

**Short Thesis for the Degree of Doctor of
Philosophy (PhD)**

**SUSTAINABILITY ASSESSMENT OF USING
GREEN CONCRETE MATERIALS FOR
RESIDENTIAL BUILDINGS IN EGYPT**

By

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Introduction

Rapid population growth is associated with a high construction activity rate that increases the number of residential buildings worldwide. Countries rely heavily on concrete consumption to support their urbanization needs and enhance socio-economic growth, particularly in countries experiencing rapid population growth and urbanization like Egypt [1]. Therefore, concrete and cement are the most common and widely used man-made materials and have become the second-fastest growing industry worldwide [2]. From an environmental perspective, using conventional concrete materials (CCM) will lead to natural resource depletion and release vast amounts of negative environmental impacts expected to continue for the next decades [3].

Increasing the priority for using sustainable construction materials with high environmental, economic, and social benefits, reducing natural resources consumption, and applying cost-effectiveness is highly recommended. Therefore, using green concrete material (GCM) for future residential building projects can meet the needs of the nation's urbanization while reducing the construction

industry's environmental burdens [4]. Whereas GCM refers to concrete that contains recycled materials or has a low environmental impact in its production process. GCMs are crucial for reducing the negative environmental impact and play a crucial role in the building's life cycle. It can incorporate innovative technology and eco-friendly materials [5],[6],[7].

Using GCM in the residential sector has shown promising solutions as an alternative green material of CCM [3],[8],[4],[5],[9]. Furthermore, selecting the right GCM suitable for residential buildings is crucial for achieving several sustainability strategies, such as the circular economy (CE) and realizing the sustainable development goals (SDGs) [10]. However, using GCM is vital in eliminating waste generation based on reducing, recycling, and reusing strategies. The lack of environmentally conscious building materials for the residential sector and the absence of a clear image regarding the role of GCM resulted in a variance in stakeholders' understanding of the GCM concept. This raises questions about whether implementing GCM can achieve sustainability and which types and strategies have opportunities when utilizing materials in the Egyptian residential sector.

Therefore, the current dissertation investigates the role of using GCMs sustainability indicators for Egyptian residential buildings and seeks insight into the drivers of selecting and using GCMs by using a system of dynamic simulations for developing the sustainability framework, and Eco-friendly assessment approaches for Egyptian residential buildings case studies to bridge the gap between industrial and academic realms of the construction sector.

In this regard, this dissertation aims to assess the sustainability performance of using GCM and investigate the effects of using and selecting the GCM on natural resource consumption, CO₂ emissions, waste generation, and cost-effectiveness, based on CE core principles, SDGs, and three sustainability pillars in the design and construction phases of residential building projects in Egypt.

Egyptian Residential Building as Study Area.

The two case studies were selected as a study area within the Egyptian residential sector in the new Egyptian cities. The New Urban Communities Authority (NUCA) was established based on the Egyptian transformation and development strategy for increased urbanization to face rapid population

growth. Aiming to create new cities to achieve the quality of life and economic prosperity. The new area is considered an attraction destination, and the urban extension should be redistributed to the new desert and remote areas, which face urban sprawl in the agricultural lands in the Nile valley. New urban communities promote the planning of new cities by increasing the availability of low-income and economic housing units, which raises the quality of life in society suited to different inhabitant levels and has all amenities and facilities.

Notably the distribution of residential building types according to their construction type, the study found that Economic housing reached 139.8 thousand units followed by average housing, luxurious housing, and above-average housing, which reached approximately 69.8, 22.6, and 13.8 thousand units, respectively. Thus, economic housing accounted for about 57%, 28%, 9%, and 6% of the total residential units in 2021/2022. Cairo governorate ranked first, followed by Alexandria in the number of building units, with 50.1 and 26.5 thousand units and 38.3% and 23% in public and private sectors, respectively. The variety between public and private residential building types was found to promote the rights of a wide range of populations to improve their quality of

life at all societal levels. This confirmed that selecting the two new cities, New Cairo City and New Borg Alarab City, as investigation areas is of tremendous importance and essential in applying the development strategy and facing the population growth to reduce the high density of Cairo and Alexandria cities in Egypt.

Materials and Methods

Eco-friendly assessment approaches are used in various research stages to assess the sustainability of using the GCM for Egyptian residential buildings. Based on the empirical study applied to the real and existing residential building case studies in various study areas utilizing various concrete materials strategies and types. Integrating the qualitative and quantitative analyses to answer the research questions. The theoretical part is applied based on the literature review of the previous research efforts for each research phase to cover all the investigation needs in the context of research goals. Furthermore, the empirical studies applied based on comparative analysis between the existing and several hypothetical scenarios for the two residential buildings located in new Egyptian cities and are applied as follows:

First, design-based solution methods (DB-S) are used to investigate the effects of using GCM in reducing environmental impact, based on concrete scenarios from building case study (I) in the early design stage. The residential building is located in New Borg Alarb City, Egypt, and is addressed for modifying, quantifying, comparing, and evaluating the environmental benefits such as reducing CO₂ emissions, cement, natural aggregates, and construction and demolition waste (CDW), and applying the following steps:

- We started by redesigning and applying the modified design to reduce the total concrete materials and improve the suitability of using GCM by creating the 2D model using AutoCAD software.
- GCM quantifies the concrete material based on optimizing cement and natural aggregate using the absolute volume method (AVM) and Revit software to quantify the total amount of concrete materials required for selected building parts.
- The CIDAC method was applied to estimate the CO₂ emissions associated with the production of cement materials.
- The performance of various scenarios was compared in terms of cement, natural aggregate (NA), recycled aggregate (RA) consumption, and CO₂

emissions, based on the comparative analysis, by using Jamovi software.

- The conceptual design framework was applied to the most optimum scenario and the 3D model by using 3Dmax software to clarify the benefits of using GCM for reducing the negative environmental impacts of CCM.

Second, the selection of GCM for achieving CE core principles using a simulation-based framework method to select the most optimum GCM among various hypothetical scenarios in the construction process phase. The system dynamic-based framework (SDB-F) was developed by creating the dynamic simulation model based on a causal loop diagram (CLD), and stock and flow diagram (SF) and applying the following:

- Identify the essential GCM parameters and base in-depth analysis for the materials selection criteria, circular economy principles, and residential buildings in terms of environmental protection and cost-effectiveness.
- Quantifying the different scenarios using PCC, RAC, and FA, based on the building drawings, bill of quantity documents (BOQ), as well as project timeline, by using AutoCAD software and collecting data and information.

- Classify five different concrete materials based on their suitability for achieving CE principles, local availability, improving the model, and selecting GC materials as follows: Type 1: Portland cement concrete reinforced (PCC-R). Type 2: Portland cement concrete non-reinforced (PCC-N). Type 3: Fly ash concrete reinforced (FA-R). Type 4: Fly ash concrete non-reinforced (FA-N). Type 5: Recycled aggregate concrete-reinforced (RAC-N).
- Creating and quantifying seven concrete scenarios for investigating the concrete mix proportions and corresponding components using the AVM and MS Project software, Microsoft Excel, and CDIAC's method.
- Create the simulation model by using Vensim software to create an SD model, by causal loop diagrams (CLD), and stock and flow (SF) diagrams for causal the interdependencies and feedback loops to investigate the inner relations among the GCM variables based on the Sterman five-stage (Sterman, 2000).
- The scenarios analysis, for selecting the most appropriate GCM scenarios. Followed by developing the model for clarifying the building drawing and mapping the relation between concrete type, critical drivers, and residential building parts. This method stage is identified in Fig 1. During the case studies process, information and data are gathered in various

ways, including the official project documents, on-site measurements, Government reports, residential building rules and regulations, concrete codes, on-site observations, and in-depth expert discussions.

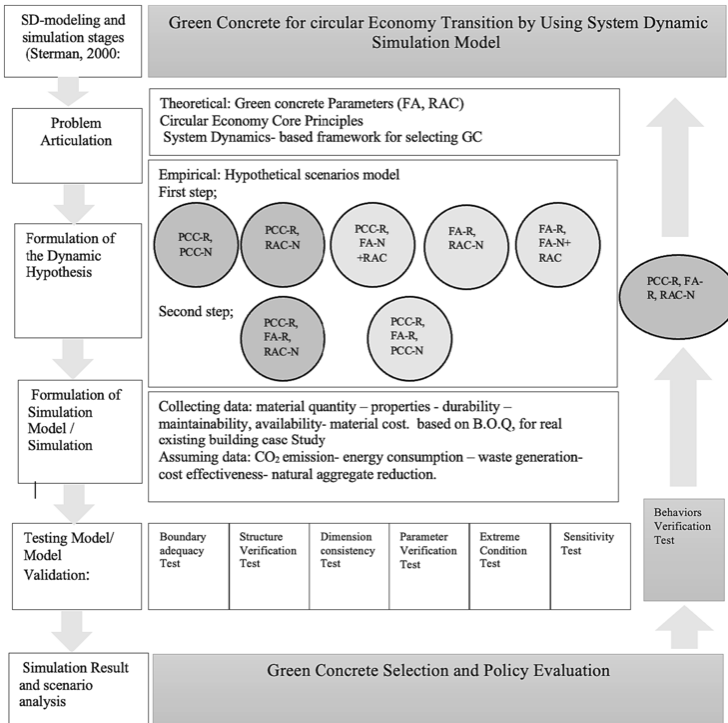


Fig1. A simulation-based framework methodology.

Third, the GCM-SF was developed using an assessment-based approach that integrates subjective and objective approaches to identify the sustainability indicators GCM-SI as an assessment method for realizing sustainable development as follows:

- Identifying the GCM sustainability indicators (GCM-SI) and proposing a conceptual framework based on data collected from the current research case studies, literature review, concrete codes and standards, and green rating systems.
- Based on the previous case studies results, the GCM-SI are detailed and weighted using casualty relationship and score matrix to identify and analyze the contribution of using GCMs and its behavior to realizing sustainability through the two sustainability global perspectives: the sustainable development goals SDGs and sustainability pillars).
- Developing a GCM sustainability framework (GCM-SF), integrating sustainability pillars and SDGs as a governing context for evaluating and enhancing the use of GCMs in the Egyptian residential sector.

Thesis 1

We have developed and used a novel approach as design-based solutions (DB-S) for reducing environmental impacts by substituting conventional concrete materials (CCM) with green concrete materials (GCM) by applying re-design and modification in concrete materials for the structural and non-structural concrete in the specific building parts in the early design stage.

The original building design was reviewed and modified to select specific building parts based on the concrete parameters; the materials selected included concrete quality with recyclable materials, considering equivalent CCM's durability, strength, and functionality. This study selected RAC, produced from local CDW, due to its ability to reduce NA consumption and waste generation. Therefore, C3 is applied for non-structural works as in the selected building parts, with the same strength and durability to play the same function as shown in Fig 2. Furthermore, the original and modified building design is presented in Fig 3.

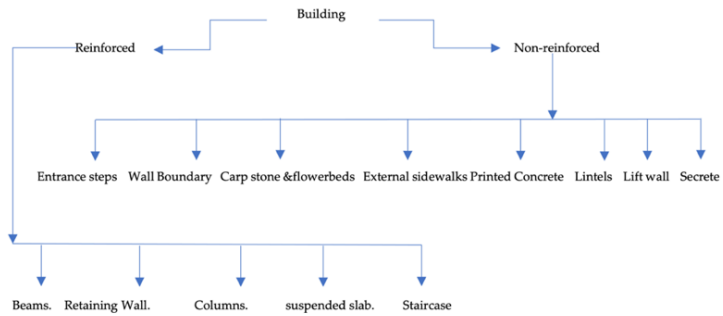


Fig2. The reinforced and non-reinforced concrete for several building parts.



Fig 3. (a) Original design front elevation (left) and the typical site plan (right). (b) Modified design front elevation (left) and the typical site plan (right).

This is considered a first step and an attempt to reduce the total consumption of concrete materials through design modification before integrating GCM. It recorded a reduction in CCM quantities by 8.14% from (original A) to (modified A), which is considered a very important indicator and achievement. Table 1 shows the C1 and C2 quantities for original A and modified A in the selected building parts. Additionally, the result identified the relationship between the selected building parts and (C1 and C2) quantities. Due to the design modification, the internal floor area increased; consequently, the CCMs quantity in modified A increased compared with the original, as shown in Fig 4.

Table 1. The concrete quantity (C1& C2) in selected building parts for original and modified building designs.

Concrete Specification	Building Part	Concrete with Ordinary Portland Cement	
		Original Building A C1 and C2, m3	Modified Building A C1 and C2, m3
Non- structural concrete	Internal floor (secrete)	47.77	52.89
	Wall boundary panel	26.46	26.46
	External sidewalk, carp stone, printed concrete	38.85	38.85
	Internal walls (lintels and lift walls)	37.49	36.79
	Entrance steps	3.60	3.60
	Structural concrete	347.34	302.09
	Total concrete	501.51	460.68
	Percentage	100%	91.9%

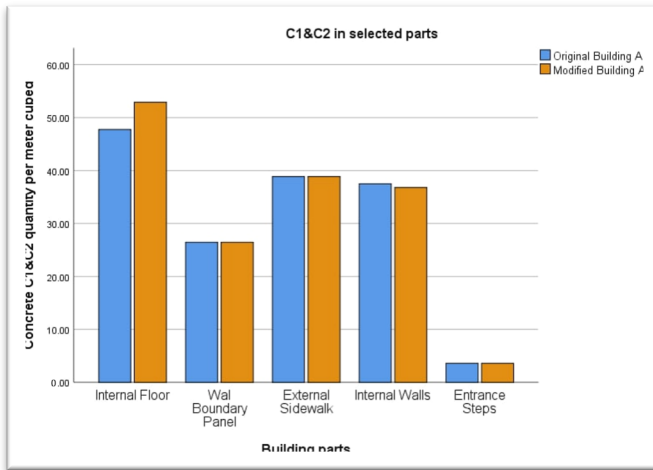


Fig 4. The relationship between selected building parts and C1 and C2 concrete materials in original A and modified A

Thesis 2

Using the original and modified building scenarios, we reduced the cement consumption and estimated the CO₂ emissions reduction based on production in all building references and scenarios. We have identified the most optimum scenario after we quantified the CCM and GCM in all scenarios' components by comparing cement, sand, natural coarse aggregate, and recycled coarse aggregate.

However, in the current research stage, we were concerned with investigating the effects of applying novel methods on reducing cement consumption in the selected building parts. We have found that (modified B)contributed to a reduction in cement by 19.5% compared with (original building A); additionally, we reduced the cement consumption by 44% in non-structural concrete as shown in Table 2.

Table 2. The cement consumption and reduction % for original and modified building references.

Original Building A and B and Modified Building A and B									
	Original A		Original B		Modified A		Modified B		
Concrete, m ³	501.51		501.501		460.68		460.68		
Mix type	CI	C2	CI	C3	CI	C2	CI	C3	
Cement, ton	189.0	47.9	189.0	25.9	164.4	49.3	164.4	26.6	
Cement, ton	236.9		214.8		213.7		191.0		
Cement C1, C2 and C3 %	100%		90.07%		90.2%		80.6%		
Cement C1, C2 and C3	100%		-9.3%		-9.8%		-19.5%		
Reduction %									
Cement C2 and C3, ton	47.9		25.9		49.3		26.6		
Cement C2 and C3 %	100%		53.8%		102%		55.5%		
Cement C2 and C3	100%		-46.2		+2.9%		-44.5%		
reduction %									

The relationship between all building references and concrete scenarios is summarized in terms of different concrete types in the structural and non-structural building parts. Therefore the cement consumption and reduction in the concrete scenarios and building references as shown in Fig 5.

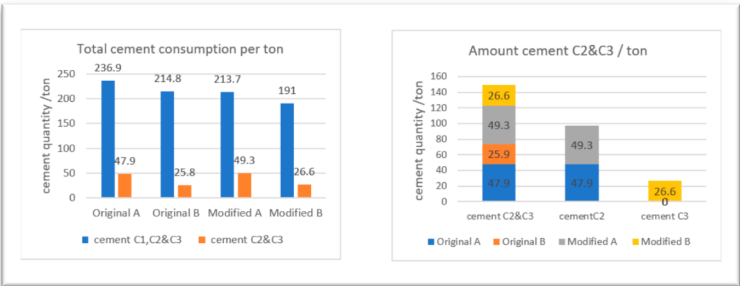


Fig 5. The cement consumption and reduction in the concrete scenarios and building references.

The doctoral thesis attempted to identify the reduction of CCM quantities in the early design stage of the Egyptian residential building. Therefore, the comparison analysis between CCM and GCM in different concrete scenarios and their components. The study showed that reducing raw materials consumption after using RAC and Modified B optimizes cement, sand, and NA consumption, as shown in Fig 6.

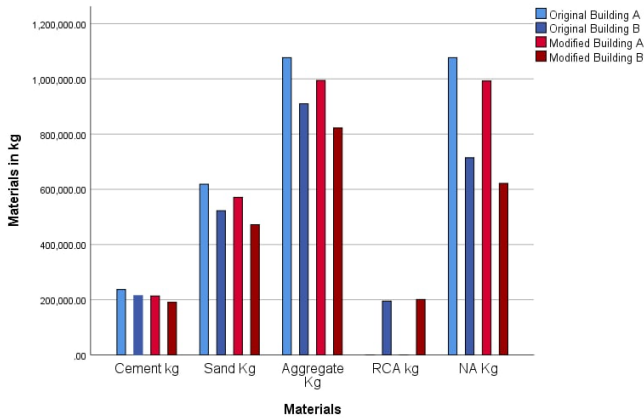


Fig 6. Distribution between the CCMs and CCM quantity components, cement, sand RCA, and NA.

We found the reduction in CO₂ emissions from the (original A) to (modified B) reached 22.95 tCO₂, which achieved a 19.4% reduction for the most optimum scenario, as shown in the previous scenarios: [(Original A = 118.45 tCO₂, (Original B) = 107.4 tCO₂, (Modified A) = 106.85 tCO₂, and (Modified B) = 95.5 tCO₂].

Thesis 3

We have created and developed the system dynamic–based framework (SDB-F) as a novel tool for selecting green concrete materials (GCM) and identified the circularity performance for achieving circular economy (CE) during the construction phase by using Vensim software to develop a dynamics simulation model (SDM).

The research presents the SDM as a novel tool for facilitating and improving the selection of the GCM for applied circularity. We applied modeling of the GCM parameters to investigate the (positive and negative) inner relations among the parameters, which helped enhance the GCMs' selection. Therefore, the study demonstrates the creation of system dynamic models (SDM) using Vensim simulation software to anticipate the model's performance over time. In this context, the SDM estimates the changes and inner relations in the construction process between different scenarios after identifying GCM parameters for achieving CE principles. Fig.7 Concrete materials and classification used for various scenarios. Furthermore, Fig.8 describes the framework of CE transitions for selecting suitable GCM in the construction process of residential building case study II.

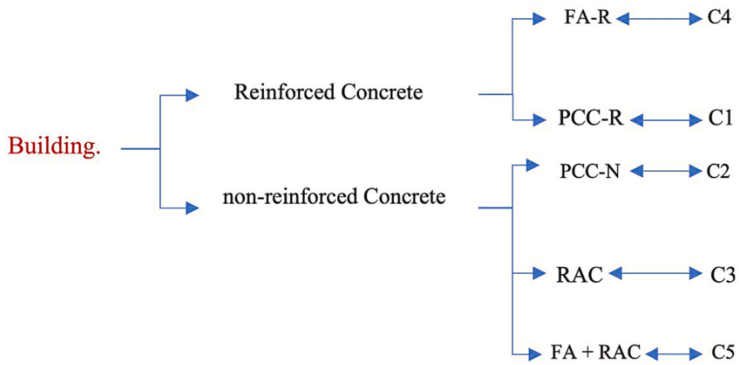


Fig. 7 Concrete materials and classification used for different scenarios.

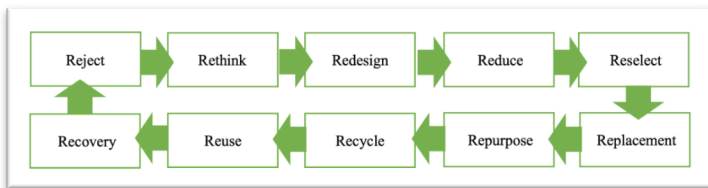


Fig 8. The conceptual framework of the SDM for GCM circularity transitions.

Thesis 4

By using the Causal Loop Diagram (CLD), we were able to visualize the individual and group causal links and feedback loops for several GCMs, which played a crucial role in demonstrating the selection of concrete materials in the construction process as a complex system and applied the system structure, based on the circular economy core principles for residential case study II.

The dynamic interactions between variables can improve and influence the system and how the feedback loops in the dynamics system are determined. The feedback loops provide an insightful description of different GCM scenarios and their dynamic behavior. Consequently, the study identifies the construction phase and the individual and group causal links of residential building case study II as key to achieving CE. For example, we found that the positive feedback loop R1 identified increases the CCM amount, increases project cement consumption and production, and increases embodied energy, thereby increasing CO₂ emissions and, finally, the concrete cost. This allows the long-term investigation to apply new policies for future residential construction projects. Fig.9 illustrates the details of the CLD.

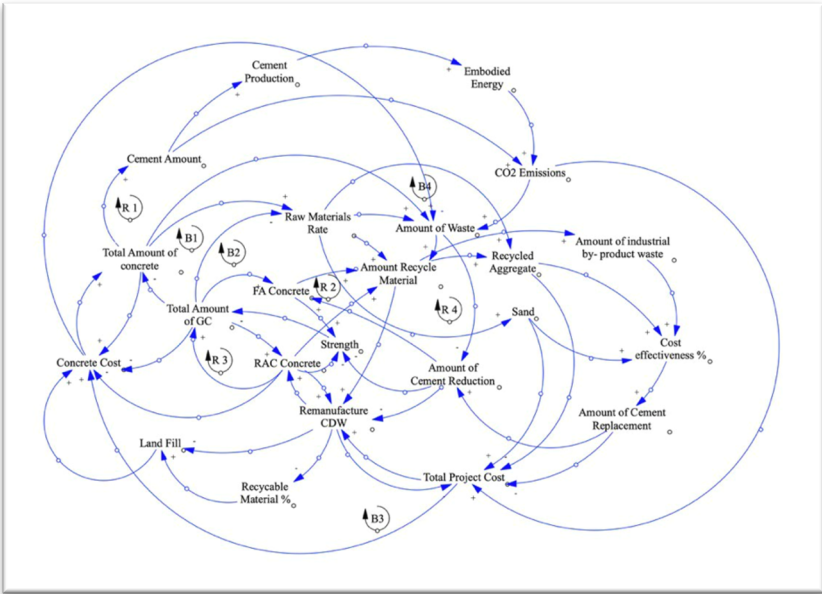


Fig 9. The green concrete Casual loop diagrams CLD for Circular Economy transition (authors).

Thesis 5

By creating several hypothetical concrete scenarios we have enhanced the GCM selection, based on our new model stock and flow (SF) diagram which is considered a novel tool that can help in selecting between several GCM scenarios. We were able to select the most optimum scenario, that has a behavior able to reduce the negative environmental impacts and enhance circularity performance during the construction.

An SF diagram identifies relationships among the various system components. It is considered a central idea of dynamic theory [14] due to its ability to map the stock and flow networks using conceptual and mathematical definitions. We created an SF diagram based on CLD, using Vensim software, to clarify and identify the circularity between concrete materials' parameters during the thirty-month construction process. In the current dissertation, a diagram describes the most significant variables by formulating the equations and using flow rate conjunctions to add to the stocks. Furthermore, the parameters were identified using the inputs and testing of structure and outputs to confirm the structure's ability to validate the behavior observed. Then, these flow rates and stock combinations by simulating the SD mode as shown in Fig.10

emissions, natural aggregate, waste reduction, and materials cost. Consequently, investigating the benefits of using different concrete scenarios led to selecting the most optimum scenario and identifying the total concrete quantity for the building case study II drawing and dimensions.

The result showed the OPC percentage in seven scenarios in CCM and GCM (RAC&FA). The cement reduction reached 19.8% and 11.4% (S7&S2) in the most optimum scenarios, as a follow, started with full ratio cement consumption of 100 % in the CCM as an S1, followed by [S2 by 89.6 %, S3by 86 %, S4 by 66.37, S5 by 62.75 %, S6 by 90.55%, and S7 by 80.19]. The total amount of cement per ton used to estimate the cost in the six hypothetical scenarios is 89.6 %, 86 %, 66.37, 62.75, 90.55%, and 80.19 %, from [S2, ..., S7] respectively. Furthermore, the reduction of NA started after using recycled materials, reaching the highest reduction of 19.1% in S2, S4, and S7. The lowest consumption level reached approximately 81%, amounting to 842.1 tons, followed by S3 and S5, which reached 83%, amounting to 863.7 tons, compared with S1 and S6, which consumed 100%, amounting to 1039.5 tons, which is the original NCA amount in the reference scenario. This result promotes variety, which adds more evidence for

controlling the consumption of cement and NA. Consequently, it reflects a high ability to apply GCM and achieve circularity in the residential sector. Furthermore, it provides insights into GCM selection to investigate their suitability for reducing, reusing, and recyclability of the total quantity of concrete components [15].

Thesis 6

Based on our previous results from the two case studies, we identified the green concrete material sustainability indicators (GCM-SI) for the Egyptian residential sector. Which helped in analyzing the contributions of the GCM sustainability behavior for realizing SDGs'.

Each GCM-SI and target are connected to all the SDGs since they are linked with their own and other goals using network analysis techniques. The dissertation investigates the higher and lower contribution levels and develops the GCM Sustainability framework for future residential building projects.

The result shows a high overall relation between the GCM-SI and SDGs through the sustainability pillars. Fig 11 clarifies the distribution of the high and very high contribution levels between the GCM-SI and the SDGs. In the same context, for more investigation of high-level contributions, which consist of (high level – very high level), we found that using GCM in residential buildings strongly contributes to SDGs. Fig 12 shows the high contribution to SDGs of 92%, 85%, 77%, 74%, and 70%

in SDG12, (SDG11, SDG6), SDG9, SDG7, and (SDG3, and SDG7) respectively. Furthermore, scored 44%, 33%, 18%, 14%,11%, within the SDG13, (SDG1, SDG5), SDG10, (SDG15, SDG2), and (SDG14, SDG16) but with limitation with other goals drivers.

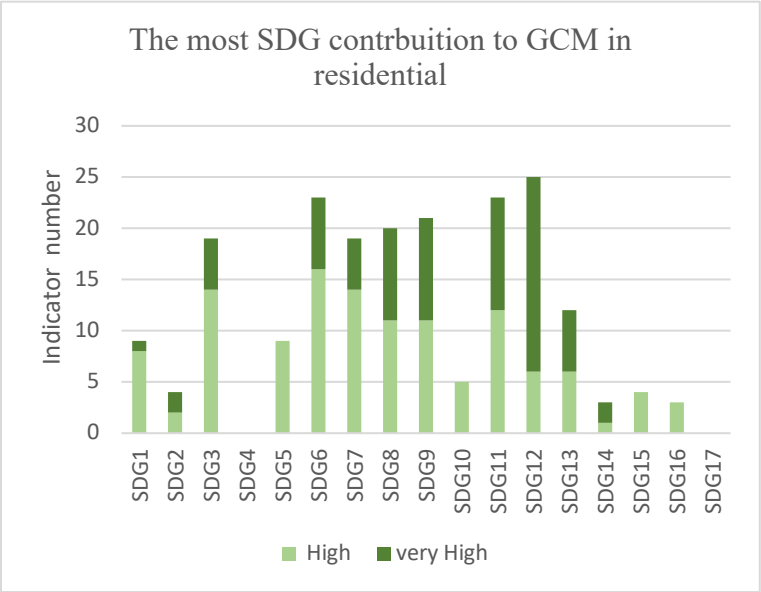


Fig 11. Most GCM-SI and SDGs contribute to high and very high levels through the sustainability pillars.

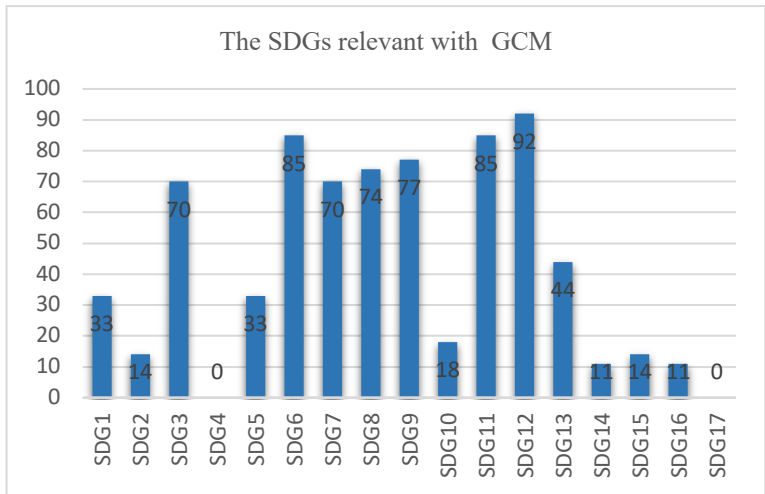


Fig 12. The most relevant SDGs for using GCM in residential buildings.

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Registry number: DEENK/597/2024.PL
Subject: PhD Publication List

Candidate: Madi Heba Alsayed Marey
Doctoral School: Doctoral School of Earth Sciences
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List of publications related to the dissertation

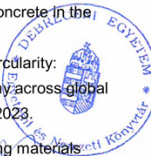
Foreign language scientific articles in international journals (2)

1. **Marey, H.**, Kozma, G., Szabó, G.: Green concrete materials selection for achieving circular economy in residential buildings using system dynamics.
Cleaner Materials. 11, 1-19, 2024. ISSN: 2772-3976.
DOI: <http://dx.doi.org/https://doi.org/10.1016/j.clema.2024.100221>
2. **Marey, H.**, Kozma, G., Szabó, G.: Effects of Using Green Concrete Materials on the CO₂ Emissions of the Residential Building Sector in Egypt.
Sustainability. 14, 1-22, 2022. ISSN: 2071-1050.
DOI: <https://doi.org/10.3390/su14063592>
IF: 3.9

List of other publications

Foreign language abstracts (5)

3. **Marey, H.**: The Role of Using Natural-Based Solutions in Residential Building Materials for Achieving Sustainable Development Goals.
In: EGU General Assembly 2024, European Geosciences Union, Vienna, 1 (EGU24-6592), 2024.
4. **Marey, H.**, Kozma, G., Szabó, G.: Towards Circular Economy by Using Green Concrete in the Egyptian Building Sector.
In: EGU General Assembly 2023 : Session ITS3.1/ERE4.7 Challenges of circularity: Considering the energy and material demands/benefits of a circular economy across global supply chains, European Geosciences Union, Munchen, 1 (EGU23-4293), 2023.
5. **Marey, H.**, Kozma, G., Szabó, G.: Developing a framework for sustainable building materials criteria in Egypt.
In: XXV. Tavaszi Szél Konferencia 2022 : Absztraktkötet. Szerk.: Molnár Dániel, Molnár Dóra, Doktoranduszok Országos Szövetsége, Budapest, 214, 2022. ISBN: 9786158205481





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6. **Marey, H.**, Kozma, G., Szabó, G.: Using the Nature-Based Solutions for Applying Circular Economy for the Construction Materials Sector in Egypt.
In: EGU General Assembly Conference Abstracts, European Geosciences Union, Munchen, 1 (EGU22-7997), 2022.
7. **Marey, H.**, Kozma, G., Szabó, G., Péntes, J.: Investigate Renewable Energy production challenges and Opportunities in Egypt.
In: X. Magyar Földrajzi Konferencia : Absztraktkötet. Szerk.: Karátson Dávid, Nagy Balázs, A Földgömb az Expedíciós Kutatásért Alapítvány, Budapest, 200-201, 2021. ISBN: 9786150128993

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