPACT 2002+ was utilized as it is recommended by many authors such as Bare et al.[66]; Jolliet et al.[67] and because this method is included in the European category.

This method provides a practical way to execute a combined midpoint/damage strategy that connects 14 midpoint categories and various kinds of LCI data to four damage categories as shown in Figure 3.2.

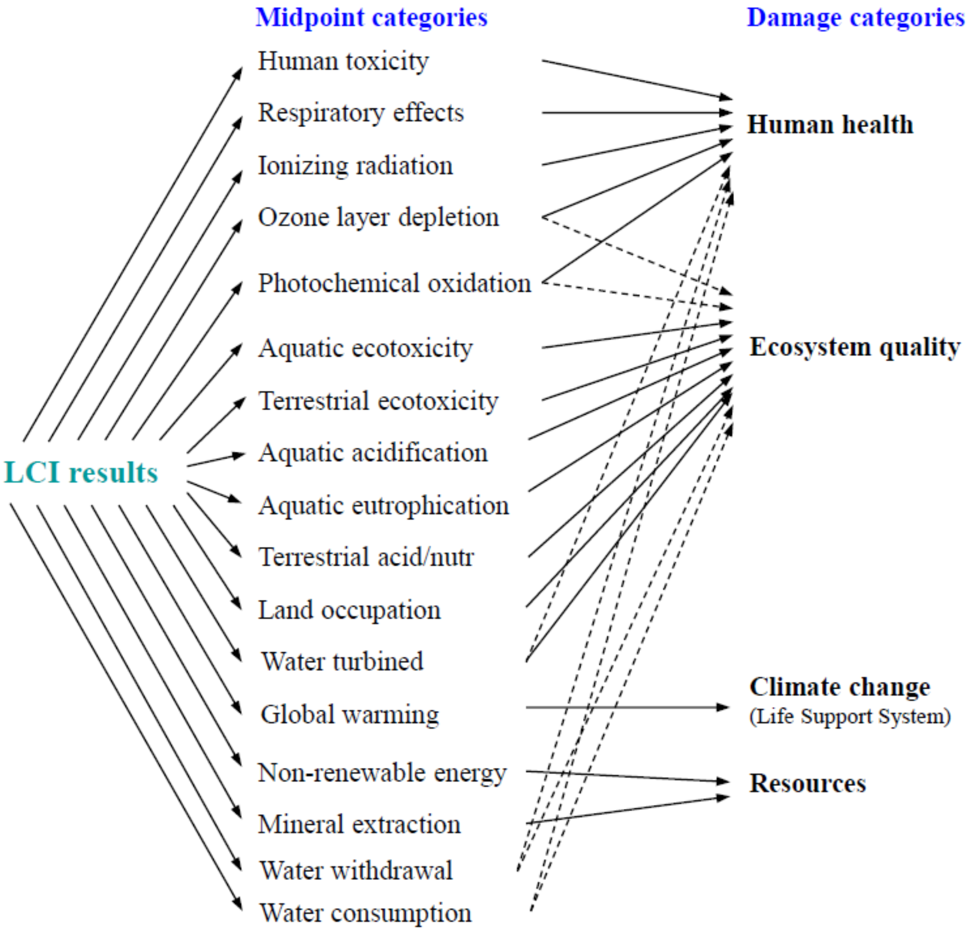


Figure 3. 2. The IMPACT 2002+ framework's overall scheme which connect LCI results via the midpoint categories to damage categories [67]

The damage categories used by IMPACT 2002+ are:

- **Human Health.** Human toxicity (carcinogenic and non-carcinogenic effects), respiratory effects (inorganics and organics), ionizing radiation, and ozone layer depletion are all factors that affect human health damages. Human health impact is expressed in “DALY”. The term "Disability-Adjusted Life Years" (DALY) describes the severity of a disease by taking into account both mortality (years of life lost due to premature death) and morbidity (the time of life with lower quality due to an illness, e.g., at hospital) [68].

- **Ecosystem Quality.** The ecosystem quality damage category is the sum of the midpoint categories aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutr, land occupation, and aquatic acidification, aquatic eutrophication and water turbines. Ecosystem quality impact is expressed in "PDF.m^2.y". PDF·m^2·y (Potentially Disappeared Fraction of species over a certain amount of m^2 during a certain amount of year) is the unit used to measure the impacts on ecosystems and represents the fraction of species that disappeared on 1 m^2 of earth surface's during one year [68].
- **Climate Change.** The midpoint category "global warming" is the same as the damage category climate change. The impact of climate change is measured in "kg CO_2-eq". The climate change damage factor of 9'950 kg CO_2-eq/point is largely dominated by CO_2 emissions [68]
- **Resources.** The midpoint categories non-renewable energy consumption and mineral extraction are combined to form the damage category Resources. "MJ" is the expression for this damage category. Non-renewable energy consumption accounts for the majority of the 152'000 MJ/point resources damage factor [68].

The Ecoinvent v3 database distinguishes between market activities, transforming activities, processing activities, import and export activities, and production and supply mixtures when describing human activity processes. One of the primary categories of activities is transformation and market processes. According to Ecoinvent v3, approximately three thousand markets and six thousand transformational activities are both present. [69]. These market processes involve inputs from manufacturing in several or a single country, in addition to inputs from transportation processes. Inputs from all connected emissions and resource extractions with the exception of transport processes, transformation processes include all the inputs needed to create a good or service [70]. In this study, transformation processes are selected.

The Ecoinvent libraries in SimaPro software are split into unit and system processes.

- Unit process: The smallest component of the life cycle inventory analysis for which input, and output data are quantified is a unit process [1]. Unit processes don't explain an entire life cycle; rather, they describe a specific phase of it. All unit processes are recorded to define their scope in a database like Ecoinvent [71].

- System process: The collection and measurement of inputs and outputs for a product's life cycle results in system processes [1]. In other words, a system process is an aggregate of all environmental flows brought on by the provision of the reference product, from cradle to gate. They are sometimes referred to as an aggregated life cycle inventory (LCI) because of this [71].

A system process only has outputs to the technosphere and inputs to the biosphere per reference product, or each individual output. In contrast, a unit process simply includes references to input from other processes as well as emissions and resource inputs from a single process step. Therefore, the unit process was selected in order to observe all resource inputs in a process [71].

3.2. Materials

Concrete waste, glass waste, roof tile, hollow brick, red clay brick, and other industrial wastes, including blast furnace slag, silica fume, and fly ash, were used as binders throughout the thesis investigations. Sodium hydroxide (NaOH) and calcium hydroxide ($Ca(OH)_2$) were utilized as activators to activate the binder for geopolymerization. Recycled aggregates from CDW were used to create mortar phase mixes.

This part of the thesis provides a thorough explanation of the experiments, mixture development, and preparation utilized in the study.

3.2.1. CDW - Based Binders

The waste materials from the demolished buildings in the province of Ankara were utilized in the thesis studies. They were divided into the following five groups: HB, RCB, RT, GW, and CW. Bricks and roof tile, which are clay-based materials, were extracted from the building's roof and wall parts during its demolition. Due to its high silica concentration and amorphous form, glass waste was utilized as one of the binders with CDW. Additionally, concrete waste was used as a binder and was sourced from the building's structural components. Within the parameters of the thesis, mortar mixes were created using RCA with the largest aggregate size of 2 mm and HB, RCB, RT, GW, and CW as binders.

To produce an appropriate particle size distribution, several processes were used for the materials acquired from demolition. Each of the demolition waste materials was used for this purpose was crushed in a jaw crusher to a size of around 0.5 cm and processed in a ball mill to roughly cement fineness. In Figure 3.3, the materials are represented in their initial, crushed, and ground states. Table 3.2 indicates the chemical composition of the CDW-based binder components as determined by X-ray fluorescence (XRF) analysis.

Table 3. 2. Chemical compositions and specific gravities of CDW-based binder materials

%	**HB**	**RCB**	**RT**	**GW**	**CW**
SiO_2	39.7	41.7	42.6	66.5	31.6
Al_2O_3	13.8	17.3	15.0	0.9	4.8
Fe_2O_3	11.8	11.3	11.6	0.3	3.5
CaO	11.6	7.7	10.7	10.0	31.3
Na_2O	1.5	1.2	1.6	13.6	5.1
MgO	6.5	6.5	6.3	3.9	0.9
SO_3	3.4	1.4	0.7	0.2	0.5
K_2O	1.6	2.7	1.6	0.2	0.7
TiO_2	1.7	1.6	1.8	0.1	0.2
P_2O_5	0.3	0.3	0.3	0.0	0.1
Cr_2O_3	0.1	0.1	0.1	0.0	0.1
Mn_2O_3	0.2	0.2	0.2	0.0	0.1
Specific Gravity (g/cm^3)	2.84	2.79	2.8	2.5	2.32

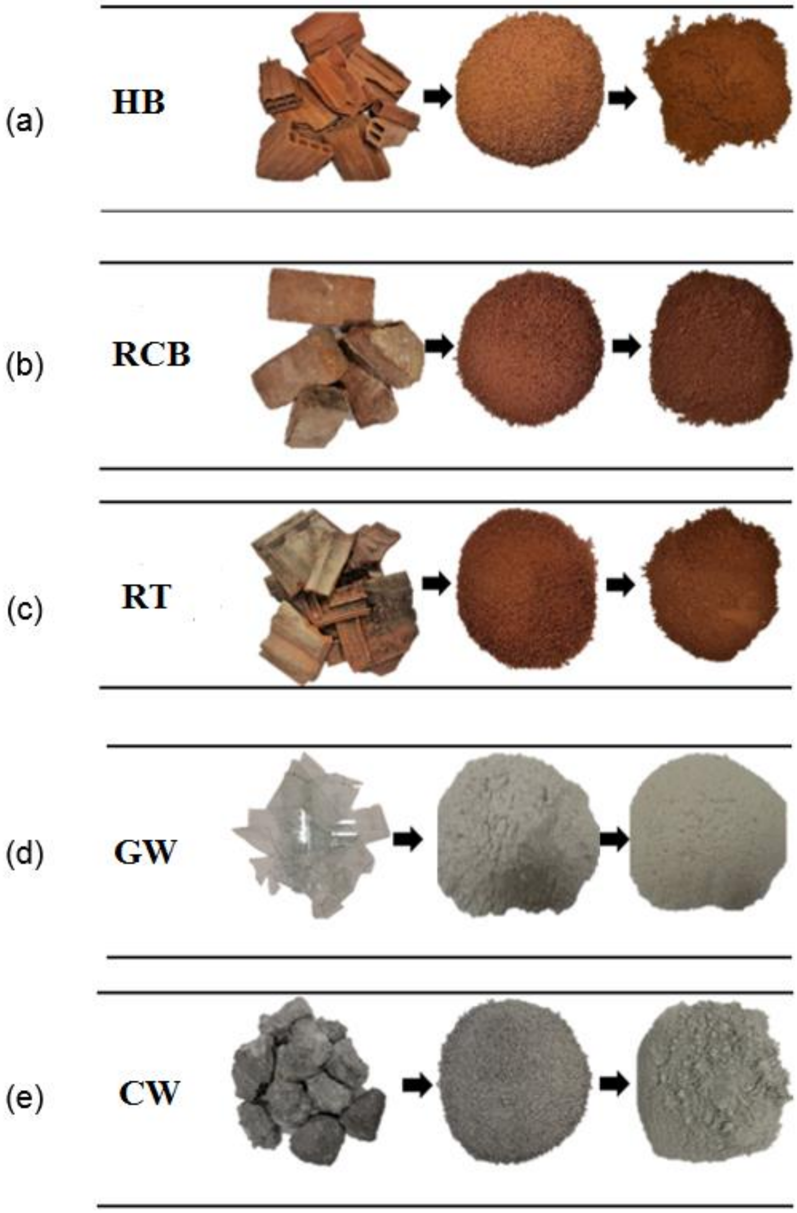


Figure 3. 3. CDW materials; (a) HB, (b) RCB, (c) RT, (d) GW and (e) CW (initial, crushed, ground state, respectively)

These precursors had similar ratios of the main oxides, although GW and CW's chemical composition was different from that of the other CDW-based precursors. GW was a soda-lime-based substance that was extracted from window glasses and had high SiO_2 (66.5%), Na_2O (13.6%), and CaO (10.0%) concentrations. SiO_2 concentration in CW was highest (31.6%), followed by CaO (31.3%) and MgO (5.1%)

3.2.2. Supplementary Cementitious Materials (SCM)

Within the scope of the thesis, the utilization of some supplementary cementitious materials to enhance the strength of CDW based binders was also considered and it was decided to use Ground Granulated Blast Furnace Slag (GGBFS), Silica Fume (SF) and Fly Ash (FA) when necessary. It is anticipated that combinations made entirely of CDW-based materials will have improved mechanical characteristics because of the high calcium and silicon compositions of GGBFS, FA, and SF. The geopolymeric system is intended to utilize these admixtures to recover waste by-product materials. Table 3.3 lists the chemical properties of the supplementary cementitious materials.

Table 3. 3. Chemical composition and specific gravities of the SCMs

%	Blast Furnace Slag	Fly Ash	Silica Fume
SiO_2	32.10	60.07	85.0
Al_2O_3	11.20	21.35	0.0
Fe_2O_3	0.62	7.41	0.0
CaO	36.10	0.99	1.0
Na_2O	0.31	0.99	0.0
MgO	5.64	1.82	0.0
SO_3	1.21	0.22	2.0
K_2O	0.83	2.91	0.0
TiO_2	1.07	0.94	0.0
P_2O_5	0.01	0.15	0.0
Cr_2O_3	0.00	0.03	0.0
Mn_2O_3	1.48	0.08	0.0
Specific Gravity(g/cm^3)	2.85	2.4	2.2

The following subsections provide more information on these supplementary cementitious materials.

3.2.2.1. Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS is an iron processing by-product obtained by the physical separation of cast iron and other oxides in a blast furnace. 90% of the slag's primary ingredients are composed of calcium oxide (CaO), silicon oxide (SiO_2), aluminum oxide (Al_2O_3), and magnesium oxide (MgO). Depending on the raw materials and industrial technique used in the manufacture of iron, it has different physical and chemical characteristics [72]. The construction industry uses GGBFS as an additional cement material because of its high calcium silicate concentration, amorphous structure, and pozzolanic qualities [73].
GGBFS, an industrial waste from the Hatay-Iskenderun iron and steel plant in Turkey, has been included in the mix design when deemed necessary as it can improve some of the engineering properties of geopolymer mixes and enhance to overcome the weaknesses of mixes containing 100% CDW-based precursors.

GGBFS also offers significant benefits in regard to energy use and emissions. The percentage of blast furnace slag utilized to make cement and/or concrete has increased to above 90% as of 2018 [74]. As a result, switching from GGBFS to cement offers the chance for lower energy use, landfill waste, and GHG emissions particularly CO2 emissions, by up to 22% [75].

Because it consumes less energy to produce and emits less CO2 than PC, alkaline activated slag is frequently used as a binder in place of PC [76]. About 1300 Mega Joule energy is needed to produce one ton slag, yet only 0.07 tons of CO2 are produced [77]. A ton of CO_2 is released into the atmosphere and 5000 MJ of energy is needed to produce an equivalent quantity of PC. Additionally, it has been observed that alkaline activated slag composites improve the mechanical and durability characteristics of concrete [78].

3.2.2.2. Fly Ash (FA)

FA, a byproduct of coal combustion in thermal power plants, consisting of clay, sand and organic matter residues in the coal leaving the furnace stack. Fly ash is divided into three categories by the American Society for Testing and Materials ("ASTM"): Class C, Class F, and Class N. The burning of lignite and/or subbituminous coal produces class C fly ash. Silica (SiO_2) and alumina (Al_2O_3) compose the majority of Class F fly ash, whereas calcium oxide (CaO) and magnesium oxide (MgO) form the majority of Class C fly ash. FAs, which are most frequently utilized in the creation of geopolymers (Class F FA according to ASTM C618), are poorer in Calcium (Ca). In this study, FA of the F class was utilized and obtained from İSKEN Sugözü Thermal Power Plant, Adana.

Typically, there is heterogeneity in the global FA particle size distribution. 50% of the particles, on average, have an equivalent diameter between 30 and 40 mm. The density of FA is between 2.2 and 2.8 g/cm3, and the specific surface ranges from 2500 to 5000 cm2/g [79].

Utilizing fly ash offers both significant environmental and financial advantages. Fly ash replaces cement and decreases CO2 emissions by one ton per ton of cement, reducing greenhouse gas emissions by 15% [75], [80]. Using FA as a cementitious substance not only lowers greenhouse gas emissions but also decreases the requirement for disposal. In Australia, 9.4 Mt of wasted fly ash was landfilled in 2011 [80]. Furthermore, China generated around 700 Mt of fly ash in 2014 [81].

3.2.2.3. Silica Fume (SF)

In this study, silica fume was received from Antalya-Etibank Ferro-Krom. In the process of producing silicon and/or ferro-silicon, silica fume is produced as a byproduct. In electric arc furnaces operating at temperatures above 2000 °C, it is formed of micro silica dioxide (SiO_2). Due to its pozzolanic properties, silica fume is utilized as a cementitious ingredient to create high-strength concrete [82], [83]. Due to its high fineness and silica concentration (more than 90%), SF is used in concrete to improve its qualities, such as compressive and bond strength and corrosion resistance [84].

The effect of SFs on geopolymers has been investigated in various studies. Okoye et al. [85], specifically studied different SF amounts on geopolymer concrete with FA that was activated with NaOH and Na_2SiO_3 and fired at 100°C. According to the findings, SF added to geopolymer concretes strengthened their compressive strength. According to Thokchom et al. [86], including silica fume up to 5% in geopolymer mortar greatly enhanced the geopolymer's characteristics when exposed to a magnesium sulfate solution.

3.2.3. Alkaline Activators

As a consequence of research conducted in several projects and a literature review, two forms of alkaline activators, NaOH and $Ca(OH)_2$, were utilized within the thesis context. Sodium hydroxide (NaOH) and calcium hydroxide ($Ca(OH)_2$) were purchased from local suppliers in Ankara.

3.2.3.1. Sodium Hydroxide (NaOH)

NaOH, which is also widely used in many sub-branches of different industries, is a material generally used in the chemical industry. Both solid and liquid forms of sodium hydroxide (NaOH) can be made by electrolyzing sodium chloride (NaCl) aqueous solutions. Although their chemical composition is similar, the solid part might take the shape of flakes, beads, or sticks. The ionization of NaOH yields (Na+) and (OH^-) ions in an aqueous solution during the extremely exothermic dissolving process with water. The dissolution and condensation processes of the Si and Al minerals present in the precursors as aluminosilicate sources are accelerated due to the rise in (OH)- ion concentration brought on by the dissociation of NaOH, which elevates the pH of the system.

The material selected for use in alkaline activation procedures is NaOH given that it is of a sufficient standard, is readily available, and is reasonably priced. The NaOH used in this study is in the form of white flakes and has a density of 2.13 g/m3.

3.2.3.2. Calcium Hydroxide ($Ca(OH)_2$)

$Ca(OH)_2$, known as hydrated lime, is produced by the interaction of quicklime with water. When dissolved in the medium, due to its chemical composition, it makes the system more alkaline. For this reason, it is a commonly used activator in geopolymerization systems. It can help accelerate processes and cause the creation of a hydration product [calcium silicate hydrate (C-S-H) or calcium aluminium silicate hydrate (C-A-S-H)], which results in the formation of a denser matrix in the system because it adds an additional source of "Ca" to the system [87]. The creation of additional C-S-H and C-A-S-H structures will result in a denser structure, which is expected to improve the matrix's mechanical characteristics when $Ca(OH)_2$ is added.

To activate geopolymer systems, calcium oxide can be applied either directly as a powder or combined with water. Solid phase $Ca(OH)_2$ with a molecular weight of 74.09 g/mol and 87% purity, and specific gravity 2.24 g/cm3 was used in this study.

3.3. Geopolymer Mortar Mixture Development

The mixture preparation, experiments and development that were utilized throughout the thesis study are thoroughly discussed in this section of the thesis.

For the modified solution to be ready for the precursor's activation, flakes of NaOH were first added to the water in a certain ratio. The prepared solution's temperature began to quickly rise after the reaction started since the NaOH dissolving process is an exothermic reaction. The produced NaOH solutions were kept in glass bottles and allowed to come to room temperature before being used. The solution was kept in a closed bottle to prevent water evaporation as the system's water/binder ratio and molarity will change if the water evaporates at this point. The ratios and amounts of the binding components, activators, and aggregates utilized in the mixes were set up in accordance with the literature and the preparatory research conducted in the thesis advisor's previous and continuing projects. To ensure uniform distribution of the powder materials, all powder components, including construction demolition waste (HB, RCB, RT, CW, and GW), mineral additives (if any, as specified in the mixture's recipe) (GGBFS, FA, and SF), and $Ca(OH)_2$ were added to the mixer and stirred at low speed for one minute. The mixer was operating at low speed when it was progressively added NaOH solution. To ensure that the sodium hydroxide was evenly distributed throughout each powdered substance, the mixture was mixed at low speed for an additional minute. After the material had been mixed in sixty seconds at medium speed, after that, the paste was placed into 50x50x50 mm cubic molds to evaluate its compressive strength. 50 x 50 x 50 mm cubic specimens were subjected to compressive strength testing at 7,14 and 28 days in line with ASTM C109 standard to ascertain the mechanical characteristics.

In this thesis study, two types of geopolymer mortar mixtures were investigated: 100% CDW and 80% CDW- 5% FA- 5% GGBFS- 10% SF. The nomenclature for these 2 mixtures will be CDW100 and CDW80SCM20, respectively.

100% CDW-based geopolymer mortar mix (CDW100): Only CDW-based materials (HB, RCB, RT, GW, and CW) were used in the designing of the mortar mixes, and 10% of the total binder by weight in these mixtures was made up of glass waste and 10% of it derived from CW. In the remaining 20%, RCB, HB and RT were distributed equally. In the mixture, the w/b (water/binder) and s/b (sand/binder) ratios were 0.33 and 0.35, respectively. Alkaline activators NaOH and $Ca(OH)_2$ were utilized in pairs. $Ca(OH)_2$ activator was added at a rate of as 4% by weight of the binder, while the system was supplemented with 10 M NaOH solution. Due to the work and experience of the thesis advisor in previous projects, it was seen that these molarities and ratios would give the best available results in geopolymer mixtures and it was decided to use them.

80% CDW-based and 20% different mineral admixtures geopolymer mortar mix (CDW80SCM20): A combination utilizing several mineral admixtures, such as GGBFS, FA, and SF, was tested in order to give the proper consistency for the mortar phase, learn the impacts of various mineral admixtures on strength and consistency, and achieve suitable compressive strength values. In this mixture, 80% of the binder material by weight is composed of CDW materials (10% concrete waste, 10% glass waste, 60% equal weight hollow brick, red clay brick and roof tile) and the remaining 20% is composed of mineral admixtures (5% GGBFS + 10% SF + 5% FA) in different usage ratios. The w/b ratio in these mixtures was 0.33 and alkaline activators were sodium hydroxide and calcium hydroxide. NaOH activator was used at a concentration of 10M and $Ca(OH)_2$ activator was used at 8% by weight of the binder. Table 3.4 displays the results of the compressive strength tests performed on these mortar samples.

Table 3. 4. Geopolymer mortar samples and their compressive strength values

				Compressive Strength (MPa)		
Sample	NaOH (M)	Ca(OH) (%)	Mineral Addition	7 Day	14 Day	28 Day
CDW100	10	4	-	9.2	12.3	15.2

CDW80 SCM20	10	8	5%GGBFS +10%SF +5%FA	23.2	24.5	34.8

3.4. LCA Methodology

3.4.1. Goal and Scope Definition

The aim of the study is to evaluate and analyze the environmental impacts of CDW-based geopolymer mortars using an LCA approach. That is, to interpret the integrated approach that includes the use of CDW, avoiding the cement used in concrete production, in order to obtain a sustainable mix, within the framework of LCA. The results of the previous research studies were out to comprehend how the material behaved on mortar mixes as well as the knowledge obtained from the literature was taken into account while designing the mortar mixes covered by the thesis. Two types of geopolymer mortars were created in this way, with ratios of 100% CDW and 80% CDW-5% Slag-5% Fly Ash-10% Silica Fume, respectively.

The present LCA study aimed to highlight the environmental impacts of 100% CDW-based geopolymer mortar and geopolymer mortars with CDW and mineral additives within the life cycle framework, and to emphasize the importance of the use of construction demolition waste. For this purpose, a readily available mix with a strength of 35 MPa was selected from Simapro Ecoinvent database to demonstrate and compare the pros and cons of geopolymer against traditional cement-based systems. The strength of 35 MPa was chosen so that the cementitious mortar system being compared would have approximately the same compressive strength as the geopolymer with mineral additives. Selecting mortar mixtures with the same compressive strength, it was aimed to indicate which one is more environmentally friendly.

The functional unit and system boundary determined within the scope are as follows;

- Functional unit: In this study, one cubic meter was used as the functional unit for geopolymer binders CDW80SCM20 and CDW100, which have specific weights of around 1972,8 kg/m^3 and 1994,6 kg/m^3, respectively.

- System boundary: The system boundary is set as “cradle to gate”. It is the process from the beginning, or the initial source of the raw materials utilized in production, through product production and delivery to the user, or from the factory gate to the consumer. A system boundary has been established for the production, transportation, processing and mixing of materials. Starting with the production of materials, the system continued with the delivery of all inputs to the laboratory, including CDW components collected from construction demolition sites. For this phase, vehicle types, capacities, and distance transported were taken into account. Then, from the materials brought in, the precursors made of concrete and bricks went through the crushing and grinding stages. The electrical energy consumed by the crusher, ball mill and sieving machine and the duration of their usage was taken into account. Sodium hydroxide, calcium hydroxide and water were added to the system during the mixing stage to create the alkaline activator. Finally, the system boundary was completed by calculating the energy consumption during the mixing phase. The system boundary for the geopolymer mortar is presented in Figure 3.4.

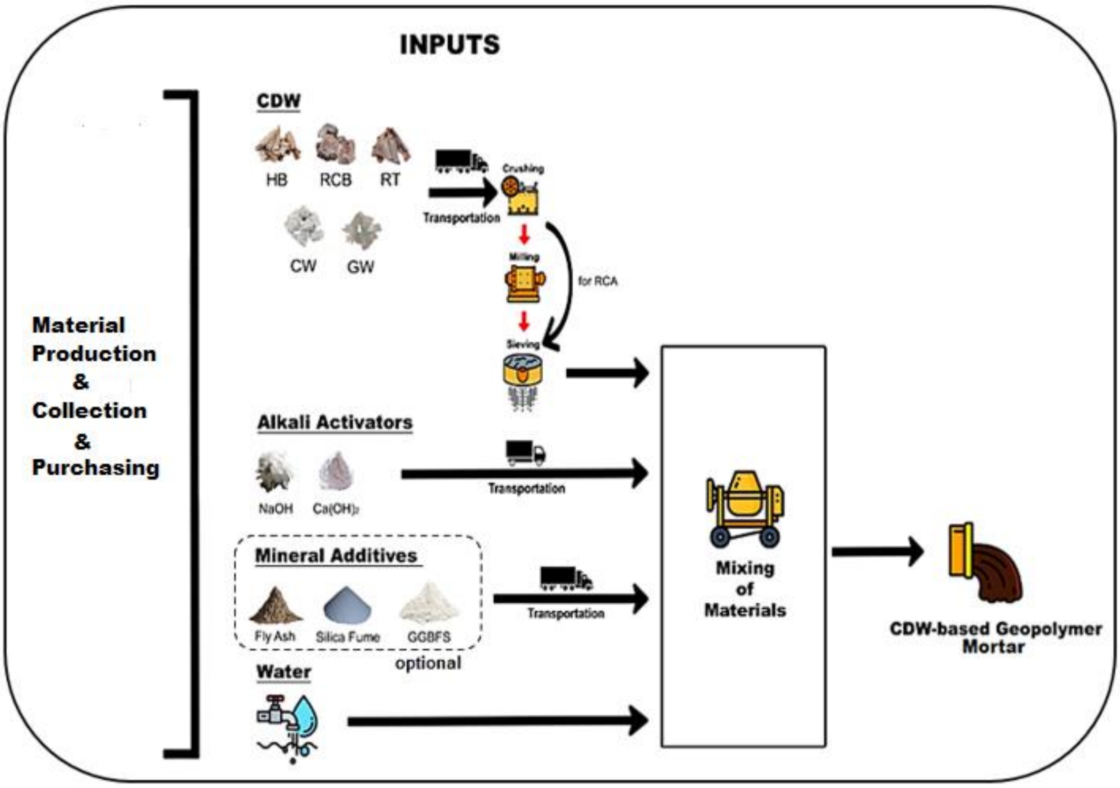


Figure 3. 4. System boundary of geopolymer mortar

3.4.2. Life Cycle Inventory (LCI)

In the LCI step, all inputs collected for geopolymer mixtures are digitized and presented together with all relevant inputs. In this section, the supply of materials, their transportation, passing them through the necessary devices in the laboratory to be ready for use, the lifetime of the devices and the electrical energy consumed are given in detail. The first step is the procurement/purchase of materials from different locations to obtain the mixtures. The CDW components of the mixes consisting of hollow bricks (HB), red clay bricks (RCB), roof tiles (RT), concrete waste (CW) and glass waste (GW) were collected from different demolition sites in Ankara, Turkey. The industrial by-products of ground blast furnace slag (GGBFS), Class F fly ash (FA) and silica fume (SF) were purchased from Iskenderun Demir Çelik A.Ş., ISKEN Sugözü Thermal Power Plant and Antalya-Etibank Ferro-Krom, respectively. Sodium hydroxide (NaOH) and calcium hydroxide ($Ca(OH)_2$) as alkaline activators were purchased from local suppliers. Transportation distances were determined using Google Maps. Different types of freight were computed in tkm based on the quantity of each material. These materials, transportation information and distances are shown in Table 3.5.

Table 3. 5. Transportation information of CDW-based geopolymer mortars

Materials	**Departure**	**Destination**	**Type of transport**	**Vehicle size class (metric ton)**	**Distance from supplier (km)**	**Tkm,freight**	
						CDW80 SCM20	100CDW
CDW	Ankara, Turkey	Beytepe, Ankara	Truck	7.5-16	20	16,684	21,540
Alkali Activators	Ankara, Turkey	Beytepe, Ankara	Pickup truck	3.5-7.5	15	3,316	2,779
Silica Fume	Antalya, Turkey	Beytepe, Ankara	Truck	7.5-16	480	50,051	0
Fly ash	Sugözü, Adana, Turkey	Beytepe, Ankara	Truck	7.5-16	560	29,196	0
Slag	İskenderun, Hatay, Turkey	Beytepe, Ankara	Truck	7.5-16	620	32,325	0

Table 3.6 shows the material quantities required for the production of 1 m^3 of CDW-based geopolymer and OPC-based mortar. Since SimaPro databases do not have country-specific data on materials and their lifecycle emissions for Turkey, RoW (Rest of World) was chosen as the geographical region. RoW was chosen as the common geography for all input elements as it is aimed to ensure compatibility for all materials.

Table 3. 6. Material Inputs

MATERIALS	(CDW80SCM20)	(CDW100)	OPC-based mortar
		kg/m^3	
Portland Cement	-	-	312
Roof Tile	208,55	287,20	-
Red Clay Brick	208,55	287,20	-
Hollow Brick	208,55	287,20	-
Concrete	104,27	107,70	-
Glass	104,27	107,70	-
Slag	52,14	0	73
Silica Fume	104,27	0	
Fly Ash	52,14	0	
Recycled Concrete Aggregate	364,96	376,95	-
Sand	-	-	1765
$Ca(OH)_2$	83,42	43,08	-
NaOH	137,64	142,16	-
Water	344,10	355,41	162
TOTAL	**1972,85**	**1994,60**	**2312**

In order to make the obtained CDWs suitable for geopolymerization, crushing of CDW elements with a jaw crusher followed by grinding of the smaller particle size was performed. While these processes were applied to all components of CDW to produce the precursor phase of geopolymeric composites, a different procedure consisting only of crushing and sieving steps was used to produce Recycled Concrete Aggregate (RCA) from concrete waste (CW). These processes were carried out with a jaw crusher, ball mill and sieving machine.

The life cycle inventory of CDW-based geopolymer mortar mixtures was derived from laboratory-scale experimental studies. However, the pertinent data were scaled up to an industrial scale utilizing industrial scale equivalents of laboratory size equipment (jaw crusher, grinder, sieving machines) for processing geopolymers in order to create a realistic comparison with OPC mortar. The major justification for this strategy is that no data exist on CDW-element processing, and the information on cement, the OPC mortar component, is based on industrial-scale manufacturing techniques.

Energy data were entered for the crushing and grinding of the precursor materials to prepare the mix, as well as for the sieving processes to prepare the recycling aggregate and for the mixer. Utilizing the capacity and consumption information from the industrial scale versions of the equipment utilized in the laboratory-based manufacturing process, the pertinent calculations were scaled. In addition, large-scale devices used in the market were also taken into account and as a result, consumption values for industrial devices were calculated. For example, the pre-crushing of CDW to make it ready for grinding was carried out by a laboratory-scale jaw crusher with a power consumption of 1.5 kW. In 5 minutes, 3.5 kg of raw CDW were crushed. The grinding operation was then carried out using a ball mill that required 1.5 kW of power for an hour. Because this process requires many iterations to produce 1 m^3 of CDW-based geopolymer mortar and does not accurately reflect energy consumption due to the material's life cycle, energy consumption calculations were based on the production capacity and power consumption of industrial-scale versions of the equipment.

The industrial-size crusher, ball mill, sieving machine, and mixer in this case each used 15 kW, 280 kW, 7.4 kW, and 10 kW, respectively. In contrast to the RoW geography used, for the electricity inputs for geopolymer and OPC mortar, electricity data for the equipment was modelled based on the Turkey (TR) grid mix, since SimaPro database has electricity data for Turkey. Table 3.7 presents data on energy consumption in the machines for the mixtures.

Table 3. 7. Machines' Electrical Energy Consumptions

	Jaw Crusher for Precursor	Jaw Crusher for RCA	Sieving for RCA	Ball Mill	Mixer	Unit
CDW80 SCM20	0,626	0,274	0,270	11,679	16,440	kWh
CDW100	0,808	0,283	0,279	15,078	16,622	kWh

In addition to calculating the electrical energy consumption of the machines, their own production and emissions from this production were also included in the life cycle assessment process. Considering the time the machines are used for these processes, values proportional to the total lifetime of the machines are calculated. If we give an example from the crushing process in the jaw crusher where CDW materials first pass through; a lifetime of 10000 hours is given for the crusher in the Simapro database. However, for this study, since the machine is not used continuously throughout its lifetime, it would not be reasonable to take all these emission values released as a result of the production of the machine. Some calculations were made for this. The calculation made separately for each of the CDW materials entering into 1m^3 geopolymer mortar is as follows: For example, the amount of glass waste entering 1 m^3 of geopolymer mortar mixture containing 100% CDW is 107.70 kg. It is calculated how many hours a 20-ton jaw crusher, which is determined as a large scale and works for 1 hour, will work for 107.70 kg. Then the desired value was obtained by proportioning the result to 10000 hours, which is the total life of the machine. Information on the lifetime of the machines is given in Table 3.8.

Table 3. 8. Knowledge of machines lifetime

Machines		Jaw crusher for precursor			Jaw crusher for RCA	Sieving for RCA	Ball Mill			Mixer
Mixture Compositions		RCB+ HB+ RT	CW	GW	CW	CW	RCB+ HB+ RT	CW	GW	Total mixture
Mixtures (kg)	CDW100	861,6	107,7	107,7	376,9	376,9	861,6	107,7	107,7	1994,6
	CDW80 SCM20	625,6	104,2	104,2	364,9	364,96	625,6	104,2	104,2	1972,8
Time used (hour)	CDW100	0,043	0,005	0,005	0,018	0,037	0,043	0,005	0,005	1,662
	CDW80 SCM20	0,031	0,005	0,005	0,018	0,036	0,031	0,005	0,005	1,644
Machine lifetime (hour)		10000			10000	10000	10000			10000
Time used / Machine Lifetime	CDW100	4,31 E-06	5,39 E-07	5,39 E-07	1,88 E-06	3,77 E-06	4,31 E-06	5,38 E-07	5,38 E-07	0,0001
	CDW80 SCM20	3,13 E-06	5,21 E-07	5,21 E-07	1,82 E-06	3,65 E-06	3,13 E-06	5,21 E-07	5,21 E-07	0,0001

3.4.3. Life Cycle Impact Assessment (LCIA)

In the LCIA phase, where the quantity and importance of potential environmental impacts are identified and assessed from the LCI data, the environmental impacts of CDW-based geopolymers and OPC mortar were determined with SimaPro 9.0.0.35 software and Ecoinvent 3 database. The IMPACT 2002+ method was utilised.[66], [67]

IMPACT 2002+ method considers has several midpoint category indicators: carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrification, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, mineral extraction. Human health, ecosystem quality, climate change, and resources are the four damage categories that are linked to all midpoint scores, which are all represented in baseline units. Six impact categories—global warming, acidification, eutrophication, ozone layer depletion, land occupation, and non-renewable energy—were taken into account to complete for this study. Table 3.9 lists the impact and damage categories for the Impact 2002+ method along with their unit expressions.

Table 3. 9. Impact and Damage Categories for Characterization Factors, Reference Substances and Unit Expressions for Impact 2002+ Method [67]

Midpoint impact category	**Midpoint reference substance**	**Damage category**	**Damage unit**
Human toxicity (carcinogens + non-carcinogens	kg_{eq} chloroethylene into air	Human health	DALY
Respiratory (inorganics)	kg_{eq} $PM_{2.5}$ into air	Human health	DALY
Ionizing radiations	Bq_{eq} carbon-14 into air	Human health	DALY
Ozone layer depletion	kg_{eq} CFC-11 into air	Human health	DALY
Photochemical oxidation [= Respiratory (organics) for human health	kg_{eq} ethylene into air	Human health	DALY
		Ecosystem quality	-
Aquatic ecotoxicity	kg_{eq} triethylene glycol into water	Ecosystem quality	$PDF \cdot m^2 \cdot y$
Terrestrial ecotoxicity	kg_{eq} triethylene glycol into water	Ecosystem quality	$PDF \cdot m^2 \cdot y$
Terrestrial acidification/nutrification	kg_{eq} SO_2 into air	Ecosystem quality	$PDF \cdot m^2 \cdot y$
Aquatic acidification	kg_{eq} SO_2 into air	Ecosystem quality	$PDF \cdot m^2 \cdot y$
Aquatic eutrophication	kg_{eq} PO_4^{3-} into water	Ecosystem quality	$PDF \cdot m^2 \cdot y$
Land occupation	m^2_{eq} organic arable land·year	Ecosystem quality	$PDF \cdot m^2 \cdot y$
Global warming	kg_{eq} CO_2 into air	Climate change (life support system)	kg_{eq} CO_2 into air
Non-renewable energy	MJ Total primary non-renewable	Resources	MJ

	or kg_{eq} crude oil (860 kg/m^3)		
Mineral extraction	MJ additional energy or kg_{eq} iron (in ore)	Resources	MJ

DALY= Disability-Adjusted Life Years; PDF= Potentially Disappeared Fraction of species; eq= equivalents; y= year

The details of the impact categories identified within the scope of this study, including information, are as follows:

- Global warming potential: The effects of global warming on the environment manifest themselves in the form of climate change. It is an effect caused by greenhouse gases released into the atmosphere as a result of various activities. It is also a category that has impacts on human health. In this respect, its impact is evaluated in line with the diseases and deaths that occur as a result of climate change. The best known of these gases is CO_2, but methane, nitrogen oxides and chlorofluorocarbons are also included in this category. The characterization factor of the impact and the damage caused is expressed in "kg CO_2-equivalent".

- Aquatic acidification: It is a category that has impacts on the ecosystem, i.e. the environment. The pollutants with the highest acidification potential are SO_2, NOx, HCl and NH_3. Atmospheric emissions of acidic substances such as sulphur dioxide and nitrous oxide from the combustion of fossil fuels can remain suspended in the air for several days. They can thus be transported thousands of kilometers away as they are transformed into chemicals such as sulfuric and nitric acid. Primary pollutants such as sulphur dioxide, nitrous oxide and ammonia, together with their reaction products, cause chemical changes in soil and surface water resources. The effect of this on the ecosystem is seen as "acidification". Substances with acidifying properties are also involved in the greenhouse effect. "kg SO_2-equivalent" is the unit of measurement for the effect's characterization factor.

- Aquatic eutrophication: The overstimulation of plant growth caused by the addition of nutrients like nitrogen and phosphorus to water is called eutrophication. Excessive nutrient uptake into the water as a result of agricultural fertilizers, urban runoff, wastewater discharge and erosion causes eutrophication[88]. Eutrophication is a natural process, but it is accelerated by human activities, leading to a change in patterns and a reduction in ecological diversity. It can also cause algae blooms, depriving the underwater environment of sunlight and causing plants to die. The death of algae reduces oxygen in the water, which affects the health of fish and aquatic animals [88], [89]. The damage and impact characterization factors are provided in "kg PO_4-equivalent."

- Ozone layer depletion: It is a category that has an impact on the environment and human health. It is caused by chemicals containing chlorine and bromine, known as ozone depleting substances. Above the stratosphere, the ozone layer prevents harmful rays from reaching the earth. Emissions of ozone-depleting substances used in the construction industry, such as chlorofluorocarbons or halons, deplete the ozone layer and cause ultraviolet (UV) rays to reach the earth [88]. The characterization factor of the impact and the damage caused is expressed in units of "kg CFC-11-equivalent".

- Land occupation: Land occupation is the ongoing use of an area of land for a particular human-controlled activity, such as farming, forestry, or construction. A delay in the restoration process might be perceived as the consequence of occupancy. If the region hadn't been inhabited over time, it would have sooner attained greater land quality. Therefore, the effect of occupation may be viewed as a quality loss that is time-integrated. The characterization factor of the impact and the damage caused is expressed in units of " m^2_{eq} organic arable land·year".

- Non-renewable energy: Energy sources that are not regenerated as rapidly as they are used up are referred to as non-renewable resources since they will ultimately run out. Because of this, a non-renewable resource is a finite resource. New resources are not produced for a very long period, even though humans are continually depleting the available supplies of these materials. Fossil fuels including coal, gas, and oil make up the majority of non-renewable energy sources. Carbon is often the primary component of fossil fuels. The characterization factor of the impact is expressed in units of "MJ primary".

3.4.4. Interpretation

In the last step, the results of the LCI and LCIA were assessed in six impact categories. The characterization results were utilized to compare the findings obtained in SimaPro. The characterization results were used to compare and evaluate 2 different geopolymer mortar mixtures and OPC mortar. In addition, recommendations were given while taking into account the objective and scope of the study.

4. RESULTS AND DISCUSSIONS

All resources and emissions used by the product throughout its life cycle have been converted into environmental impacts during the impact assessment step of this LCA study. In this section, the results of the life cycle inventory and life cycle impact assessment are systematically evaluated, interpreted and recommendations are made according to the purpose and scope of the study.

4.1 Impact Assessment and Contribution Analysis

The current section comprises the contribution analyzes of each geopolymer mortar per the selected impact evaluation categories in IMPACT 2002+. Towards this purpose, environmental impacts of 100% CDW-based (CDW100) and CDW-based SCM-substituted (CDW80SCM20) geopolymer mortars were determined, and the contribution of each ingredient of mortars was analyzed. Besides, to compare the environmental impacts and to reveal positive and negative aspects of the CDW-based geopolymers, impact assessment and contribution analyzes were performed on the predefined Ordinary Portland Cement-based mortar.

The impact assessment results of investigated geopolymer and cement-based mortars are presented in Table 4.1 and Figure 4.1. According to the findings, it can be stated that CDW-based geopolymer mortars exhibited considerably lower environmental impacts, except for aquatic eutrophication and ozone layer depletion. The advantages of geopolymer mortars in terms of environmental impacts made it possible to reduce the global warming impact at 48.1%, aquatic acidification at 22.1%, land occupation at 45.2%, non-renewable energy at 1.83%. However, aquatic eutrophication and ozone layer depletion were found to be higher compared to the OPC Mortar. On the ozone layer depletion, the main reason behind the disadvantage of geopolymer mortars is the use of carbon tetrachloride to recover chlorine from gas streams in the chlor-alkali process in the production of sodium hydroxide[90], [91].

Compared to the CDW100, CDW80SCM20 exhibited a slightly higher impact on the environmental impact categories. The largest difference in this comparison was for land occupation and global warming, with 30.8% and 16.9%, respectively. These outputs revealed that the geopolymer system containing only CDW is more advantageous in terms of environmental impact, while the potential disadvantageous caused by the use of SCM still maintains its advantage (except for non-renewable energy) compared to OPC Mortar.

Table 4. 1. Impact Assessment Results-Characterization, Impact 2002+ Method

Impact category	Unit	CDW100	CDW80SCM20	OPC Mortar
Global warming	kg CO_2 eq	260.4723	313.2633	501.4795
Ozone layer depletion	kg CFC-11 eq	0.000120	0.000123	2.11E-05
Aquatic acidification	kg SO_2 eq	1.182360	1.260245	1.518108
Aquatic eutrophication	kg PO_4 P-lim	0.064777	0.066773	0.046474
Land occupation	m^2org.arable	2.902153	4.194819	5.294807
Non-renewable energy	MJ primary	3292.037	3769.278	3353.460

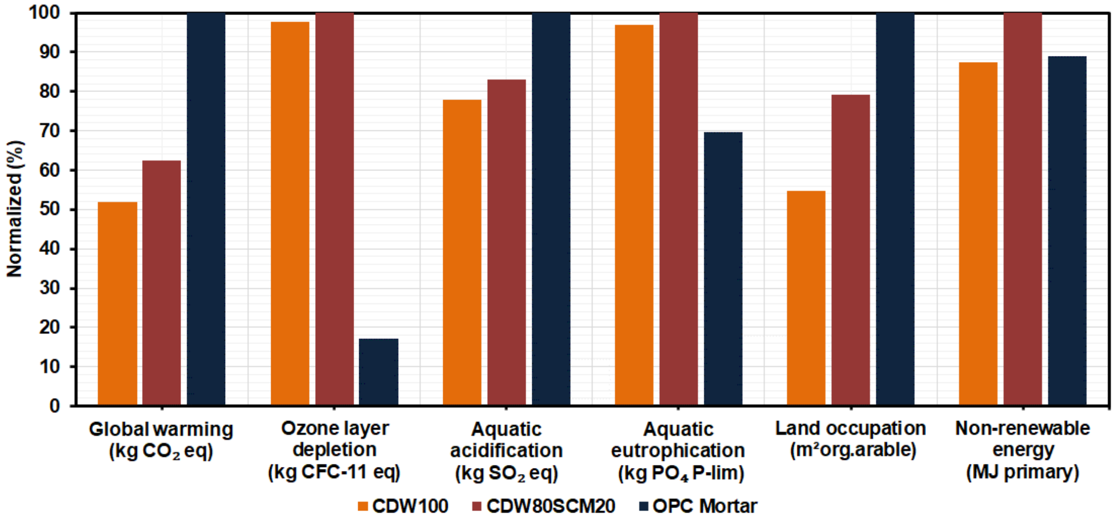


Figure 4. 1. Comparison of impact assessment results

Figure 4.2 demonstrates the environmental impacts and contribution analysis of 100% CDW-based (CDW100) geopolymer mortar. For all impact categories, sodium hydroxide has the highest contribution, especially in the ozone layer depletion category it was the most dominant factor with a 95.2% contribution. As stated above, this behavior is directly related to the chlor-alkali process in the production of sodium hydroxide [90], [91]. Among the impact categories, the lowest contribution of sodium hydroxide with 69.8%, was global warming, the most critical and highly weighted impact category according to the European Commission [92]. According to other impact categories, contributions were 78.4% for acidification, 82.8% for eutrophication, 74.8% for land occupation and 76.8% for non-renewable energy. Calcium hydroxide exhibited the second highest contribution to the environmental impact, with 1.9-15.6%, in general, and the highest contribution was on the global warming impact. While the electrical energy consumed in grinding and mixing has values between 3-4% in global warming, acidification, eutrophication and nonrenewable energy, it is followed by the production of machines with 2-3%. Overall, it can be stated that alkali activator phases, an essential factor in activating aluminosilicate CDW-based binders, shared the dominant contribution in the environmental impact categories. Following, the most effective parameters were the pre-treatment of CDW-based binders; however, the contribution of these parameters had a maximum share of 15.6%, while the contribution of transportation had a maximum share of 6.9%.

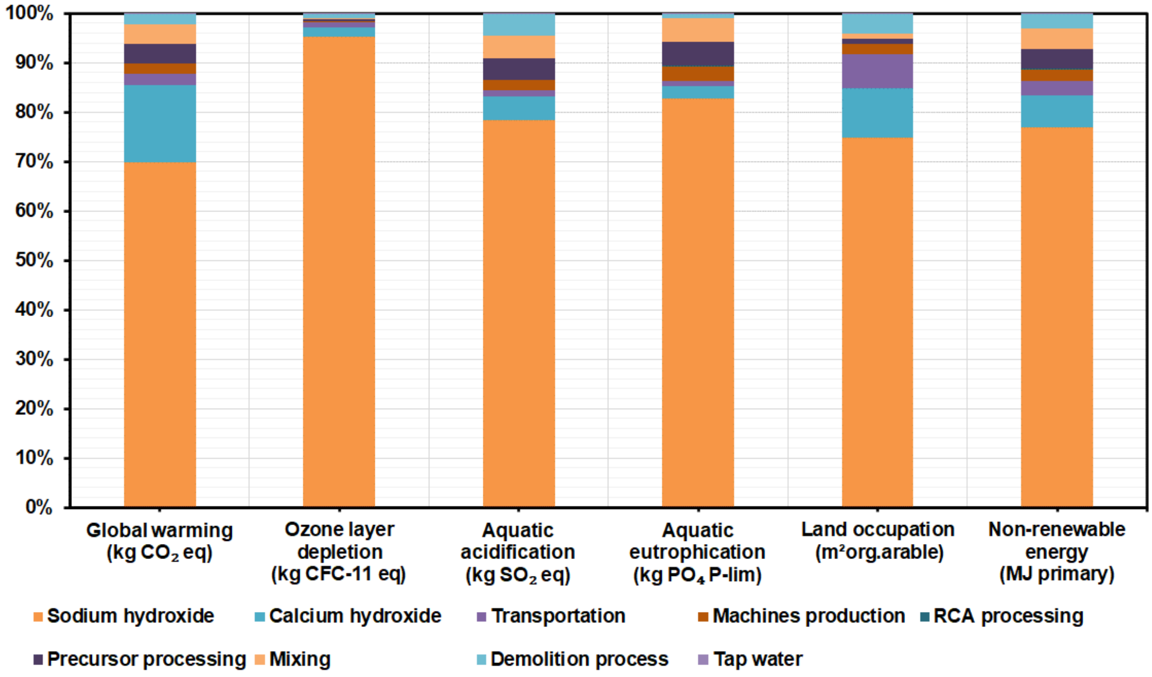


Figure 4. 2. Impact assessment and contribution analysis of CDW100

As seen in Figure 4.3, similar to outcomes from the 100% CDW-based geopolymer mortar, sodium hydroxide has the highest effect in all categories. In particular, it has the highest effect on the ozone layer depletion potential with a rate of 90.12%. In general, the second largest contributor was calcium hydroxide. For the global warming category, share of sodium hydroxide was 56.26%, followed by calcium hydroxide with 25.08%.

Considering the pre-treatment operations and machine production, contribution varied between 1.9-14.5%, whereas for transportation variation was between 4.2-23.9%.

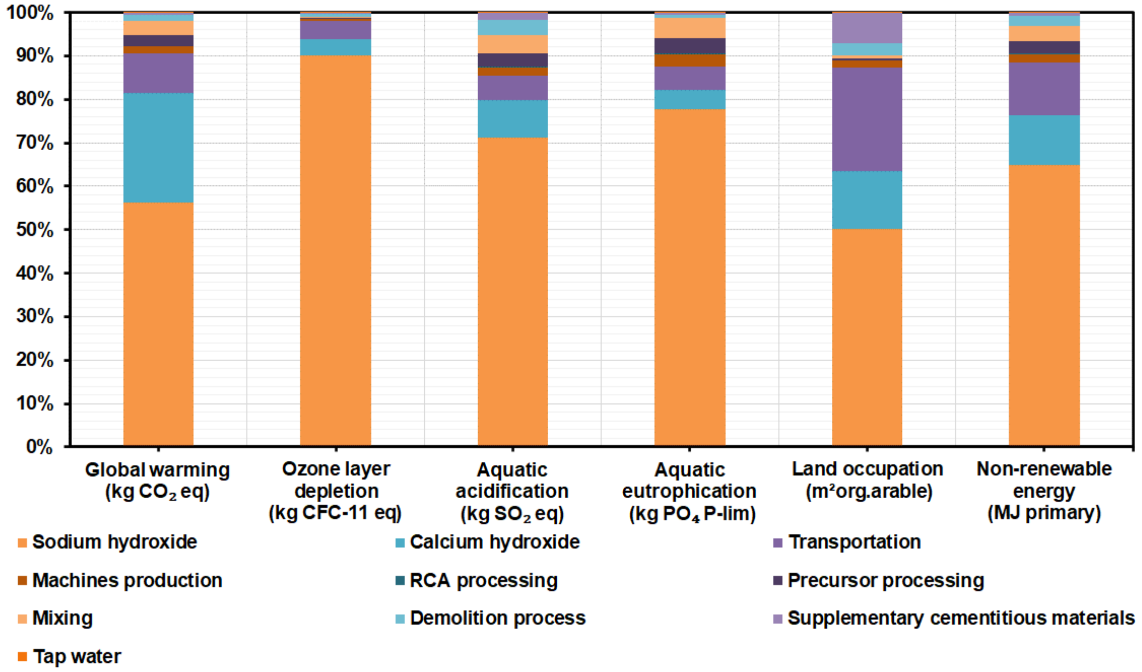


Figure 4. 3. Impact assessment and contribution analysis of CDW80SCM20

Figure 4.4 demonstrates the contribution comparison of CDW100 and CDW80SCM20 on investigated impact categories according to their contribution degree in three main phases, including pre-treatment, transport, and alkali activator. On the global warming impact and non-renewable energy, which is important for enabling the development of sustainable materials with less energy consumption and carbon emissions, it can be stated that the solely usage of CDW, to produce geopolymer caused a slightly higher contribution on impacts regarding the alkali activator and pre-treatment. On the other hand, solely usage of CDW within the production location dependent transportation data defined in the system boundary caused a lower contribution to the environmental impacts compared to SCM-substituted version. This finding revealed that transportation-related energy consumption and carbon emissions of SCMs produced in production facilities close to the location of the natural or secondary source can be reduced by means of CDWs that are easily accessible almost everywhere in the world. On the ozone layer depletion, SCM-substitution ensured less impact regarding to the alkali activator content; however, this impact was remained minor. Pre-treatment phase related contribution was found to be increased for aquatic acidification and aquatic eutrophication, while the SCM had a slight impact on reduction in their contribution. For the land occupation, influence of SCM on the alkali activator contribution was most significant among all impact factors, with a 21.3% reduction rate. Reversibly, this decrease caused an increase in the transport contribution. In a broader context, an ultimate conclusion can be drawn that the SCM-substitution can have an auxiliary role in the optimization of CDW-based geopolymer production to increase mechanical performances, and reduce alkali activator content and pre-treatment processes.

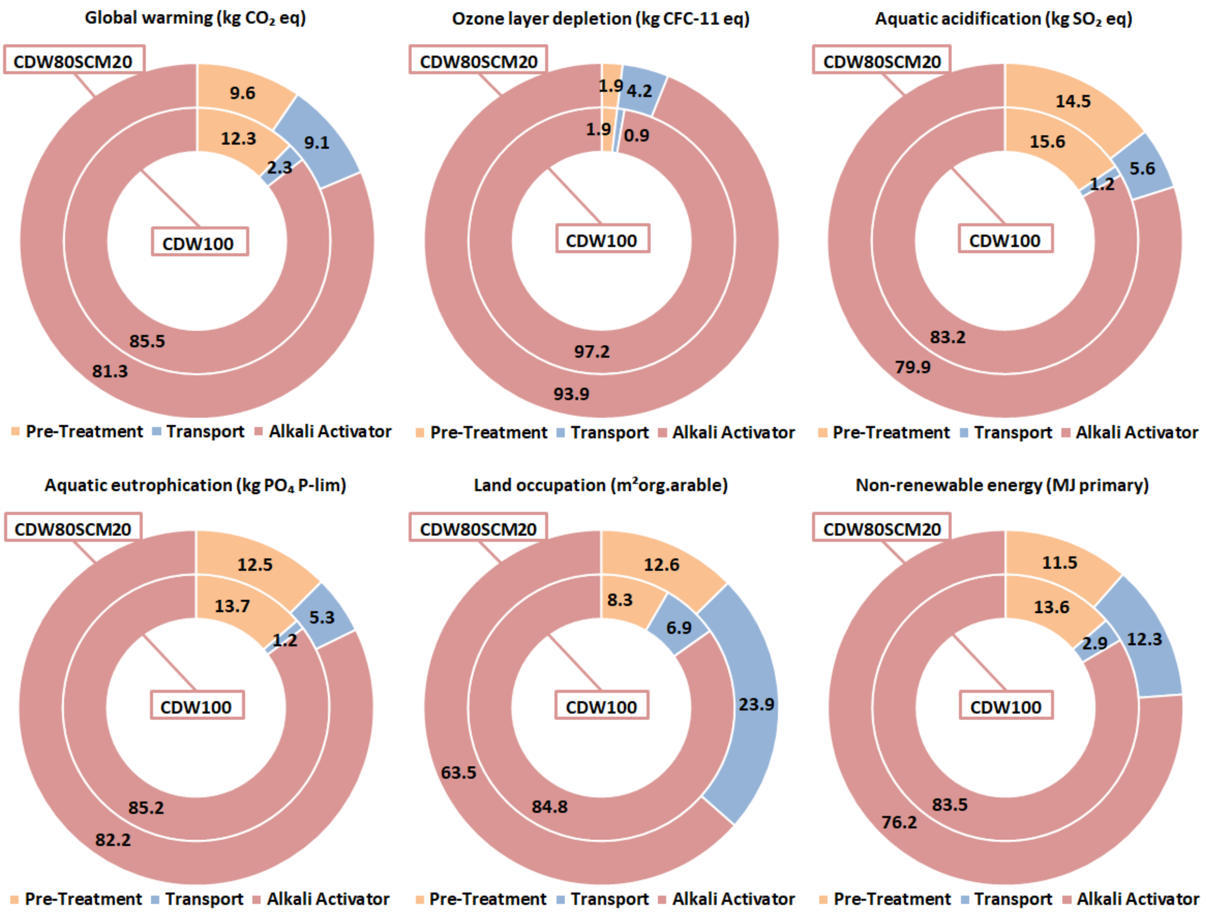


Figure 4. 4. Comparison of the impact factor contribution of geopolymer mortars (inner circle depicts CDW100, outer circle depicts CDW80SCM20

The considerably high contribution of the Portland cement in OPC mortar can be seen in Figure 4.5. Considering all impact categories, the contribution of OPC varied between 30.9-80.5%; the minimum contribution was noted for land occupation, while the maximum was for the global warming category. Portland cement was followed by silica sand with a contribution between 13.1-43.9%, especially contribution was noted higher for land occupation. The impact of the processing of cement and transportation varied depending on the impact category, with the third highest contribution. For instance, whereas processing was dominant in the categories of global warming, aquatic acidification, aquatic eutrophication, and non-renewable energy, transporting had a more significant impact on ozone layer depletion and land occupation. In addition, it was determined that heat and tap water had a minor, insignificant impact. A holistic assessment reveals that the contribution of Portland cement, an essential component of OPC Mortar, reaching drastic levels in the impact categories is, unfortunately, an unchangeable disadvantage in the absence of any replacement. For geopolymer mortars, on the other hand, this is not the case since it is evident from the mixtures produced in the current study that the environmental impacts can be further minimized by optimizing the alkaline activator concentrations and SCM content while taking the on-purpose design into account.

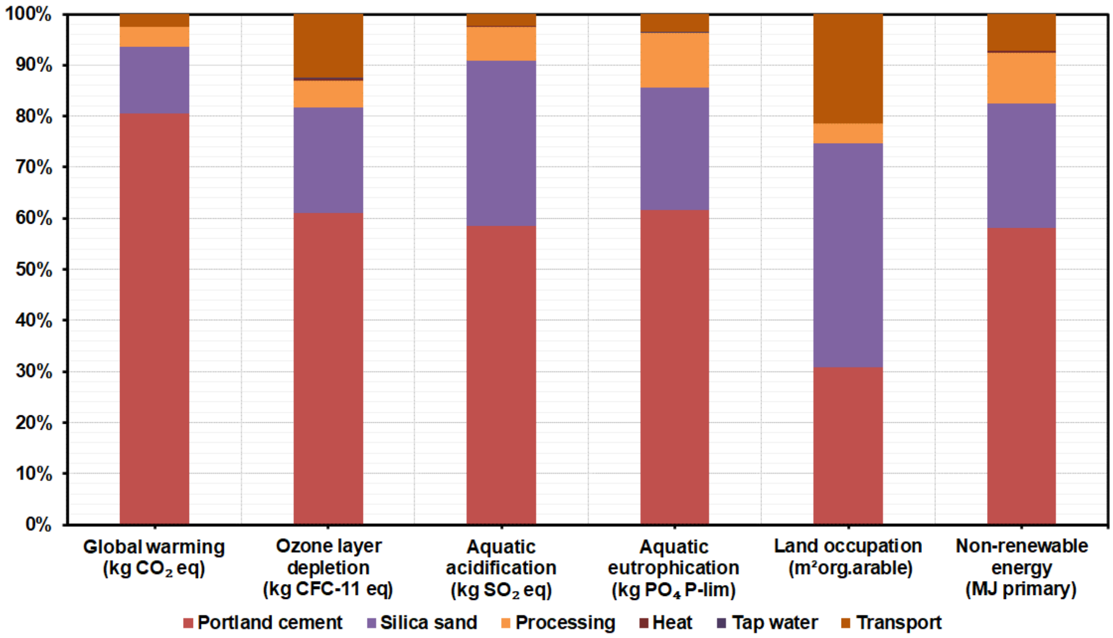


Figure 4. 5. Impact assessment and contribution analysis of OPC mortar

4.2 Damage Assessment Results

Impact categories are assigned to one or more damage categories. The damage indicator result, which is created by multiplying the damage factor by the inventory data, serves as a quantitative representation of this quality change. All impact scores relate to four damage categories: human health, ecological quality, climate change, and resources. They are all stated in units of a reference substance.

Figure 4.6 depicts the damage assessment comparison of geopolymer and OPC mortars. It was clear that geopolymer mortars had provided an advantage of up to 48.1% in terms of climate change. On the contrary, for other factors, the damage risen from the geopolymers was directly dependent on the share of CDW-based elements. In other words, for the ecosystem quality and resources category, geopolymer mortar only incorporated CDW-based elements (CDW100) had comparable performance to OPC mortar, while the addition of SCM (CDW80SCM20) negatively affected this performance. On the other hand, for the human health category, OPC mortar had a significantly low damage factor compared to geopolymer mortars, which was attributed to the alkali activator content in geopolymers.

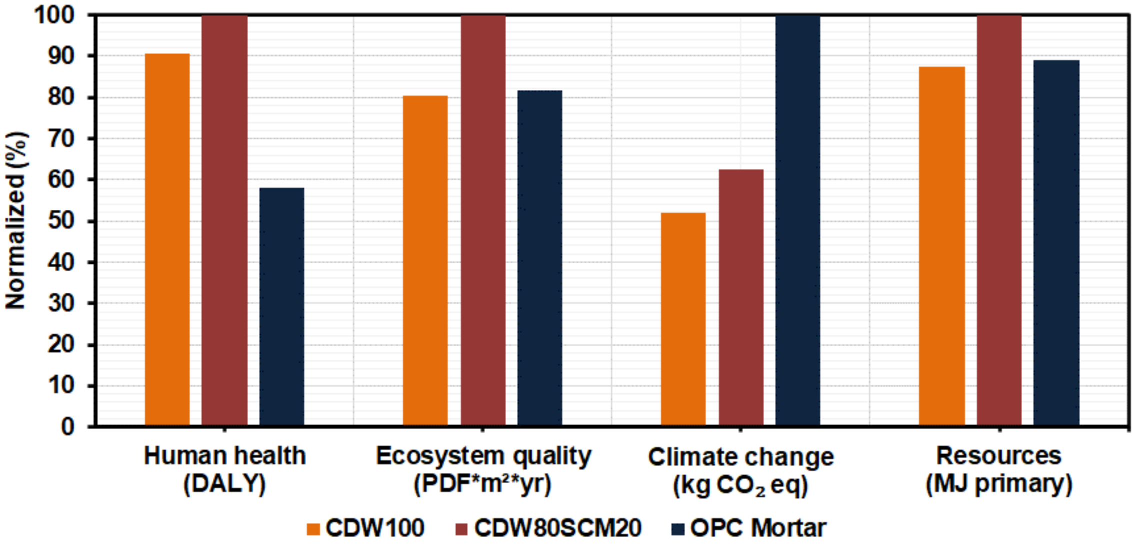


Figure 4. 6. Comparison of damage assessment

In Figure 4.7, the contribution of the mortars' components for both geopolymers and OPC mortar is illustrated. According to the findings, it can be stated that the alkali activator content of the geopolymer mortars was the main responsible for the damage categories, followed by the precursor processing, demolition process, and mixing operation, especially for CDW100. In addition to these, transportation was noted as the other important contributor to the damage of CDW80SCM20. For the OPC mortar, Portland cement was responsible for the higher share, except in the ecosystem quality category, where the contribution of silica sand and cement was comparable. The contribution of transportation and processing, which had the third highest impact on damage, varied by damage category, while the share of heat was insignificant.

Overall, using solely CDW in the geopolymer production ensured lower or comparable damage against OPC mortar, except for the human health category due to the presence of alkali activators in ingredients. However, the substitution of SCM to obtain higher mechanical performances caused an increase in damage; in some cases, an excessive increase in damage compared to OPC mortar was observed. Nevertheless, even in the presence of SCM in geopolymer mortar, the damage was significantly lower for the climate change category.

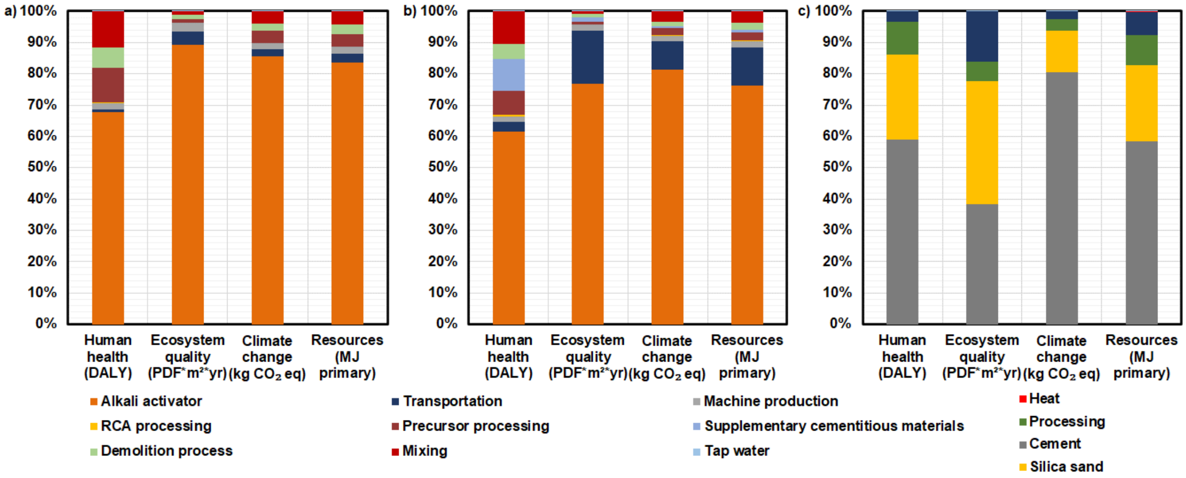


Figure 4. 7. Contribution of materials' components on damage assessment

4.3. Limitations of the Study

This section will present the design or methodology features that influence the interpretation of the findings of the study. The locations where the materials were obtained, their transportation values, the machines used and the electrical energy consumed in these machines will be evaluated.

- First of all, the results could have changed if a different alkali material (e.g., sodium silicate) had been used instead of NaOH, which was used as an alkali activator for the geopolymer mortar and was the main responsible for most of the impact categories. Or if a better mixture could have been developed and the NaOH molarity could have been lowered, the results could have been better in ozone layer potential than the cementitious mixture.
- Although silica fume, fly ash and slag are used as by-products in CDW80SCM20 geopolymer, the most important factor in the high impact values compared to

CDW100 is the high transportation values of these materials. In this study, the results may change when the transportation distances given as 480, 560 and 620 km, respectively, for silica fume, fly ash and slag obtained from different cities are changed, and even better results could be obtained in CDW80SCM20 geopolymer mixture if these values are reduced.

- The capacity and power values of the large-scale machines used for the crusher, ball mill, sieving machine and mixer used to make the obtained CDWs suitable for geopolymerization are respectively; 20 tons/15 kW, 20 tons/280 kW, 10 tons/7.4 kW, 1200 kg/10 kW. If machines with different capacities and power were used instead of these used machines, changes could be observed in the results.
- Finally, for the OPC mortar mix compared with geopolymer mortars, a 35 MPa mix with similar strength to CDW80SCM20 (34.8 MPa) was determined and this mix was also compared with CDW100. However, a comparison could have been made with another OPC mortar with a strength of 15 MPa close to the strength of CDW100 mortar (15.2 MPa) and different results could have been obtained.

5. CONCLUSION

The current study is centered on the environmental impact evaluation of geopolymer mortar mixtures produced by construction and demolition waste (CDW) through a cradle-to-gate life cycle assessment (LCA) analysis. In this context, for a completely CDW-based geopolymer mortar (CDW100) and supplementary cementitious materials (SCM) substituted geopolymer mortar (CDW80SCM20), all components of the process from the demolition stage to the production of the final product were discussed. A Portland cement-based mortar of similar compressive strength class (OPC Mortar) was also included in the analysis to compare the environmental impact of CDW-based geopolymers with conventional cementitious systems. The results of the LCA analysis, using IMPACT 2002+ as the life cycle impact assessment methodology, can be drawn as follows:

- With regard to environmental impacts, geopolymer mortars' advantages allowed for significant reductions in global warming (48.1%), land occupation (45.2%), aquatic acidification (21.1%), and non-renewable energy (1.83%). The ozone layer depletion and aquatic eutrophication, however, were found to be worse than with the OPC Mortar due to the chlor-alkali process in the production of sodium hydroxide.

- The CDW80SCM20 demonstrated a slightly higher impact on the environmental impact categories when compared to the CDW100. With 16.9% and 30.8%, respectively, the highest differences were identified for global warming and land occupation. The geopolymer system containing completely CDW was more advantageous in terms of environmental impact; on the other hand, although the use of SCM caused a disadvantage, it had a lower environmental impact compared to OPC Mortar (excluding non-renewable energy).

- The environmental impact categories were dominated by alkali activator phases for geopolymer mortars. The pre-treatment of CDW-based binders was the second-most dominant characteristic, yet its share in the total contribution was limited to 15.6%, while that of transportation was limited to 6.9%.

- The SCM substitution played an important role in optimizing CDW-based geopolymers in terms of reducing the alkaline activator content (dominant in ozone depletion layer) and pretreatment processes (dominant in non-renewable energy), as well as improving mechanical performances.

- Portland cement, the constant component of OPC Mortar, had the highest contribution to impact factors (varied between 30.9-80.5%), followed by silica sand (varied between 13.1-43.9%). On the other hand, the environmental impact of geopolymer mortars has already low, and when an on-purpose design is performed, it is possible to optimize the overall and component-related environmental impacts, as well as improve mechanical performance.

- According to the damage assessment, in the climate change category, geopolymer mortars' had shown an advantage of up to 48.1%. Geopolymer mortar that only incorporated CDW-based elements (CDW100) had similar performance to OPC mortar in the category of ecosystem quality and resources; however, the addition of SCM (CDW80SCM20) caused a negative impact. Compared to geopolymer mortars, OPC mortar had a substantially lower damage factor for the human health category, which was attributed to the alkali activator content in geopolymers.

- The alkali activator content of the geopolymer mortars was the main responsible for the damage categories, followed by the precursor processing, demolition process, mixing operation, and transportation; the last one had more share for CDW80SCM20. For the OPC mortar, Portland cement was responsible for the higher share, except in the ecosystem quality category, where the contribution of silica sand and cement was comparable.

6. REFERENCES

[1] ISO 14040, ‘Environmental management — Life cycle assessment — Principles and framework’, 2006.

[2] J. B. Guinée *et al.*, “Life cycle assessment: Past, present, and future,” *Environ Sci Technol*, vol. 45, no. 1, pp. 90–96, Jan. 2011, doi: 10.1021/ES101316V/ASSET/IMAGES/LARGE/ES-2010-01316V_0003.JPEG.

[3] EPA, ‘Life Cycle Assessment: Principles and Practice’, U.S. ENVIRONMENTAL PROTECTION AGENCY, 2006.

[4] A. K. Menoufi, “Life cycle analysis and life cyle impact assessment methodologies: a state of the art,” 2011, [Online]. Available: https://repositori.udl.cat/handle/10459.1/45831 [Accessed: 6 Sept.2022]

[5] C. Jiménez-González, S. Kim, and M. R. Overcash, “Methodology for developing gate-to-gate Life Cycle Inventory information,” *International Journal of Life Cycle Assessment*, vol. 5, no. 3, pp. 153–159, 2000, doi: 10.1007/BF02978615/METRICS.

[6] M. Goedkoop, A. De Schyver, M. Oele, S. Durksz, and D. De Roest, ‘Introduction to LCA with SimaPro 7’, PRé Consult. Netherlands. Version, pp. 1–88, 2008.

[7] Zbicinski I., John Stavenuiter J., Barbara Kozlowska B., van de Coevering H., Product Design and Life Cycle Assessment, The Baltic University Press, Uppsala, 2006.

[8] D. W. Pennington *et al.*, “Life cycle assessment Part 2: Current impact assessment practice,” *Environ Int*, vol. 30, no. 5, pp. 721–739, Jul. 2004, doi: 10.1016/J.ENVINT.2003.12.009.

[9] Curran M.A., Life Cycle Assessment: Principles and Practice, National Risk Management Research Laboratory, US Environmental Protection Agency, EPA/600/R-06/060, 1-80, 2006.

[10] A. Josa, A. Aguado, A. Cardim, and E. Byars, “Comparative analysis of the life cycle impact assessment of available cement inventories in the EU,” *Cem Concr Res*, vol. 37, no. 5, pp. 781–788, May 2007, doi: 10.1016/J.CEMCONRES.2007.02.004.

[11] PRe, ‘SimaPro 7: Database Manual’, Methods Libr., pp. 1–52, 2008.

[12] GaBi Paper Clip Tutorial. Handbook for Life Cycle Assessment (LCA) Using the GaBi Software.

[13] P. C. Aïtcin, “Cements of yesterday and today - concrete of tomorrow,” *Cem Concr Res*, vol. 30, no. 9, pp. 1349–1359, 2000, doi: 10.1016/S0008-8846(00)00365-3.

[14] K. L. Scrivener and R. J. Kirkpatrick, “Innovation in use and research on cementitious material,” *Cem Concr Res*, vol. 38, no. 2, pp. 128–136, Feb. 2008, doi: 10.1016/J.CEMCONRES.2007.09.025.

[15] J. G. J. Olivier, J. A. H. W. Peters, and G. Janssens-Maenhout, “Trends in global CO2 emissions. 2012 Report,” 2012, doi: 10.2788/33777.

[16] E. Gartner, “Industrially interesting approaches to ‘low-CO2’ cements,” *Cem Concr Res*, vol. 34, no. 9, pp. 1489–1498, Sep. 2004, doi: 10.1016/J.CEMCONRES.2004.01.021.

[17] J. Cagiao, B. Gómez, J. L. Doménech, S. G. Mainar, and H. G. Lanza, “Calculation of the corporate carbon footprint of the cement industry by the application of MC3 methodology,” *Ecol Indic*, vol. 11, no. 6, pp. 1526–1540, Nov. 2011, doi: 10.1016/J.ECOLIND.2011.02.013.

[18] C. Chen, G. Habert, Y. Bouzidi, and A. Jullien, “Environmental impact of cement production: detail of the different processes and cement plant variability evaluation,” *J Clean Prod*, vol. 18, no. 5, pp. 478–485, Mar. 2010, doi: 10.1016/J.JCLEPRO.2009.12.014.

[19] G. Habert, “Assessing the environmental impact of conventional and ‘green’ cement production,” *Eco-Efficient Construction and Building Materials: Life Cycle Assessment (LCA), Eco-Labelling and Case Studies*, pp. 199–238, Jan. 2014, doi: 10.1533/9780857097729.2.199.

[20] C. L. Sabine *et al.*, “The oceanic sink for anthropogenic CO2,” *Science (1979)*, vol. 305, no. 5682, pp. 367–371, Jul. 2004, doi: 10.1126/SCIENCE.1097403/SUPPL_FILE/SABINE.SOM.PDF.

[21] R. A. Feely *et al.*, “Impact of anthropogenic CO2 on the CaCO3 system in the oceans,” *Science (1979)*, vol. 305, no. 5682, pp. 362–366, Jul. 2004, doi: 10.1126/SCIENCE.1097329/SUPPL_FILE/FEELY.SOM.PDF.

[22] EPA-Cement Manufacturing Enforcement Initiative. Available: https://www.epa.gov/enforcement/cement-manufacturing-enforcement-initiative. [Accessed: 10 April 2022]

[23] General Directorate of Industry and Efficiency of Ministry of Industry and Technology of Turkey. Cement Industry Report (2020).

[24] TURKSTAT. (2021). TURKISH GREENHOUSE GAS INVENTORY 1990 - 2019.

[25] Construction Waste Market - Global Industry Analysis and Forecast 2017 - 2025 | TMR. Transparencymarketresearch.com. (2021).

[26] United States Environmental Protection Agency. (2018). Advancing Sustainable Materials Management: 2018 Fact Sheet.

[27] P. Villoria Sáez and M. Osmani, "A diagnosis of construction and demolition waste generation and recovery practice in the European Union," *J Clean Prod*, vol. 241, p. 118400, Dec. 2019, doi: 10.1016/J.JCLEPRO.2019.118400.

[28] B. J. Sealey, P. S. Phillips, and G. J. Hill, "Waste management issues for the UK ready-mixed concrete industry," *Resour Conserv Recycl*, vol. 32, no. 3–4, pp. 321–331, Jul. 2001, doi: 10.1016/S0921-3449(01)00069-6.

[29] Craven, D.J., Okraglik, H.M., and Eilenberg, I.M. (1994). Construction waste and a new design methodology, In: C.J. Kibert (ed.), Proceedings of the First Conference of CIB TG 16 on Sustainable Construction, pp. 89–98, Tampa.

[30] Poon C.S (2007) Reducing Construction Waste. Waste Management 27: 1715–1716.

[31] Ch. F. Hendriks and G. M. T. Janssen, "Construction and demolition waste: General process aspects," *HERON, vol. 46 (2), 2001,* vol. 46, Jan. 2001.

[32] Ölmez E. ve Yıldız, Ş., 'İnşaat ve Yıkıntı Atıklarının Yönetimi ve Planlanan İstanbul Modeli', Kent Yönetimi, İnsan ve Çevre Sorunları Sempozyumu (2008).

[33] J. Davidovits, "The need to create a new technical language for the transfer of basic scientific information," 1982, [Online]. Available: https://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=PASCAL83X0012244, [Accessed: 13 May 2022]

[34] J. Davidovits, "Geopolymers: Inorganic polymeric new materials," *J Therm Anal Calorim*, vol. 37, no. 8, pp. 1633–1656, Jul. 1991, doi: 10.1007/BF01912193.

[35] Wastiels, J., Wu, X., Faignet, S. and Patfoort, G.: Mineral polymer based on fly ash. In: Proceedings of the 9th International Conference on Solid Waste Management, Philadelphia, PA. 8pp. Widener University (1993).

[36] P. Duxson, A. Fernández-Jiménez, J. L. Provis, G. C. Lukey, A. Palomo, and J. S. J. van Deventer, "Geopolymer technology: The current state of the art," *J Mater*

Sci, vol. 42, no. 9, pp. 2917–2933, May 2007, doi: 10.1007/S10853-006-0637-Z/FIGURES/15.

[37] A. Palomo and J. I. López de la Fuente, “Alkali-activated cementitous materials: Alternative matrices for the immobilisation of hazardous wastes: Part I. Stabilisation of boron,” *Cem Concr Res*, vol. 33, no. 2, pp. 281–288, Feb. 2003, doi: 10.1016/S0008-8846(02)00963-8.

[38] Krivenko PV In: Krivenko PV (ed) Proceedings of the first international conference on alkaline cements, concretes. (1994) VIPOL Stock Company, Kiev, Ukraine, pp 11– 129.

[39] H. Rahier, B. van Mele, M. Biesemans, J. Wastiels, and X. Wu, “Low-temperature synthesized aluminosilicate glasses: Part I. Low-temperature reaction stoichiometry and structure of a model compound,” *J Mater Sci*, vol. 31, no. 1, pp. 71–79, 1996, doi: 10.1007/BF00355128/METRICS.

[40] Sofi M, Van Deventer JSJ, Mendis PA, Lukey GC. (2006). J Mater Sci (this issue).

[41] Mallicoat S, Sarin P, Kriven WM. Novel alkali-bonded ceramic filtration membranes. (2005) Ceram Eng Sci Proc 26:26–37.

[42] Y. Bao, M. W. Grutzeck, and C. M. Jantzen, “Preparation and Properties of Hydroceramic Waste Forms Made with Simulated Hanford Low-Activity Waste,” *Journal of the American Ceramic Society*, vol. 88, no. 12, pp. 3287–3302, Dec. 2005, doi: 10.1111/J.1551-2916.2005.00775.X.

[43] Shi C., Krivenko P.V., and Roy D. Alkali-activated cements and concretes, (2006), Taylor & Francis, London.

[44] K. J. D. Mackenzie, “What are These Things Called Geopolymers? A Physicochemical Perspective,” *Ceramic Transactions*, vol. 153, pp. 173–186, 2004, doi: 10.1002/9781118406892.CH12.

[45] C. A. Rees, J. L. Provis, G. C. Lukey, and J. S. J. van Deventer, “Attenuated total reflectance fourier transform infrared analysis of fly ash geopolymer gel aging,” *Langmuir*, vol. 23, no. 15, pp. 8170–8179, Jul. 2007, doi: 10.1021/LA700713G/SUPPL_FILE/LA700713G-FILE002.PDF.

[46] ACI Committee 226 (1987) Ground granulated blast-furnace slag as a cementitious constituent in concrete. ACI Materials Journal, 84, 327–342.

[47] B. Sabir, S. Wild, and J. Bai, “Metakaolin and calcined clays as pozzolans for concrete: a review,” *Cem Concr Compos*, vol. 23, no. 6, pp. 441–454, Dec. 2001, doi: 10.1016/S0958-9465(00)00092-5.

[48] I. G. Richardson, "Tobermorite/jennite- and tobermorite/calcium hydroxide-based models for the structure of C-S-H: applicability to hardened pastes of tricalcium silicate, β-dicalcium silicate, Portland cement, and blends of Portland cement with blast-furnace slag, metakaolin, or silica fume," *Cem Concr Res*, vol. 34, no. 9, pp. 1733–1777, Sep. 2004, doi: 10.1016/J.CEMCONRES.2004.05.034.

[49] A. Allahverdi and E. Najafi Kani, "Construction Wastes as Raw Materials for Geopolymer Binders," *International Journal of Civil Engineering*, vol. 7, no. 3, pp. 154–160, 2009, [Online]. Available: http://ijce.iust.ac.ir/article-1-286-en.html, [Accessed: 7 August 2022]

[50] R. A. Robayo-Salazar, J. F. Rivera, and R. Mejía de Gutiérrez, "Alkali-activated building materials made with recycled construction and demolition wastes," *Constr Build Mater*, vol. 149, pp. 130–138, Sep. 2017, doi: 10.1016/J.CONBUILDMAT.2017.05.122.

[51] Z. X. Yang, N. R. Ha, M. S. Jang, and K. H. Hwang, "Geopolymer Concrete Fabricated by Waste Concrete Sludge with Silica Fume," *Materials Science Forum*, vol. 620–622, pp. 791–794, 2009, doi: 10.4028/WWW.SCIENTIFIC.NET/MSF.620-622.791.

[52] A. Allahverdi and E. N. Kani, "Use of construction and demolition waste (CDW) for alkali-activated or geopolymer cements," *Handbook of Recycled Concrete and Demolition Waste*, pp. 439–475, Jan. 2013, doi: 10.1533/9780857096906.3.439.

[53] S. Ahmari, X. Ren, V. Toufigh, and L. Zhang, "Production of geopolymeric binder from blended waste concrete powder and fly ash," *Constr Build Mater*, vol. 35, pp. 718–729, Oct. 2012, doi: 10.1016/J.CONBUILDMAT.2012.04.044.

[54] K. Komnitsas and D. Zaharaki, "Co-utilization of construction and demolition with industrial wastes for the production of geopolymers," 2015.

[55] G. Yıldırım *et al.*, "Development of alkali-activated binders from recycled mixed masonry-originated waste," *Journal of Building Engineering*, vol. 33, p. 101690, Jan. 2021, doi: 10.1016/J.JOBE.2020.101690.

[56] G. Habert, J. B. D'Espinose De Lacaillerie, and N. Roussel, "An environmental evaluation of geopolymer based concrete production: reviewing current research trends," *J Clean Prod*, vol. 19, no. 11, pp. 1229–1238, Jul. 2011, doi: 10.1016/J.JCLEPRO.2011.03.012.

[57] M. Weil, K. Dombrowski, and A. Buchwald, "Life-cycle analysis of geopolymers," *Geopolymers: Structures, Processing, Properties and Industrial Applications*, pp. 194–210, Jan. 2009, doi: 10.1533/9781845696382.2.194.

[58] D. A. Salas, A. D. Ramirez, N. Ulloa, H. Baykara, and A. J. Boero, "Life cycle assessment of geopolymer concrete," *Constr Build Mater*, vol. 190, pp. 170–177, Nov. 2018, doi: 10.1016/J.CONBUILDMAT.2018.09.123.

[59] R. Bajpai, K. Choudhary, A. Srivastava, K. S. Sangwan, and M. Singh, "Environmental impact assessment of fly ash and silica fume based geopolymer concrete," *J Clean Prod*, vol. 254, p. 120147, May 2020, doi: 10.1016/J.JCLEPRO.2020.120147.

[60] L. Imtiaz *et al.*, "Life Cycle Impact Assessment of Recycled Aggregate Concrete, Geopolymer Concrete, and Recycled Aggregate-Based Geopolymer Concrete," *Sustainability 2021, Vol. 13, Page 13515*, vol. 13, no. 24, p. 13515, Dec. 2021, doi: 10.3390/SU132413515.

[61] F. Colangelo, & Tomás, G. Navarro, I. Farina, and A. Petrillo, "Comparative LCA of concrete with recycled aggregates: a circular economy mindset in Europe", doi: 10.1007/s11367-020-01798-6/Published.

[62] M. Goedkoop, M. Oele, J. Leijting, T. Ponsioen, and E. Meijer, 'Introduction to LCA with SimaPro', PRé. 2016.

[63] G. Han and J. Srebric, "Life-cycle assessment tools for building analysis," *phrc.psu.edu*,[Online].Available:http://www.phrc.psu.edu/assets/docs/Publications/RB0511.pdf, [Accessed: 8 July 2022]

[64] ecoinvent center-About ecoinvent. Available: https://ecoinvent.org/the-ecoinvent-association [Accessed: 4 July 2022].

[65] Geographies-ecoinvent.Available:https://ecoinvent.org/the-ecoinvent database/geographies [Accessed: 10 July 2022]

[66] J. C. Bare, P. Hofstetter, D. W. Pennington, and H. A. U. de Haes, "Midpoints versus endpoints: The sacrifices and benefits," *The International Journal of Life Cycle Assessment 2000 5:6*, vol. 5, no. 6, pp. 319–326, Nov. 2000, doi: 10.1007/BF02978665.

[67] O. Jolliet *et al.*, "IMPACT 2002+: A New Life Cycle Impact Assessment Methodology," *International Journal of Life Cycle Assessment*, vol. 8, no. 6, pp. 324–330, 2003, doi: 10.1007/BF02978505/METRICS.

[68] S. Humbert, A. de Schryver, X. Bengoa, M. Margni, O. Jolliet, IMPACT 2002+: User Guide, (2012). https://doi.org/10.1007/BF02978505.

[69] B. P. Weidema et al., ‘Overview and methodology: data quality guideline for the ecoinvent database version 3’, 2013.

[70] SimaPro Help Center, ‘What is the difference between ecoinvent market and transformation processes?’ [Online]. Available: https://support.simapro.com/articles/FAQ/What-is-the-difference-between-ecoinvent-market-and-transformation-processes. [Accessed: 18-April-2022].

[71] Simapro Help Center, What are unit and system processes? Available: https://support.simapro.com/articles/FAQ/What-are-unit-and-system-processes/#:~:text=a%20system%20process%20only%20contains,to%20input%20from%20other%20processes. [Accessed:20 May 2022].

[72] T. Bakharev, J. G. Sanjayan, and Y. B. Cheng, “Alkali activation of Australian slag cements,” *Cem Concr Res*, vol. 29, no. 1, pp. 113–120, Jan. 1999, doi: 10.1016/S0008-8846(98)00170-7.

[73] I. B. Topçu, “High-volume ground granulated blast furnace slag (GGBFS) concrete,” *Eco-Efficient Concrete*, pp. 218–240, Jan. 2013, doi: 10.1533/9780857098993.2.218.

[74] K. L. Scrivener, V. M. John, and E. M. Gartner, “Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry,” *Cem Concr Res*, vol. 114, pp. 2–26, Dec. 2018, doi: 10.1016/J.CEMCONRES.2018.03.015.

[75] J. Turk, Z. Cotič, A. Mladenovič, and A. Šajna, “Environmental evaluation of green concretes versus conventional concrete by means of LCA,” *Waste Management*, vol. 45, pp. 194–205, Nov. 2015, doi: 10.1016/J.WASMAN.2015.06.035.

[76] M. Jiang, X. Chen, F. Rajabipour, and C. T. Hendrickson, “Comparative Life Cycle Assessment of Conventional, Glass Powder, and Alkali-Activated Slag Concrete and Mortar,” *Journal of Infrastructure Systems*, vol. 20, no. 4, p. 04014020, Feb. 2014, doi: 10.1061/(ASCE)IS.1943-555X.0000211.

[77] P. Awoyera and A. Adesina, “A critical review on application of alkali activated slag as a sustainable composite binder,” *Case Studies in Construction Materials*, vol. 11, p. e00268, Dec. 2019, doi: 10.1016/J.CSCM.2019.E00268.

[78] A. M. Rashad, “A comprehensive overview about the influence of different additives on the properties of alkali-activated slag – A guide for Civil Engineer,” *Constr Build Mater*, vol. 47, pp. 29–55, Oct. 2013, doi: 10.1016/J.CONBUILDMAT.2013.04.011.

[79] F. Pacheco-Torgal, J. Labrincha, C. Leonelli, and A. Palomo, “Handbook of alkali-activated cements, mortars and concretes,” 2017, [Online]. Available: https://books.google.com/books?hl=tr&lr=&id=KXQmBAAAQBAJ&oi=fnd&pg=PP1&dq=Handbook+of+alkali-activated+cements,+mortars+and+concretes&ots=FIyu2k87UW&sig=Fh7WWhnf-DkSFEXj04eYS-R63VA. [Accessed:19 July 2022]

[80] P. K. Sarker, Fly Ash: Sources, Applications and Potential Environments Impacts. 2013.

[81] J. J. Wang, Y. F. Wang, Y. W. Sun, D. D. Tingley, and Y. R. Zhang, “Life cycle sustainability assessment of fly ash concrete structures,” *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 1162–1174, Dec. 2017, doi: 10.1016/J.RSER.2017.05.232.

[82] K. Kohno, F. Aihara, and K. Ohno, “Relative Durability Properties and Strengths of Mortars Containing Finely Ground Silica and Silica Fume,” *Special Publication*, vol. 114, pp. 815–826, May 1989, doi: 10.14359/2405.

[83] A. Cheng, S. J. Chao, and W. T. Lin, “Effects of Leaching Behavior of Calcium Ions on Compression and Durability of Cement-Based Materials with Mineral Admixtures,” *Materials 2013, Vol. 6, Pages 1851-1872*, vol. 6, no. 5, pp. 1851–1872, May 2013, doi: 10.3390/MA6051851.

[84] N. K. Lee, G. H. An, K. T. Koh, and G. S. Ryu, “Improved Reactivity of Fly Ash-Slag Geopolymer by the Addition of Silica Fume,” *Advances in Materials Science and Engineering*, vol. 2016, 2016, doi: 10.1155/2016/2192053.

[85] F. N. Okoye, J. Durgaprasad, and N. B. Singh, “Effect of silica fume on the mechanical properties of fly ash based-geopolymer concrete,” *Ceram Int*, vol. 42, no. 2, pp. 3000–3006, Feb. 2016, doi: 10.1016/J.CERAMINT.2015.10.084.

[86] S. Thokchom, D. Dutta, and S. G. and, “Effect of incorporating silica fume in fly ash geopolymers,” *academia.edu*, 2011, [Online]. Available: https://www.academia.edu/download/79840679/pdf.pdf,[Accessed: 24 Sept 2022]

[87] J. Temuujin, A. van Riessen, and R. Williams, “Influence of calcium compounds on the mechanical properties of fly ash geopolymer pastes,” *J Hazard Mater*, vol. 167, no. 1–3, pp. 82–88, Aug. 2009, doi: 10.1016/J.JHAZMAT.2008.12.121.

[88] G. K. C. Ding, “Sustainable construction—The role of environmental assessment tools,” *J Environ Manage*, vol. 86, no. 3, pp. 451–464, Feb. 2008, doi: 10.1016/J.JENVMAN.2006.12.025.

[89] Calkins M.,. Materials For Sustainable Sites : a complete guide to the evaluation, selection, and use of sustainable construction, Wiley, Hoboken, N.J. 2009.

[90] Knudson, J. C., Crane, G. B., & Briggs, R. S. (1971). Atmospheric Emissions from Chlor-alkali Manufacture. Environmental Protection Agency, Air Pollution Control Office.

[91] Imtiaz, L., Kashif-ur-Rehman, S., Alaloul, W. S., Nazir, K., Javed, M. F., Aslam, F., & Musarat, M. A. (2021). Life cycle impact assessment of recycled aggregate concrete, geopolymer concrete, and recycled aggregate-based geopolymer concrete. Sustainability, 13(24), 13515.

[92] European Commission. (2018). Product Environmental Footprint Category Rules Guidance.