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RESUSPENSION VELOCITY PREDICTION OF FINE SEDIMENT USING RADIAL BASIS FUNCTION AND RECURRENT NEURAL NETWORK

Ren Jie Chin[1*], Sai Hin Lai[2], Kok Zee Kwong[3]

Abstract

Siltation, originating from urbanisation and large-scale development, constitutes a form of water pollution precipitated by the presence of fine sediment, primarily silt and clay. As runoff from sloping terrain carries eroded soil into water bodies, it gives rise to turbid water, detrimentally impacting water quality. Despite numerous research efforts to investigate sedimentation concerns, a comprehensive understanding of siltation problems is still limited. Hence, this study aims to formulate a mathematical model to predict the resuspension velocity of fine sediment in water bodies. Two distinct techniques were employed to construct the predictive model, namely radial basis function (RBF) and recurrent neural network (RNN). The input variables included particle size, flow rate, y-axis movement, d_{max}, and d/d_{max}, while resuspension velocities served as the output. To ensure robust training, the experimental data were partitioned into a ratio of 80:20, with 80% allocated for training and the remainder for testing. The efficacy of the developed AI models was assessed using metrics such as mean absolute error (MAE), root-mean-square error (RMSE), and coefficient of determination (R^2). RBF appears as the model with better performance, with MAE of 0.0003, RMSE of 0.0003 and R^2 of 0.6584.

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Fine sediment; Radial basis function; Recurrent neural network; Resuspension velocity

1.0 INTRODUCTION

Siltation represents a significant challenge stemming from urbanisation and large-scale development, resulting from the presence of fine sediment, commonly comprised of silt and clay. The runoff of fine sediment from sloped terrain and eroded soil into water bodies substantially impacts water quality, typically with adverse consequences. In Malaysia, several guidelines and regulations exist to manage erosion and sediment, including the Environment Quality Act 1974 by the Department of Environment Malaysia, as well as the Guideline for Erosion and Sediment Control (DID, 2010) and Urban Stormwater Management Manual for Malaysia (MSMA2) (DID, 2012) by the Department of Irrigation and Drainage Malaysia. Retention ponds are mandated in development projects to address erosion control and flood mitigation. However, numerous ponds are encountering low dissolved oxygen levels, primarily due to elevated biological oxygen demand. The persistent issue of siltation within these ponds remains unresolved.

Numerous research endeavours have aimed to mitigate siltation and sediment pollution (Cui *et al.,* 2021; Khozani *et al.,* 2021; Mohammadi *et al.* 2021; Samantaray & Ghose, 2019; Yadav *et al.,* 2021). However, there remains a notable gap in the exploration of fine sediment prediction, particularly within retention structures, owing to the intricate hydrodynamic behavior of fine sediment in water (Deng *et al.,* 2019; Zhang *et al.,* 2020; Zhuang, *et al.,* 2020). Current methods for fine sediment study, particularly particle image velocimetry (PIV) (Kashani *et al.,* 2016a; Kashani *et al.,* 2016b), though effective, are prohibitively costly and impractical for widespread use.

Artificial intelligence, with its capacity for machine learning, offers a viable solution capable of processing vast amounts of complex data, provided sufficient data is supplied to the model. While several studies have explored artificial intelligence in water management, such as water level prediction (Deng, *et al.,* 2021; Deng, *et al.,* 2022), reservoir operation (Chaves *et al.,* 2004), nitrogen level prediction (Chin, *et al.,* 2022) and wall slip researches (Chin *et al.,* 2019; Chin *et al.,* 2020). Therefore, the primary focus of this study is to develop a model to predict the resuspension velocity of fine sediment in water bodies.

2.0 MATERIALS AND METHODS

2.1 Data Collection and Preparation

The dataset utilised in this investigation originates from a prior study (Kashani *et al.,* 2016a), focusing on the hydrodynamic characteristics of fine sediment within retention structures using Particle Image Velocimetry (PIV). It comprises 297 data sets, each featuring six parameters: particle size (μm), flow rate (cm/s), y-axis movement (mm), maximum diameter (d_{max}, mm), the ratio of particle diameter to maximum diameter (d/d_{max}), and the velocity of fine sediment (m/s). The dataset was divided into a training set comprising 80% of the data and a testing set containing the remaining 20%.

2.2 Model Development

In this study, MATLAB was used for the model development. The radial basis function (RBF) network comprises three fixed layers: an input layer, a hidden layer utilising radial basis functions, and an output layer, as shown in Figure 1. The input layer receives the training data, while the hidden layer employs a radial basis Gaussian function as its activation function. The output layer utilises a linear function to produce output. Training the radial basis function network model is straightforward and offers relatively fast training speeds compared to other types of neural networks. The dataset is organised and classified into matrix form for training within the RBF network model. Training the radial basis function network model is user-friendly and exhibits relatively rapid training speeds in comparison to other neural networks. The dataset is structured and organised into a matrix format for training within the RBF network model. The only adjustable training parameter in the RBF network model developed in MATLAB is the spread constant. Consequently, the training process involves various values for the spread constant, starting from 0.1 to 1.0, with incrementing in intervals of 0.1. The detail of the model development is shown in Table 1.

On the other hand, the architecture of the Recurrent Neural Network (RNN) model varies in terms of the number of layers and nodes, depending on the input values of both parameters. Information input into the RNN model is processed through a loop within the layers, where the output of each layer serves as the input for the subsequent layer, thus allowing for the refinement of results, as shown in Figure 2. Consequently, training the RNN model requires a longer duration due to this iterative process. MATLAB offers the Layer Recurrent Network, which enables users to customise the training function, learning function, and performance function of the network model. The user interface facilitates easy adjustment of the desired number of layers and neurons to meet specific requirements. The RNN model employed the TRAINLM training function, LEARNGDM learning function, and MSE performance function.

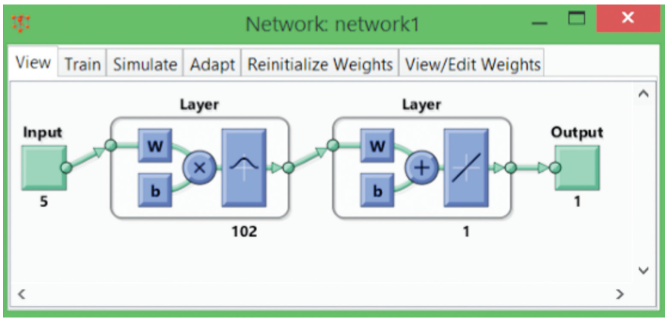

Figure 1: Architecture of RBF model

Table 1: Detail of the developed RBF models

Models	Spread Constant
Model I	0.1
Model II	0.2
Model III	0.3
Model IV	0.4
Model V	0.5
Model VI	0.6
Model VII	0.7
Model VIII	0.8
Model IX	0.9
Model X	1.0

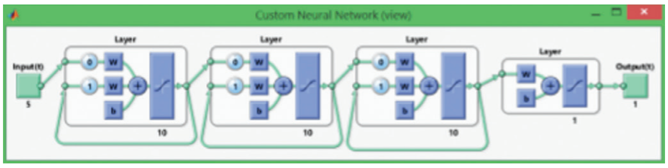

Figure 2: Architecture of the RNN model

Table 2: Detail of the developed RNN models

Models	No. of Neuron			
	Layer 1	Layer 2	Layer 3	Layer 4
Model I	20	10	1	-
Model II	20	20	1	-
Model III	20	30	1	-
Model IV	30	10	1	-
Model V	30	20	1	-
Model VI	30	30	1	-
Model VII	10	10	10	1
Model VIII	20	20	20	1
Model IX	30	30	30	1

The adjustable training parameters include epoch, training time, goal, minimum gradient, and maximum number of failures. However, after several training attempts, altering these parameters does not significantly impact the outcomes. Consequently, these parameters are kept constant for subsequent training sessions, with values set as follows: (i) epoch number: 1000, (ii) training time: infinity, (iii) goal: 0, (iv) minimum gradient: 1x10-7, and (v) maximum number of failures: 6. The RNN model was trained with varying numbers of layers and neurons as shown in Table 2.

2.3 Evaluation Metrics

On the other hand, the model evaluation is an essential step to test the accuracy or reliability of a model in performing the prediction. In this study, three statistical indicators were chosen for analysis purposes and comparison, which are mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination (R^2) (Lai *et al.,* 2022; Loh *et al.,* 2021). The equation for MAE, RMSE and R^2 are as shown:

$$\text{MAE} = \frac{\sum|y_i - x_i|}{n} \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum(y_i - x_i)^2} \quad (2)$$

$$R^2 = \left[\frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - (\sum x_i)^2}\sqrt{n\sum y_i^2 - (\sum y_i)^2}}\right]^2 \quad (3)$$

where n is the number of data pairs, x is the observed variable, and y is the predicted variable.

3.0 RESULTS AND DISCUSSION

3.1 Model Evaluation for RBF

Table 3 shows the statistical analyses of the developed RBF models. To rank the model with better performance, lower MAE and RMSE values are preferable, indicating a lower error of the model. Meanwhile, for the comparison in terms of R^2, a higher value should be selected, showing that the predicted value fits closer to the actual value.

In general, the MAE value ranges between 0.0003 and 0.00059. The lowest MAE value was recorded at 0.0003, by Models I and II. Meanwhile, from the perspective of RMSE, both Model I and Model II have shown a similar value, which is 0.0003. The RMSE value is the lowest if compared with the other developed RBF models.

On the other hand, R^2 value approaching 1 represents a better proportion of the variance in the predicted variable in a regression model. A higher R^2 value is always favourable. Hence, for this study, the highest R^2 value is 0.6584, recorded by Model II.

In summary, based on the statistical metrics, such as MAE, RMSE and R^2, Model II appears as the best-performed model as it has the lowest MAE and RMSE values, showing at 0.0005 and 0.0006 respectively, and the highest R^2 value of 0.6584.

Table 3: Statistical analyses of the developed RBF Models

Models	MAE	RMSE	R^2
Model I	0.0003	0.0003	0.6345
Model II	0.0003	0.0003	0.6584
Model III	0.0012	0.0013	0.0881
Model IV	0.0006	0.0007	0.4452
Model V	0.0015	0.0019	0.0117
Model VI	0.0011	0.0016	0.0083
Model VII	0.0019	0.0028	0.0005
Model VIII	0.0028	0.0044	0.0090
Model IX	0.0041	0.0070	0.0201
Model X	0.0059	0.0109	0.0239

Table 4: Statistical analyses of the developed RBF Models

Models	MAE	RMSE	R^2
Model I	0.0004	0.0009	0.3148
Model II	0.0006	0.0008	0.2446
Model III	0.0007	0.0014	0.1384
Model IV	0.0007	0.0010	0.1929
Model V	0.0005	0.0006	0.3558
Model VI	0.0006	0.0009	0.2143
Model VII	0.0005	0.0009	0.2873
Model VIII	0.0003	0.0003	0.4381
Model IX	0.0004	0.0004	0.3611

Table 5: Comparison between the outperformed RBF and RNN models

Models	MAE	RMSE	R^2
RBF Model II	0.0003	0.0003	0.6584
RNN Model VIII	0.0003	0.0003	0.4381

3.2 Model Evaluation for RNN

Table 4 presents the statistical analyses of the developed RNN models, in terms of MAE, RMSE, and R^2. Across the models, MAE values range from 0.0003 to 0.0007, showing the difference in terms of MAE among the models is relatively small. Meanwhile, referring to the RMSE, the highest value is 0.0014 while the lowest value is 0.0003, recorded by Model III and Model VIII, respectively. On the other hand, in terms of R^2, the value varies from 0.1384 to 0.4381. The lowest value is shown by Model III, indicating the predicted value of Model III has a relatively high deviation from the actual value.

In a nutshell, considering MAE, RMSE, and R^2, Model VIII emerges as the best-performing model with the lowest MAE and RMSE values of 0.0003 and 0.0003 respectively, along with the highest R^2 value of 0.4381.

3.3 Summary

From the statistical analyses, RBF Model II and RNN Model VIII outperform the other RBF and RNN models. With a further comparison between the two selected models, according to Table 5, it is noticed that the RBF Model II has shown a better performance than the RNN Model VIII. In terms of MAE and RMSE, both models exhibit the same value, recorded at 0.0003, which is a relatively small value. Meanwhile, from the perspective of R^2 as shown in Figures 3 and 4, RBF Model II displays a higher value, recorded at 0.6584.

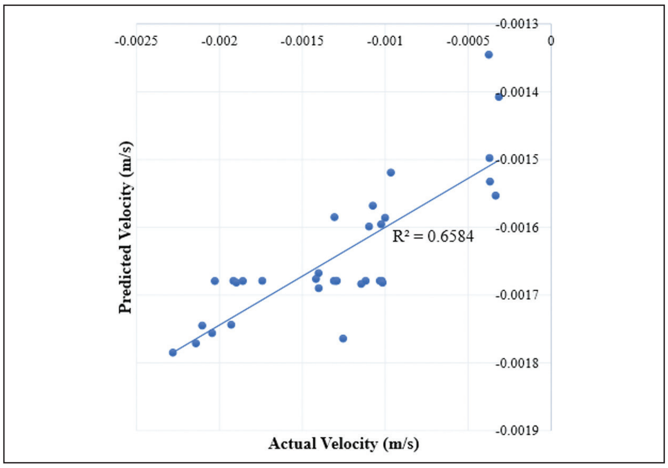

Figure 3: Scatter plot of predicted resuspension velocity versus actual resuspension velocity for RBF Model II

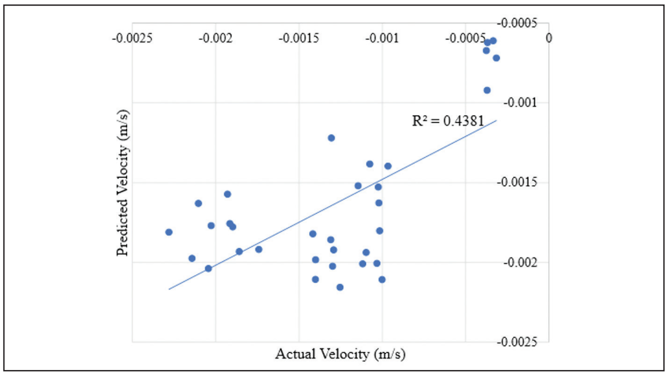

Figure 4: Scatter plot of predicted resuspension velocity versus actual resuspension velocity for RNN Model VIII

4.0 CONCLUSION

Two different mathematical models were utilised for the training and testing processes to predict the resuspension velocity of fine sediment. Each model employed a distinct approach to handling the data. The efficiency of the RBF model surpassed that of the RNN model. The RBF network exhibited faster training times and offered a more straightforward operational procedure compared to the RNN. In terms of result analysis, the RBF network model achieved R^2 values closer to 1 (with a value of 0.6584) in the resuspension velocity prediction task, outperforming the RNN model, with a value of 0.4381. Meanwhile, the MAE and RMSE values of the best-performed model for both RBF and RNN techniques are the same.

This study is limited to the application of RBF and RNN models. The model accuracy may be further improved. So, there are some recommendations for future work. First of all, a wider range of datasets could be collected to improve the prediction accuracy of the developed AI models. In addition, rather than having conventional machine learning models, hybrid or metaheuristic AI approaches (such as artificial neural network-particle swarm optimisation (ANN-PSO) model, genetic algorithm based support vector machine (GA-SVM) model, etc.) can be implemented to predict the resuspension velocity of fine sediment in water bodies. ■

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AUTHORS' CONTRIBUTIONS

- **Ren Jie Chin**: Conceptualisation, study design, data collection, formal analysis and Writing—original draft preparation.
- **Sai Hin Lai**: Conceptualisation, and Supervision.
- **Kok Zee Kwong**: Literature review, and Writing—Review and Editing.

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COMPARATIVE ANALYSIS OF CARBON EMISSIONS BETWEEN REINFORCED CONCRETE AND STEEL STRUCTURES IN A LOW-RISE COMMERCIAL BUILDING

Zhi Xian Chew[1], Yu Hoe Tang[2*], Jing Ying Wong[3]

Abstract

The construction industry's rapid expansion has brought various environmental challenges, such as greenhouse gases, specifically in terms of carbon emissions. Construction industry contributes more than half of the global greenhouse gas emissions, leading to climate change. This study aims to evaluate and compare the embodied carbon emissions of two commonly used construction materials used in Malaysia, which are reinforced concrete and steel structure, applied to a four storeys commercial building. This research utilises a comparative life cycle assessment (LCA) approach to access the carbon emissions during both the construction and demolition phases. Building Information Modelling (BIM) is used to develop the structural models and perform quantity take-off to obtain primary data for the carbon emissions' calculations of the reinforced concrete and steel structure. The study findings indicate that the reinforced concrete structure has carbon emission of 288.71 tCO_2 while the steel structure emitted 32% less carbon of 196.49 tCO_2 during the construction phase. In the demolition phase, the reinforced concrete structure produces 28.87 tCO_2, compared to 19.65 tCO_2 for the steel structure. These results show the potential of steel structures to significantly reduce embodied carbon emissions. This study aligns with Malaysia's sustainability goals, including its commitment to reducing greenhouse gas emissions under the Paris Agreement and its efforts to promote green building practices. By prioritising steel as a primary building material, the construction industry can make substantial progress toward achieving sustainable construction. Practitioners are encouraged to adopt steel and other eco-friendly materials while utilising tools like BIM to facilitate data-driven decision-making and enhance sustainability in design and construction. This research highlights the need for industry-wide advocacy, and policy incentives to drive the adoption of low-carbon construction practices in Malaysia.

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Building information modelling (BIM), Carbon emissions, Reinforced concrete structure, Steel structure, Sustainable construction

1.0 INTRODUCTION

The construction sector is one of the most active industries in any economy especially in the developing countries experiencing rapid growth and urbanisation. This industry encompasses a variety of activities, including manufacturing, building, renovating, repairing, and demolishing structures and infrastructures, all of which contribute significantly to a country's economic development. Countries such as India, China, Japan, United States, and Canada have made significant contributions to the industry, with an average growth rate of 67% worldwide and a 5.2% annual increase, resulting in substantial improvements each year (Onat & Kucukvar, 2020).

Despite these benefits, the construction industry's rapid growth has led to significant environmental impact, namely, the greenhouse effect, which contributes to global warming. The term "greenhouse" refers to atmospheric gases that are transparent to solar radiation, similar to the effect of glass in a greenhouse (Mitchell, 1989). Some of the most prevalent greenhouse gases are carbon dioxide, methane, and water vapour (Berman *et al.,* 2012). In this regard, buildings are the primary source of greenhouse gas emissions, contributing to 28% of global emissions (Röck *et al.,* 2020). Furthermore, the construction industry is responsible for 37% of global carbon emissions, with developing countries accounting for the majority of the industry's carbon footprint (Zhou *et al.,* 2022).

Construction is considered the most material intensive activity (Bui *et al.,* 2016) and carbon emissions based on different materials used for the construction of a building differs likewise. Although the operational stage in a building's life cycle contributed over 80% of the total energy used including the carbon emissions (Li & Chen, 2017), the main objective in this research would be focusing on the construction and demolition of the multi-storeys building with different materials of reinforced concrete and steel. The development of the Building Information Modelling (BIM) has progressed rapidly and provided efficient methods for the implementation of Life Cycle Assessment (LCA) in recent years (Lu *et al.,* 2019). The combination of BIM and LCA could provide a platform to determine the carbon emissions of the multi-storeys building during the construction and demolition periods.

Low-rise buildings such as terrace houses and shop lots are a dominant feature of Malaysia's urban and suburban landscapes. Terrace houses are among the most common residential developments in Malaysia. They are typically arranged in rows, sharing party walls, which makes them a cost-effective and space-efficient housing solution. Similarly, shop lots are found in towns and cities nationwide, where these low-rise structures serve as a base for small businesses on the ground. It makes them an integral part of local economies, particularly in smaller towns and suburban neighbourhoods. The construction of low-rise buildings in Malaysia has seen a steady increase, driven by the rising demand for affordable and versatile spaces. Developers often choose low-rise projects for their shorter construction timelines, reduced costs, and adaptability to Malaysia's tropical climate (Lapisa *et al.,* 2018).

Malaysia has set a goal of becoming a carbon-neutral country by 2050 (Hamid, 2017). Despite the implementation of several policy frameworks at the national and city-level, there has been a lack of action taken by both industries and communities. This inaction could be attributed to the limited amount of research available that proves that industrial activities in Malaysia are causing serious environmental pollution. As a result, the severity of environmental degradation is not fully understood by both current and future generations. Therefore, this research paper aims to evaluate and compare the carbon emissions of materials of reinforced concrete and steel during construction and demolition for a low-rise four storeys building designed for commercial use. It will provide new insights on the carbon emissions of different building materials in Malaysia, which could help raise awareness among the construction communities. The comparison in this study could act as a reference and assist the selection of structural system of buildings in Malaysia.

2.0 LITERATURE REVIEW

An overview of the greenhouse gases, specifically carbon emissions would be presented next, followed by Life Cycle Assessment (LCA) which serves as the primary tool applied in this study. In addition, Building Information Modelling (BIM) and the use of typical construction materials are briefly explained below.

2.1 Greenhouse Gases

Many studies indicated that the construction industry is the primary contributor of global greenhouse gas (GHG) emissions, which plays a significant role in global warming (Hong *et al.,* 2015). Greenhouse gases are formed by carbon dioxide, methane, nitrous oxide, water vapour, and fluorinated gases, with carbon dioxide as the primary emitted gas. Nowadays, the construction of new buildings as well as for the refurbishment of existing buildings account for 11% of global overall energy thus process greenhouse gases, with more than half of the emissions related to the materials of cement and steel (Röck *et al.,* 2020). Greenhouse gases are also called as the radiatively active gases in the Earth's atmosphere which could increase the global mean surface temperature by 30K. The rise in the gases has led to an increase in radiative heating at Earth's surface, resulting in changes to water vapour, snow cover, sea ice, and cloud patterns, contributing to the observed warming trend to date. (Mitchell, 1989). As it leads to the global-mean surface warming becomes very probable, greenhouse effect comes about where greenhouse gases tend to absorb and keep the energy from being radiated back into the space when solar radiation hits the Earth (Lave, 1988). Based on Lave (1988), greenhouse effect has attributes of being:

- Global: all regions are affected.
- Long term: the impacts are undetectable in the future.
- Ethical: involves human who are not born yet, plants, animals, and the environment.
- Potentially catastrophic: large changes in environment, massive loss of human life and properties.
- Contentious: the difficulty of enforcing agreements even when there are incentives for individual nations to cheat.

2.2 Carbon Emissions in Building Structures

In 2012, global energy-related carbon dioxide emissions reached a historic high of 31.6 gigatonnes with buildings contributed a quarter of the global total carbon emissions (Hong *et al.,* 2015). For instance, China had become the greatest carbon emitter country in the world since 2008 for its continuous economic boom which attracted extensive attentions from academia, politicians, and the public (Zhang *et al.,* 2014). 27.9% to 34.3% of the overall carbon emissions from construction industry are estimated in China between 1995 and 2010 which had resulted in a substantial amount (Du *et al.,* 2018).

Four major emissions sources on construction sites are summarised which are the building materials production and transportation, energy use during construction such as machine, energy use for processing resources, and the disposal of construction waste. There are many methods in measuring the carbon emissions such as the Life Cycle Assessment (LCA) as well as the carbon emissions coefficient method (Hu *et al.,* 2022) which would be presented in this research study. The carbon emissions factors are the coefficients used to measure the amount of carbon dioxide released due to construction activities. There are two types of emissions during construction, which are the direct and indirect emissions as stated as below (Zhou *et al.,* 2022):

1. Direct emissions
   - Energy consumption of construction equipment
   - Onsite transportation
   - Construction electricity usage
   - Assembly and miscellaneous works (welding and thermal insulating)
   - Onsite worker activities
2. Indirect emissions
   - Building materials production and transportation
   - Transportation of construction equipment
   - Offsite staff activities

In addition, the carbon emissions are also categorised into the embodied carbon emission and the operation carbon emission. The embodied carbon emission focuses on the construction phase such as manufacturing, transportation, installation, and demolition while the operation carbon emission emphasis on the energy consumption (Wan Omar *et al.,* 2014). Figure 1 presents the carbon emissions of a building whole life cycle from production to demolition (Zhou *et al.,* 2022). The figure shows that design phases would start by producing the best proposal before the launching of construction phase. The carbon emissions could be calculated based on the figure below for the life cycle of a building to obtain data to reduce the carbon emissions into the surroundings.

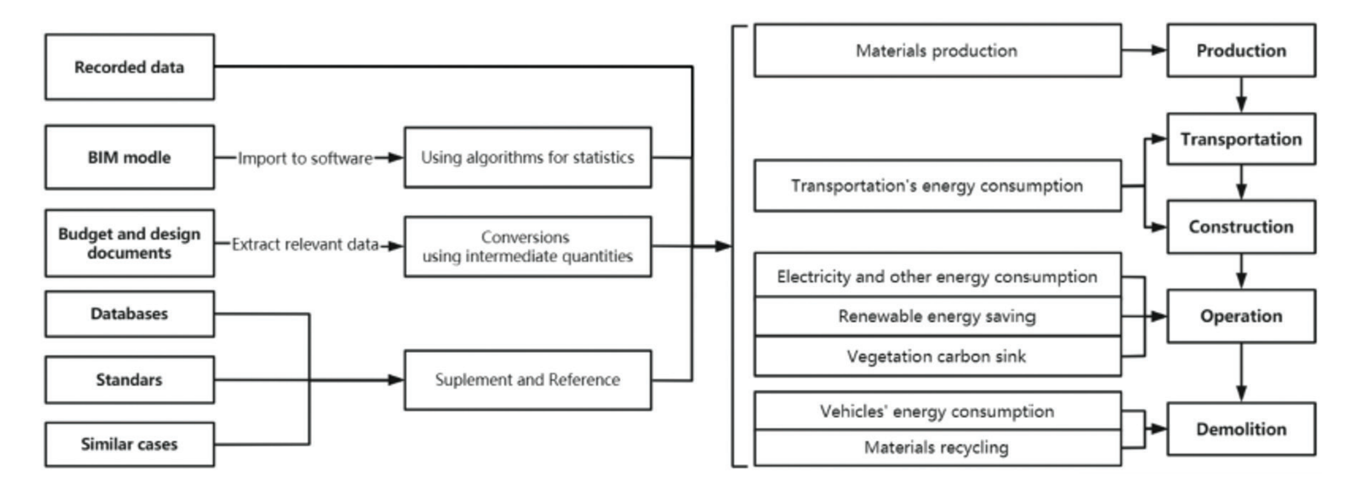

Figure 1: Building whole life cycle carbon emissions framework (Zhou et al., 2022)

2.3 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is used to examine the environmental and social impacts for a building's entire life cycle (Lu *et al.,* 2019). It aims to evaluate the environmental burdens associated with a product, process, or an activity by identifying and quantifying the energy and material uses that would release back to the environment, as well as evaluate and implement opportunities to affect the environmental improvements (Chau *et al.,* 2015). The interest in LCA has grown significantly since the 1990s when it was met with high expectations, but its results were often criticised. Since then, a strong development and harmonisation has taken effect, produced an international standard and complemented by several guidelines (Finnveden *et al.,* 2009). The first appearance of LCA in its current modern understanding was in a study held by Coca-Cola to assess the environmental impacts of cycle from cradle to grave (Hunt & Franklin, 1996).

There were more initiatives taken to standardise the application of life cycle assessment, such as the Canadian Standards Association released the world's first national LCA guideline Z-760 Environmental Life Cycle Assessment in 1994 (Khasreen *et al.,* 2009). The development of the International Standards for life cycle assessment has become an important move to consolidate the procedures and methods of LCA (ISO, 2016). The organisation has developed with two latest standards that act as references to all stakeholders and the international community:

- ISO 14040:2006, Environmental management- Life cycle assessment
  Principles and framework, offers a clear overview of the practice, applications, and limitations of LCA to a broad range of potential users and stakeholders, including those with a limited knowledge of life cycle assessment.
- ISO 14044:2006, Environmental management- Life cycle assessment
  Requirements and guidelines, is designed for the preparation of, conduct of, and critical review of. Life cycle inventory analysis. It also offers guidance on the impact assessment phase of LCA and on the interpretation of LCA results, as well as the nature and quality of the data collected.

Both standards are the latest updated versions from the previous standards of ISO 14040:1997, ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000 with improvements on the readability and minor amendments. In the construction industry, all stakeholders such as designers, engineers and contractors are all affected by the trend of sustainable production and eco-green strategies. LCA could become a method to assist in achieving sustainable building practices by obtaining environmental-related information such as the amount of carbon emissions for different phases of building's life cycle (Khasreen *et al.,* 2009). Figure 2 below shows the framework of the whole life cycle assessment which could evaluate all resources inputs, including energy, water, materials, and environmental loadings such as carbon dioxide, solid or liquid wastes of a product (Chau *et al.,* 2015).

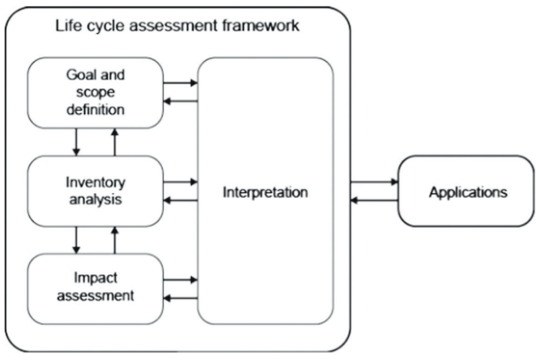

Figure 2: Life cycle assessment framework (Chau et al., 2015)

2.3.1 Integration of Life Cycle Assessment in Environmental Evaluation

Life Cycle Assessment (LCA) is extensively utilised as a method that systematically evaluates the environmental impact of a building throughout its entire life cycle. Xu *et al.* (2022) developed a BIM-integrated LCA solution to automate the environmental assessment of prefabricated buildings based on a five-level framework, consisting of material, component, assembly, flat, and building. The framework was developed based on three modules, such as the BIM data preparation, data extraction and integration, and embodied carbon (EC) assessment. In addition, Kayacetin and Tanyer (2019) developed an integrated LCA-EC assessment method for the built environment at neighbourhood scale which the results were validated based on three neighbourhood-scale mass housing projects in Ankara, Turkey.

Khan *et al.* (2022) aimed to provide a comprehensive and holistic approach to data analysis, including measurement, management, and reduction of embodied carbon. It also analyses the introduction of the assessment process from the early stages of building design and to explore mitigation and management strategies at different levels, such as the neighbourhood, urban, and national levels. Other than that, a study investigates the variations of EC intensities of materials and identifies their parameter variations in hybrid life cycle assessment (Omar, Doh & Panuwatwanich, 2014). The Malaysian Input-Output (I-O) tables are used to derive indirect energy and carbon intensities which are then merged for detailed process LCA analysis. Liang *et al.* (2023) had done further step to account for the embodied carbon emissions in buildings in 2020 for the Guangdong-Hong Kong Macau Greater Bay Area in China (GBA). They integrated remote sensing techniques such as night-time light data (NLT) and building material flows analysis to calculate and spatialise the newly generated building material stocks (MS) using LCA method.

2.4 Building Information Modelling (BIM) in Construction Industry

Building Information Modelling (BIM) is widely seen as a catalyst for innovation and productivity in the construction industry. It could assist for a more sustainable construction process which in turn might contribute to eradicating poverty in developing countries such as Malaysia, China, and India (Bui *et al.,* 2016). Complex construction projects from where buildings are conceived, designed, constructed, operated, maintained, and demolished require inter-organisational associations and to ensure success in project ventures, trust between the different projects partners is a key success factor. Therefore, BIM could be the key approach to create the integration by shifting all data to an Integrated Database paradigm for more efficient communications (Bryde *et al.,* 2013).

BIM software allows engineers and designers to build a 3D virtual model, and it can export information to other computer-modelling platforms to perform data analysis (Hao *et al.,* 2020). Due to the advancements in building materials and technology, the life cycle assessment (LCA) has become a great burden to engineers as the evaluation of environmental issues becomes more complicated. Thus, BIM software could assist in obtaining the information in an easy and accurate manner (Shin & Cho, 2015). Röck *et al.* (2018) proved that the BIM-integrated approach enables identification of design specific hotspots which can be visualised on the building model for communication of LCA results and visual design guidance.

2.5 Construction Material: Concrete

Concrete is the most common construction material in Malaysia. It is the mixed product of water, cement, fine aggregates, and coarse aggregates. The design of right water-cement ratio would produce strong and high compressive strength of concrete to withstand the loads of structures. For instance, the 163 storeys Burj Khalifa in Dubai, world tallest skyscraper was rose with more than 330,000 m^3 of concrete and 39,000 tons of steel rebar (Hamza, 2021). Portland cement is the most frequently seen manufactured finely ground power in the industry. The production of cement, which is an essential constituent of concrete, could lead to the release of significant amounts of carbon dioxide, where production of one ton of Portland cement produces about one ton of carbon dioxide (Naik, 2008). After water, concrete is the most widely used substance on Earth.

If the cement industry is a country, it would be the third largest carbon dioxide emitter in the world with up to 2.8 billion tons, surpassed only by China and United States (The Guardian, 2019). From 2013 to 2022, production of cement in Malaysia is at average of 20 million metric tons. In year 2022, Malaysia had produced 19.86 million metric tons of cement. As concrete is the most common construction material in Malaysia, Malaysia has many top-rated cement manufacturers which produce quality cement such as YTL Cement Berhad and Lafarge Malaysia. The nation's reliance on this material significantly contributes to its carbon footprint. This highlights the pressing need to address the environmental impact of cement and concrete production, particularly in the context of reducing carbon emissions. In the Malaysian context, addressing these challenges is particularly urgent given the country's commitment to international climate agreements, such as the Paris Agreement (Wong *et al.,* 2022). Reducing emissions from cement and concrete production aligns with broader efforts to transition to a low-carbon economy and achieve sustainability in the construction sector.

2.6 Construction Material: Steel

Steel is one of the most sustainable construction materials on Earth. This is due to the reason that many steel frame structures nowadays are designed in consideration for the demolition of the whole structure. Steel has many desirable characteristics which could be exploited in a wide range of construction applications. It is corrosion-resistant and long-lasting, making thinner and more durable structure possible. Furthermore, it could be presented in many possibilities of shapes and forms while being tough, hygienic, adaptable as well as recyclable (Baddoo, 2008). Therefore, using steel as construction materials brings more benefits especially for long life cycle building. The ECSC study has confirmed that steel construction products within Western Europe have high recycling rates with 83% recycling at the end-of-life cycle, 14% are re-used and only 3% are landfilled or disposed (Durmisevic, 2003).

The annual consumption of steel has increased at a compound growth rate of 5% over the last 20 years as steel producers are continually developing the manufacturing of steel with the aims of reducing cost, shortening lead times, and improving quality (Baddoo, 2008). In Malaysia, steel demand is increasing gradually, where Malaysia’s apparent steel consumption (ASC) predicted that the nation would reach 12.4 million metric tons in 2025. This increasing demand highlights the need to address the carbon footprint associated with steel production, as the construction industry's environmental impact is one of the largest contributors to global greenhouse gas emissions.

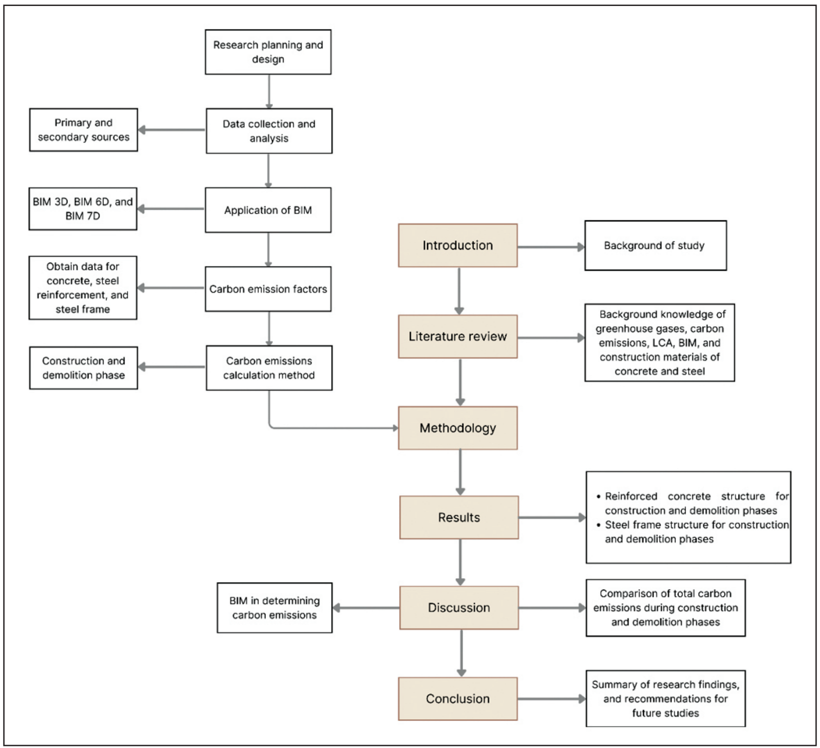

Figure 3: Research framework

- The research is mainly focusing on the materials' embodied carbon emissions; thus it will be categorised under indirect carbon emissions analysis.

The collected data obtained is further analysed using Microsoft Excel. The total carbon emissions of buildings are calculated based on the amount of concrete, steel rebars and the steel structure's components. Discussion is made in depth based on the findings obtained with the comparisons between reinforced concrete and steel structures that are being discussed and studied. Moreover, the application of Building Information Modelling (BIM) for conducting Life Cycle Assessment (LCA) of carbon emissions from buildings is also being evaluated.

3.3 Application of BIM

Figure 4 illustrates the BIM dimensions for the whole life cycle of the buildings. In this research study, some dimensions are included and applied to determine the carbon emissions for the construction and demolition phases of the multi-story building.

3.0 RESEARCH METHODOLOGY

The whole research process would be applied with the Life Cycle Assessment (LCA) for a more detailed investigation on this environmental issue. Life cycle assessment is an important tool to help decision making (Navarro *et al.,* 2020). The overall framework of the LCA is as presented in Figure 2. In addition, a research flow chart, integrating the LCA procedure is presented in Figure 3, to produce a more sequenced evaluation process.

3.1 Research Planning and Design

The research performs a case study analysis, utilising a multi-story building which would give an outcome on the amount of carbon dioxide emitted by both RC and steel buildings, using the units of $kgCO_2$ or tCO_2. In addition, the research further studies the recommendations on the application of Building information modelling (BIM) and its tools in determining carbon emissions.

3.2 Data Collection and Analysis

The data collection is divided into two categories:

- Primary sources
  Two 3D models for reinforced concrete and steel are designed and modelled using Autodesk Revit 2022 to review and obtain the material quantities such as volume used for the whole building through quantity take off method.
- Secondary sources
  The embodied carbon coefficient factors are referred to research articles and journals before selecting the preferred factors to use for concrete, steel reinforcement bar and steel.

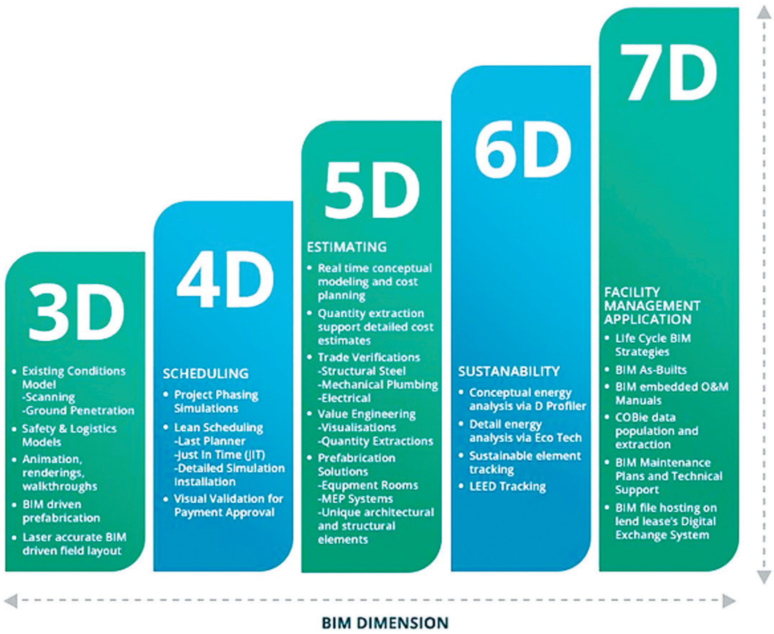

Figure 4: BIM dimensions (Rodriguez, 2022)

1. BIM 3D

3D models of reinforced concrete of steel structures are designed based on loading calculations and detailed calculations on beams, columns, and slabs. The pad foundation of both structures is designed as well but it would not be considered in the comparison due to the same dimension. Autodesk Revit 2022 is used to draw and visualised the two models. After the models are completed, quantity take off is generated from Autodesk Revit 2022 as well to obtain the data as below:

- Construction material name and types
- Columns' locations
- Columns', beams', and slabs' levels

- Types of Universal Column and Beam
- Lengths of column and beam
- Cross sectional areas of concrete columns and beams
- Areas of slabs
- Volumes of columns, beams, and slabs

An example of the information obtained from Revit 2022 is provided in the Appendix.

2. BIM 6D

Both buildings are analysed to obtain the carbon emissions and discuss the comparison between two construction materials for the construction and demolition phases. Moving on, suggestions on approaches to reduce carbon emissions will be made.

3. BIM 7D

BIM 7D mainly focus on the facility management such as operation and maintenance of the building during its life cycle. However, in this research paper, BIM 7D would be focusing on the carbon emissions during the demolition of both buildings.

3.4 Carbon Emission Factors

Carbon emission factor is also known as the carbon intensity and emission coefficient. It is a measure of the amount of carbon dioxide emitted per unit of activity, typically $kgCO_2$/kg, tCO_2/m^3 and tCO_2/t. They are used to calculate the carbon footprint and to assess the environmental impact of the construction materials. Various sources are referred to determine the appropriate carbon emissions factor for this study. As this research focuses on the construction materials, hence the coefficients of concrete, steel reinforcement bar and steel frame are obtained. Based on the design of the reinforced concrete structure, concrete of grade 30 MPa is used.

Tables 1, 2, and 3 show the summarised data collection of embodied carbon emission factors from various sources. The research is an indirect carbon emissions analysis, as the study is focusing on comparing two materials' embodied carbon emissions. Based on the data obtained, it shows that most of the research regarding the carbon footprint in construction industry are carrying out in China, as China is one of the greatest carbon emission countries. The carbon emission factors from Li *et al.* (2021) are adopted for this investigation, because it offers the latest research outcomes, compared to other research papers. This paper has evaluated the impacts and values of carbon emissions by analysing four building projects in the Fujian Province of China. Apart from that, the coefficient from Zhang (2021) with the greatest value of 0.3410 $kgCO_2$/kg is not selected in this paper due to the reason that the coefficient included the production and transportation of the concrete carbon emission.

3.5 Carbon Emissions Calculation Method

3.5.1 Construction Phase

The carbon emissions (ec_i) of concrete, steel reinforcement and steel frame in BIM could be computed using the equation:

$$ec_i = \sum_{j=1}^{n} ecf_j * q_j \tag{1}$$

where $i = 1... ...m, ecf_j$ includes the embodied carbon emission factors for different material types used in building component (concrete, steel, etc.) which could be obtained from section 3.4. q_j is the material quantity obtained directly from the BIM model (Eleftheriadis **et al.,** 2018). The resulting values are calculated in $kgCO_2$ using equation above.

Based on Eleftheriadis (2018) the total embodied carbon could also be calculated by the sum of the embodied carbon emissions from all the building components divided by the total internal floor area from ground floor (a_1) to the top floor (a_k) using the equation below:

$$EC = \sum_{i=1}^{m} ec_i \, / \sum_{z=1}^{k} a_z \tag{2}$$

Where k is the total number of floors. Therefore, in this case the carbon emissions should calculated with the units of tCO_2/m^2 or $kgCO_2/m^2$. Table 4 shows the area for every floor and the total floor area of whole building obtained from the BIM room layout feature. Both building of reinforced concrete and steel frame have the same area for each floor.

Table 1: List of carbon emission factor for concrete

Coefficient	Unit	Publication	Article
0.3410	$kgCO_2$/kg	Zhang *et al.,* 2021	Sustainable design of reinforced concrete structural members
0.1590	$kgCO_2$/kg	Yan *et al.,* 2010	A Case study of One Peking in Hong Kong
0.2700	tCO_2/m^3	Li *et al.,* 2017	A case study in Shenzhen
0.2877	tCO_2/m^3	Li *et al.,* 2021	Using BIM to research carbon footprint
0.1980	$kgCO_2$/kg	Wan *et al.,* 2014	Assessment of the embodied carbon in precast concrete

Table 2: List of carbon emission factor for steel reinforcement

Coefficient	Unit	Publication	Article
1.242	$kgCO_2$/kg	Yan *et al.,* 2010	A Case study of One Peking in Hong Kong
2.206	tCO_2/t	Li *et al.,* 2017	A case study in Shenzhen
2.670	tCO_2/t	Li *et al.,* 2021	Using BIM to research carbon footprint
3.5862	$kgCO_2$/kg	Wan *et al.,* 2014	Assessment of the embodied carbon in precast concrete

Table 3: List of carbon emission factor for steel frame

Coefficient	Unit	Publication	Article
1.722	tCO_2/t	Li *et al.,* 2017	A case study in Shenzhen
1.860	tCO_2/t	Li *et al.,* 2021	Using BIM to research carbon footprint
1.740	$kgCO_2$/kg	Steelconstruction.info, 2013	Embodied carbon data for common framing materials

Table 4: Summary of floors' area

Floor	Level (m)	Floor Area	Unit
Ground Floor	0	297.000	m^2
First Floor	3.0	297.000	m^2
Second Floor	6.0	297.000	m^2
Roof Floor	9.0	76.125	m^2
Total	9.0	967.125	m^2

3.5.2 Demolition Phase

Due to the lack of basic data on building demolition, the relevant studies have widely used the empirical value method to estimate the carbon emissions in this phase (Architectural Institute of Japan, 2003). Based on several literature reviews on previous research articles, the demolition phase is dependent on the construction phase, as data for the demolition stage of buildings are difficult to obtain (Wang *et al.,* 2007). Lu & Wang (2019) had done much research on the demolition stage and found out that the demolition phase is approximately equal to 10% of the construction stage. Yao *et al.* (2023) had also utilised this analysis method to calculate the carbon emission of demolition phase for residential building in n Liaocheng City, Shandong Province, China. Therefore, the formula for the calculation to estimate the carbon emissions at the demolition stage is:

$$C_{dem} = C_{con} \times 10\% \quad (3)$$

where C_{dem} is the carbon emission of concrete, steel reinforcement and steel frame at demolition phase. C_{con} is the carbon emissions at construction phase, which is ec_i from section 3.5.1 above. The demolition phase would be executed at least after 50 years of the buildings' life cycle.

Table 5: Summary of volume and weight for concrete and steel reinforcement

Materials	Components	Volume (m^3)	Density (kg/m^3)	Weight (kg)
Concrete	Column	33.80	2380	80,444
	Beam	77.69	2380	184,902
	Slab	137.22	2380	326,584
	Total	248.71	2380	591,930
Steel Reinforcement	Column	1.41	7848	11,053
	Beam	3.24	7848	25,407
	Slab	5.72	7848	44,872
	Total	10.37	7848	81,331

4.0 ANALYSIS AND DISCUSSION

4.1 Reinforced Concrete Structure

The proposed low-rise multi-storey building is designed as hostel for the accommodation of guests who are visiting The University of Nottingham Malaysia. It has a Gross Internal Area (GIA) of 315m^2 (15x21m), equipped with 13 deluxe rooms including room for disabled individual at ground floor and few common areas. It takes 6 months to fully construct the building structure. The whole project involves the Building Information Modelling (BIM) dimensions from 3D to 7D and this research engages few parts in it. This structure is designed for a 50-year lifespan.

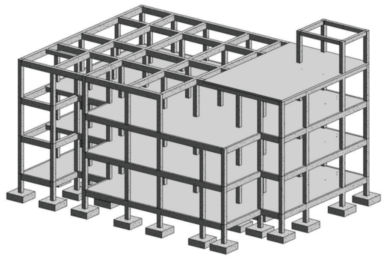

Figure 5: Reinforced concrete structure model

The reinforced concrete structural model is illustrated in Figure 5 and it is modelled using the intelligent 3D modelling in BIM. As shown in Figure 5, only the main construction components are included in the analysis, while other architectural and structural components such as walls, ceilings, doors, roofs, and façade are not included in the analysis. The foundations are not included in this study as both comparing structures have the same pad footing design. All quantities needed for the carbon emissions analysis are obtained from the primary source, which is from the model using quantity take-off method in Autodesk Revit 2022.

4.1.1 Construction Phase

After obtaining the data needed by quantity take-off in Revit 2022, the data analysis is conducted using Microsoft Excel. All components for concrete and steel reinforcement are analysed separately in spreadsheets. Table 5 shows the determination of weight for both materials. The concrete has a weight of 591.9 tons, which is around 7 times greater than the steel reinforcement. Table 6 shows the carbon emissions for each material as well as the grand total carbon emission for the whole reinforced concrete structure.

Table 6: Summary of reinforced concrete carbon emission

Materials	Components	Weight (kg)	Carbon Coefficient	Units	Carbon Coefficient ($kgCO_2/kg$)	Carbon Emission ($kgCO_2$)
Concrete	Column	80,444	287.70	$kgCO_2/m^3$	0.121	9,724
	Beam	184,902	287.70	$kgCO_2/m^3$	0.121	22,351
	Slab	326,584	287.70	$kgCO_2/m^3$	0.121	39,478
	Total	591,930	287.70	$kgCO_2/m^3$	0.121	71,554
Steel Reinforcement	Column	11,053	2.67	tCO_2/t	2.67	29,512
	Beam	25,407	2.67	tCO_2/t	2.67	67,836
	Slab	44,872	2.67	tCO_2/t	2.67	119,807
	Total	81,331	2.67	tCO_2/t	2.67	217,155
					Grand Total:	**288,709**

The carbon emission factors obtained from secondary sources as presented in section 3.4 are first converted to the same unit of $kgCO_2/kg$ before multiplying the weight to obtain the carbon emissions in $kgCO_2$. The grand total carbon emission for the whole structure is 288.71 tCO_2 with the slabs occupying the most quantity for both concrete and steel reinforcement. This is because slabs have the largest areas at every floor with thickness of 150mm.

Based on BS EN 1992-1-1:2004, the maximum percentage of steel reinforcement for column, beam, and slab are 4%. Therefore, it is proven that the volume of steel reinforcement remains as 4% of the volume of the reinforced concrete while the concrete grade 30 occupies the remaining 96% of the total volume. Based on the grand total carbon emission of 288.71 tCO_2, concrete only built up 24.78% from the grand total while steel reinforcement built up 75.22%. Concrete emitted 71.55 tCO_2 while steel reinforcement emitted 217.16 tCO_2. This shows that steel reinforcement is the dominant in the carbon emission of reinforced concrete. One of the reasons of high carbon emission in steel reinforcement might be the relatively high carbon emission factor as shown in Table 4.2. Steel reinforcement has a coefficient of 2.67 $kgCO_2/kg$ while concrete has coefficient of 0.121 $kgCO_2/kg$ only. In the result, the steel reinforcement coefficient is 22 times greater than concrete, conducting to more carbon emission despite having lesser volume than concrete.

As it is proven that steel reinforcement is the major contributor to the carbon emission of reinforced concrete, some approaches must be implemented to reduce the reinforcement carbon emission. For instance, steel could be reused for the cast in-situ construction as steel is very durable and long lasting without losing its properties. Based on the research of Mastali *et al.* (2018), using recycled steel as replacement for the steel reinforcement could reduce the carbon emissions by an average of 20% after conducting several investigations. In addition, proper management of materials should be implemented to avoid any material wastage during construction. The amount of materials needed for construction should be estimated and calculated in detailed and only order the adequate amount of steel reinforcement as well as concrete.

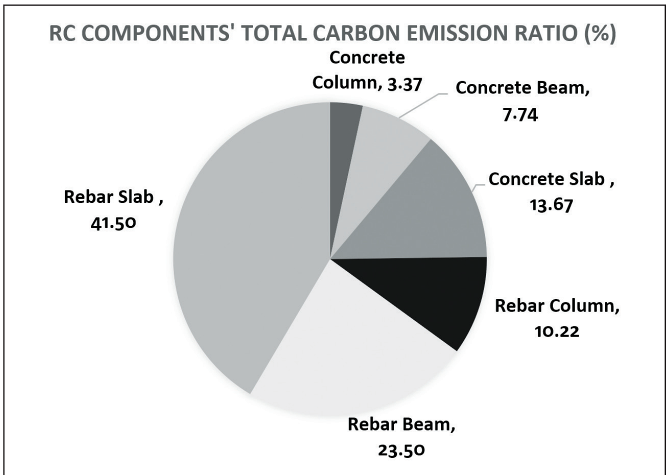

Figure 6: Reinforced concrete components' total carbon emission ratio

Moving on, the total carbon emission ratio for the reinforced concrete is illustrated in Figure 6. Based on the analysis by components, the reinforced slab contributed the most for both concrete and steel reinforcement due to its large volume. However, in this case the amount of steel reinforcement used for the cast in-situ slab is more critical due to the 41.50% of carbon emitted for the entire structure. Therefore, engineers should be more concerned about the reinforcement detailed designs to find a balance between the component's strength and the carbon emission. The greater the amount of volume for slab, the more steel reinforcement needed to increase the strength of the entire slab. In addition, the beam is the second most carbon emitted for the structure, with 31.24% contributed. Column has the least carbon emission with 13.59% emitted due to its lower volume but adequate strength to transfer the loadings to the foundations.

This has proven that Malaysia has emitted million tons of carbon dioxide in construction as reinforced concrete building is the most common structure design in Malaysia, no matter low-rise buildings or skyscrapers. In addition, not only buildings but other structures like bridges and highway flyovers are built with reinforced concrete as well in Malaysia.

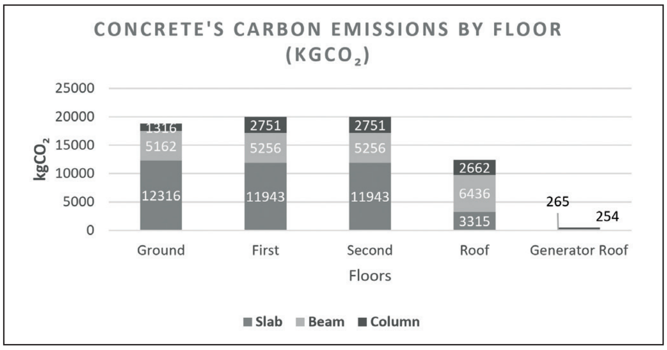

Figure 7: Concrete's carbon emissions by floors

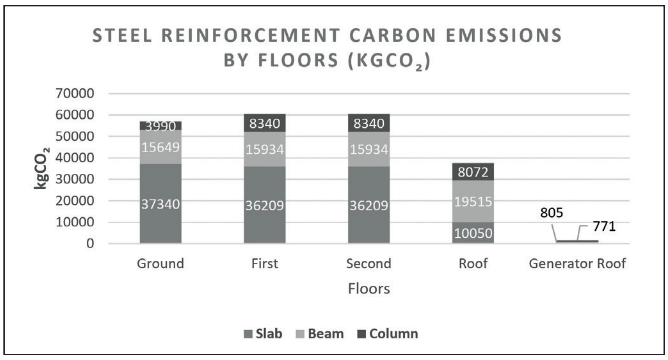

Figure 8: Steel reinforcement's carbon emissions by floors

Figure 7 and Figure 8 show the concrete and steel reinforcement carbon emissions by each floor. As shown in both figures, first floor and second floor have the same carbon emission due to the exact same design and amount of column, beam, and slab. Both floors emitted 19.95 tCO_2 of carbon dioxide from concrete and 60.48 tCO_2 from the steel reinforcement.

In addition, the ground floor emitted slightly lesser carbon dioxide for both materials due to lesser volume accumulated with 75.77 tCO_2 emission. The length of column for the ground floor to the foundation level is shorter with dimension of 1500 mm comparing to other floors' column with dimension of 3000 mm. Therefore, lesser concrete and steel reinforcement used, conducting to lesser carbon emission. The carbon emission for the roof floor is lesser compared to the first three floors mainly due to the smaller area of slab, with 12.41 tCO_2 emitted for concrete and 37.64 tCO_2 for steel reinforcement. Furthermore, the generator roof level without slab only emitted 520 $kgCO_2$ for concrete and 1576 $kgCO_2$ for steel reinforcement.

Based on previous analysis discussions, it still proved that the steel reinforcement carbon emission analysis by floors is greater than the concrete carbon emission. Due to larger coefficient, steel reinforcement emitted 50.44% more carbon dioxide than the concrete.

Tables 7 and 8 show the total embodied carbon emissions of concrete and steel reinforcement by total internal floor area. Determining the value of embodied carbon emissions in this section could observe the carbon emissions per meter square (m^2) for each floor. The embodied carbon emission is analysed by floors as each floor has different values of carbon emissions. The generator roof is not considered in this part as this level does not have slab and an internal floor area. Based on the comparison between the concrete and steel reinforcement embodied carbon emissions by internal floor area, steel reinforcement emitted more carbon dioxide per floor area for every floor comparing to the concrete. The embodied carbon emissions per internal floor area for first and second floor are the same due to same amount of carbon emitted and same floor area designed.

Table 7: Embodied carbon emission of concrete by total internal floor area

Floors	Carbon Emission ($kgCO_2$)	Floor Area (m^2)	Embodied Carbon Emission ($kgCO_2/m^2$)
Ground	18,794	297.000	63.28
First	19,949	297.000	67.17
Second	19,949	297.000	67.17
Roof	12,413	76.125	163.06
		Total:	**360.68**

Table 8: Embodied carbon emission of steel reinforcement by total internal floor area

Floors	Carbon Emission ($kgCO_2$)	Floor Area (m^2)	Embodied Carbon Emission ($kgCO_2/m^2$)
Ground	56,979	297.000	191.85
First	60,482	297.000	203.64
Second	60,482	297.000	203.64
Roof	37,636	76.125	494.40
		Total:	**1093.54**

4.1.2 Demolition Phase

Based on Lu & Wang (2019), the demolition phase is approximately equal to 10% of the construction phase. Therefore, the equation obtained in carbon emission calculation method in section 3.5.2 would be used to determine the carbon emission for demolition at least after 50 years of the building's life cycle. The calculation for this stage only includes the demolishing of concrete and steel reinforcement from the building structure, without considering the transportation, disposal, and recycle process.

Table 9 presented the summary of reinforced concrete carbon emission at demolition phase. The total carbon emission for the whole structure is estimated to be 28.87 tCO_2, where concrete emitted 7.16 tCO_2 and steel reinforcement emitted 21.72 tCO_2 of carbon dioxide. The slab which has the largest volume emitted the most carbon compared to column and beam.

Table 9: Summary of reinforced concrete carbon emission at demolition phase

Materials	Components	C_{con} ($kgCO_2$)	Per (%)	C_{dem} ($kgCO_2$)
Concrete	Column	9,724	10	972
	Beam	22,351	10	2,235
	Slab	39,478	10	3,948
	Total	71,554	10	7,155
Steel Reinforcement	Column	29,512	10	2,951
	Beam	67,836	10	6,784
	Slab	119,807	10	11,981
	Total	217,155	10	21,715
	Grand Total:	**288,709**	**Grand Total:**	**28,871**

4.2 Steel Frame Structure

The steel frame structure has the same architectural design, gross internal area, room layouts and internal facilities as the reinforced concrete structure. The steel frame structural model is illustrated in Figure 9, modelled using the intelligent 3D modelling in BIM. As shown in figure below, only the column, beam, and slab are considered in this analysis, while other architectural and structural components such as foundations, walls, ceilings, doors, roofs, and façade are not included. All quantities required for the carbon emissions analysis are obtained from Autodesk Revit 2022 quantity take-off.

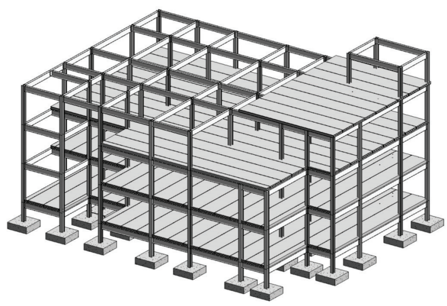

Figure 9: Steel frame structure

4.2.1 Construction Phase

Table 10 shows the determination of weight for the steel structure. The total weight of the entire structure consisting of column, beam, and slab is around 361.76 tons. Furthermore, Table 11 presented the grand total carbon emission for the steel frame. The carbon emission factors for steel and concrete chosen from section 3.4 are first converted to the same unit of $kgCO_2/kg$ before multiplying the weight to obtain the carbon emissions for each component in $kgCO_2$. The equation used to measure the carbon emissions of column, beam, and slab is shown in section 3.5, before summing up to get the grand total carbon emission of the entire structure. The grand total carbon emission is 196.49 tCO_2, with the steel column and steel beam having greater carbon emissions, compared to the precast concrete slab.

The beam emitted the most carbon for the entire structure with 43.31% of total emission following by the column with 39.82% emission. The beam has emitted 85.1 tCO_2 of carbon dioxide while the column emitted 78.2 tCO_2 of carbon dioxide. Despite the high volume of the slab, the slab emitted the least carbon dioxide among the three components with only 16.87% of total emission, 33.1 tCO_2 carbon emitted. This is due to the reason that steel has higher carbon emission factor compared to concrete. Based on Table 11, steel has carbon emission factor of 1.860 $kgCO_2/kg$ while the concrete only has 0.121 $kgCO_2/kg$, which is around 15 times greater than concrete.

This has proven that despite lesser volume of universal column and universal beam, it could still release large amount of carbon dioxide due to its larger carbon emission factor. Therefore, engineers should use the appropriate and sufficient design of structural components which could take the loads designed after considering the safety factors as well.

Table 10: Summary of volume and weight for steel frame

Materials	Components	Volume (m^3)	Density (kg/m^3)	Weight (kg)
Steel	Column	5.36	7,848	42,065
	Beam	5.83	7,848	45,754
	Slab	115.1	2,380	273,938
	Total	126.29		361,757

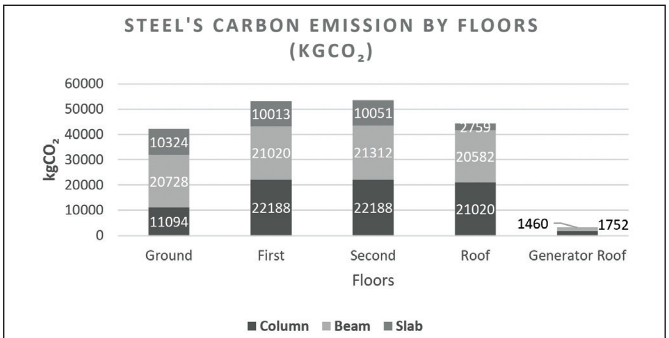

Figure 10: Steel's carbon emission by floors

Figure 10 illustrates the steel's carbon emissions by floors. The first and second floors have similar amount of carbon emissions of 53.2 tCO_2 and 53.5 tCO_2. Next, the roof floor emitted 44.4 tCO_2 of carbon while the ground floor emitted 42.1 tCO_2. By comparing both figures below, it showed that slab which has greatest volume, emitted the least carbon dioxide among the three components for each floor, except the generator roof's floor. As for the ground floor, the carbon emission of column is lesser than beam because the column of the ground floor is shorter with 1500mm only, comparing to other floors' column with length of 3000mm.

Table 12 shows the embodied carbon emission of steel by total internal floor area. The equation used and the total internal floor area obtained from Autodesk Revit 2022 could be found from the carbon emission calculation method in section 3.5.1. The generator roof is as well not considered in this section due to the absence of slab and internal floor area. Based on the table below, roof floor has the greatest embodied carbon emission by total internal floor area due to its large carbon emission but small floor area.

4.2.2 Demolition Phase

The carbon emission of steel frame for the demolition phase is same as the calculation in reinforced concrete structure, which is based on the research of Lu & Wang (2019) in section 3.5.2. The action of demolishing the structure would also be implemented at least after 50 years of the building's life cycle. The calculation for the demolition stage only includes the demolition of steel frame components of column, beam, and slab, without considering the transportation, disposal, and recycling process.

Table 13 shows the summary of steel frame carbon emission at demolition phase. C_{con} indicates the carbon emissions at construction phase while C_{dem} indicates the carbon emissions at demolition phase. Based on the table below, the total carbon emission for the whole structure is 19.6 tCO_2, where the column emitted 7.8 tCO_2 and beam emitted 8.5 tCO_2. The slab has the lowest carbon emission during demolition phase with 3.3 tCO_2.

Table 12: Embodied carbon emission of steel by total internal floor area

Floors	Carbon Emission ($kgCO_2$)	Floor Area (m^2)	Embodied Carbon Emission ($kgCO_2/m^2$)
Ground	42,146	297.000	141.91
First	53,221	297.000	179.20
Second	53,550	297.000	180.30
Roof	44,361	76.125	582.74
		Total:	**1084.15**

Table 13: Embodied carbon emission of steel at demolition phase

Materials	Components	C_{con} ($kgCO_2$)	Per (%)	C_{dem} ($kgCO_2$)
Steel	Column	78,241	10	7,824
	Beam	85,102	10	8,510
	Slab	33,146	10	3,315
	Total	196,490	10	19,649

Table 11: Summary of steel frame carbon emission

Materials	Components	Weight (kg)	Carbon Coefficient	Units	Carbon Coefficient ($kgCO_2/kg$)	Carbon emission ($kgCO_2$)
Steel	Column	42,065	1.860	tCO2/t	1.860	78,241
	Beam	45,754	1.860	tCO2/t	1.860	85,102
	Slab	273,938	287.70	kgCO2/m3	0.121	33,146
	Total	361,757			**Grand Total:**	**196,490**

4.3 Comparison of Total Carbon Emissions during Construction and Demolition Phases

Based on the results and analysis of both reinforced concrete and steel structure above, the grand total carbon emissions for both buildings are summarised in Figure 11 Reinforced concrete structure has carbon emission of 288.71 tCO_2 while the steel structure has 196.49 tCO_2. It shows that the reinforced concrete structure emitted 32% more carbon dioxide than the steel structure. In this case, both structures' carbon emissions do not consider manufactures, materials wastages, use of machines and other construction works that would emit carbon to the surrounding. For the reinforced concrete structure, the maximum cross-sectional area of 4% of steel reinforcement for column, beam, and slab is used. Besides, the reinforced concrete structure has larger volume for each component conducting to more carbon emissions. Therefore, proper and appropriate design for the structure would reduce the carbon emission. For instance, recycled steel could replace newly industrial manufactured for steel reinforcement. In addition, study and design new water-cement ratio for concrete or replacing the elements of concrete (fine aggregates, coarse aggregates, water, and cement) with sustainable materials could reduce the carbon emissions.

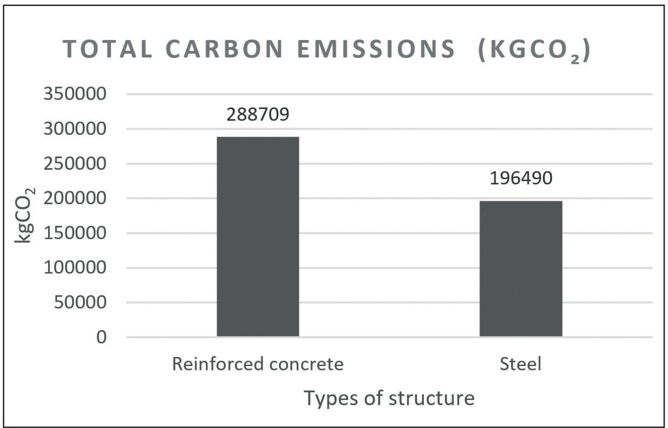

Figure 11: Total carbon emissions of reinforced concrete and steel structure during construction

Based on ISO 14044:2006, the equivalence of the systems being compared shall be evaluated before interpreting the results for different stages. Therefore, the components of reinforced concrete and steel structure involved for both construction and demolition stages remain the same in quantities and properties. The total carbon emissions during demolition phase are dependent on the construction phase. The carbon emission of reinforced concrete structure during demolition stage is 28.87 tCO_2 while the steel is 19.65 tCO_2. This indicates that steel has lesser carbon emission for both construction and demolition phase.

In the result, steel's carbon emission is lesser even at the demolition stage. Apart from that, the steel frame could be removed parts by parts and could be reused for other purposes without losing its properties and strength. The precast slabs which come in pieces could be removed in its original form and could be reused or recycled too. As for the reinforced concrete, the concrete would be crushed and disposed which would produce more carbon emissions. However, the steel reinforcement might be recycled for other usage without consider it as material wastage.

4.4 BIM in Determining Carbon Emissions

BIM is a tool applied since the beginning of the research to build two 3D models of reinforced concrete and steel frame structure. First, the loadings consisting permanent loads and live loads are designed before selecting the sizes of the components. Then, Autodesk Revit has efficiently assisted in building the two models with the exact dimensions of column, beam, and slab. The models created could be easily viewed from every corner which is very convenient to check any minor mistakes. As the models must be tested to ensure that the structure could take the loads, another BIM software which is called Autodesk Robot Structural Analysis is applied to carry out the load testing. At this stage, the ability of BIM in communicating has shown up by creating an integrated data among the Autodesk Revit and Robot Structural Analysis. As both are two different software, one is for creating a 3D model and another for structural load tests, but both software could communicate with only one model, which could save time and avoid doing two times amendment works.

Apart from that, as this research study requires some of the dimensions and measurement data from every single column, beam, and slab of both models, hence obtaining the values of each component manually would take extremely long time. Therefore, BIM could also perform quantity take-off by listing the data of every single component needed such as the length, area, and volume. However, the input of the components' dimensions must be correct when creating the model especially the universal column (UC) and beam (UB) with flange and web. This is due to the reason that the software would automatically generate the area, volume, and all other data needed from the input's dimensions and properties. In addition, additional input such as the UC's and UB's wrapping constant, elastic and plastic modulus as well as the second moment of area are all required to perform the most detailed analysis for load testing. This concludes that Building Information Modelling is very convenient and time saving as different works could be integrated with one model created only, where all could communicate using that single model. When there are some corrections for the main model, other software could update instantly to provide the latest version of the model.

Furthermore, analysing and discussing on the carbon emissions of both model is also part of BIM 6D as the determination of carbon emissions are based on the models. As mentioned above, all works including the sustainability study could be performed by BIM under one data environment. After getting the results, some suggestions are made to reduce the carbon emissions such as using recycled steel. Aside from that, BIM 7D focuses on the facility management after the construction of buildings are completed as well as the demolition of the building after 50 years. As in this case the demolition of construction materials is the focus of this study, thus the carbon emissions during demolishing of the structures are well discussed and compared.

While BIM offers significant advantages in integrating workflows and providing detailed insights into carbon emissions, it is not without limitations when applied to LCA and sustainability analysis. One limitation is its reliance on the accuracy and completeness of input data. If material properties, manufacturing emissions, or transportation impacts are not fully or accurately integrated into the model, the results may underestimate or overlook indirect emissions. While BIM excels in quantity take-offs and structural analysis, it might lack of capabilities for comprehensive LCA, particularly for assessing embodied carbon at a component level or comparing various material alternatives across the entire lifecycle.

To improve BIM's capability in sustainability assessments, future developments could include more detailed integration of LCA databases and sustainability metrics into BIM platforms. Enhanced interoperability between BIM tools and specialised LCA plugins would allow for more detailed assessments. Additionally, incorporating real-time environmental data and adopting artificial intelligence for predictive modelling could further refine sustainability analyses. These enhancements would support a more holistic understanding of a building's environmental impact and facilitate data-driven decision-making for greener construction practices.

5.0 CONCLUSION

The objectives of this study are met by comparing the carbon emissions between reinforced concrete and steel for 4 storeys building. In the results, the carbon emission of reinforced concrete during construction phase is 288.71 tCO_2 where concrete contributes to 71.55 tCO_2 while the steel reinforcement contributes to 217.15 tCO_2, which is 67% more than concrete. Furthermore, the carbon emission of steel structure is 196.5 tCO_2, which is 32% lesser than the reinforced concrete structure. The reinforced concrete structure is built with cast in-situ with concrete and steel reinforcement while the steel structure is built with simply supported frame. Based on the results, it is found that the carbon emission factors obtained from Li *et al.* (2021) for steel and steel reinforcement are greater than concrete, leading to higher carbon emissions. The total embodied carbon emissions per internal floor area of reinforced concrete and steel structure are 1454.22 $kgCO_2/m^2$ and 1084.15 $kgCO_2/m^2$.

At the demolition stage, the carbon emission of reinforced concrete structure is 28.87 tCO_2 while the carbon emission of steel structure is 19.65 tCO_2. The carbon emissions of both structures during demolition stage are still relatively high although it is 90% lesser than construction stage. The total carbon emissions per internal floor area of reinforced concrete and steel structure are 145.42 $kgCO_2$ and 108.41 $kgCO_2$ respectively. In summary, steel is a more sustainable construction material compared to reinforced concrete as it releases 32% less carbon. However, steel is not a popular construction material in Malaysia compared to the more common reinforced concrete. Therefore, this research wishes to provide some comprehension of the carbon emissions impacts to the environment based on the selection of reinforced concrete and steel as construction materials in Malaysia.

In general, steel structure induces a better impact on the environment, and it is suggested that construction professionals in Malaysia should consider using steel for building's materials. This would require changes in the traditional practices and perceptions of the Malaysia's construction industry, such as the implementation of green building standards and the promotion of sustainable construction practices. In addition, reinforced concrete structure could also reduce carbon emission by replacing newly manufactured steel with recycled steel as could reduce carbon emission by 20%. However, cost considerations in the Malaysian market play a critical role, as recycled steel and sustainable materials often involve higher initial expenses compared to conventional alternatives. Additionally, the availability and accessibility of recycled steel and advanced construction technologies may vary across different regions, posing further challenges. Addressing these constraints through policy incentives, subsidies, and increased industry awareness could facilitate a smoother transition toward more sustainable construction practices in Malaysia.

Aside from that, BIM has performed greatly throughout each LCA stage. BIM could assist in the initial phase of creating the models, conducting load tests, perform quantity take-off and more until the demolition phase, which is the end-of-life cycle of a building. It creates a single data environment while different types of works in this research study could rely on one source only, which is the model of reinforced concrete and steel structure.

As BIM is not developed to fully integrate with LCA and sustainability analysis, some recommendations could be provided for future studies. Incorporating advanced technologies into BIM tools could facilitate a more effective and immediate response to the environmental challenges (Chew *et al.,* 2024). For instance, plugins available such as One Click LCA, Insight and Tally, which come with LCA and embodied carbon database can be utilised in BIM tools. Autodesk Revit has a visual programming tool called Dynamo that allows users to create custom logic and automate tasks. It can automate repetitive tasks based on own preferences and facilitate embodied analysis workflows by writing their own scripts or using pre-built nodes.

Dynamo can perform generative design which supports the exploration of various sustainable building design options and embodied carbon optimisations. By utilising artificial intelligence (AI) algorithms and parametric modelling, it can suggest alternative structural designs and building materials that minimise environmental impact while maintaining performance. For instance, Dynamo can simulate the effects of replacing conventional materials with low-carbon or recycled alternatives, assess the viability of lightweight structures, or propose design modifications that enhance material efficiency. Moreover, its iterative approach supports the identification of optimal design solutions by analysing the trade-offs between sustainability objectives, construction feasibility, and long-term performance. This capability enables engineers to evaluate multiple configurations, material substitutions, and structural systems to identify solutions that reduce embodied carbon, promoting more sustainable construction practices and aligning with sustainability goals such as Paris Agreement. ■

AUTHORS' CONTRIBUTIONS

- **Zhi Xian Chew**: Study design, data collection, methodology, formal software analysis, and journal writing.
- **Ioannes, Yu Hoe Tang**: Review, editing, final manuscript approval, and supervision.
- **Jing Ying Wong**: Review, editing, final manuscript approval, and supervision.

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APPENDIX

<Floor Schedule>

A	B	C	D	E
Structural Material	Type	Level	Area	Volume
Concrete, Precast	Generic 200mm 2	Ground Floor	297 m²	59.40 m³
Concrete, Precast	Generic 200mm 2	First Floor	288 m²	57.60 m³
Concrete, Precast	Generic 200mm 2	Second Floor	288 m²	57.60 m³
Concrete, Precast	Generic 200mm 2	Roof	80 m²	15.98 m³

Example of the slab information obtained from Revit 2022

Concrete, Cast-in-Place gray						
Type	Reference Lvl	Length (mm)	C.S Area (m2)	Volume (m^3)	Density (kg/m3)	Weight (kg)
300 x 450mm 2	Ground Floor	15000	0.135	1.55	2380	3689
300 x 450mm 2	Ground Floor	21000	0.135	2.16	2380	5140.8
300 x 450mm 2	Ground Floor	10400	0.135	1.08	2380	2570.4
300 x 450mm 2	Ground Floor	4600	0.135	0.47	2380	1118.6
300 x 450mm 2	Ground Floor	13000	0.135	1.33	2380	3165.4
300 x 450mm 2	Ground Floor	3000	0.135	0.3	2380	714
300 x 450mm 2	Ground Floor	15000	0.135	1.28	2380	3046.4
300 x 450mm 2	Ground Floor	15000	0.135	1.28	2380	3046.4
300 x 450mm 2	Ground Floor	15000	0.135	1.24	2380	2951.2
300 x 450mm 2	Ground Floor	15000	0.135	1.24	2380	2951.2
300 x 450mm 2	Ground Floor	15000	0.135	1.24	2380	2951.2
300 x 450mm 2	Ground Floor	21000	0.135	1.73	2380	4117.4
300 x 450mm 2	Ground Floor	21000	0.135	1.73	2380	4117.4
300 x 450mm 2	Ground Floor	3000	0.135	0.3	2380	714

Example of column analysis spreadsheet

PROFILES

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WASTE-TO-WEALTH: CIRCULAR ECONOMY MODELS IN NIGERIAN CONSTRUCTION

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Abstract

The construction industry is a major consumer of natural resources and a significant generator of solid waste, with Nigeria experiencing critical inefficiencies in managing construction and demolition waste. This study investigates the adoption of circular economy (CE) principles in Nigeria's construction sector, focusing on current waste management practices, material utilisation efficiency, and the potential economic and environmental benefits of transitioning from a linear to a circular model. Using a mixed-methods research design, the study integrates quantitative surveys, qualitative interviews, and direct field observations across major construction hubs in Lagos, Abuja, and Port Harcourt. Results reveal that landfilling remains the dominant disposal method, with concrete accounting for 45% of total construction waste, followed by wood (20%), metal (15%), plastic (10%), and mixed debris (10%). Despite growing global emphasis on circular construction, awareness of CE principles remains low in Nigeria, with only 32% of firms reporting high familiarity. Barriers such as weak regulatory enforcement, limited investment in waste recovery infrastructure, and a lack of financial incentives were identified as key constraints. Logistic regression analysis indicates that financial constraints negatively affect CE adoption, while policy support significantly improves the likelihood of implementation. Nonetheless, the study highlights considerable benefits associated with CE adoption, including a projected 30% reduction in waste disposal costs, a 25% increase in material efficiency, a 35% decrease in carbon emissions, and a 20% rise in job creation within recycling and waste-to-wealth sectors. To accelerate CE uptake, the study recommends stronger regulatory frameworks, investment in recycling infrastructure, integration of digital material tracking technologies, and the promotion of modular construction techniques. A collaborative, multi-stakeholder approach involving government, industry, and research institutions is essential to driving the transition towards a sustainable, circular construction economy in Nigeria.

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Circular economy, construction waste management, sustainable construction, resource efficiency, material recovery, policy innovation

1.0 INTRODUCTION

The construction industry in Nigeria plays a pivotal role in national economic development, contributing approximately 9% to the country's Gross Domestic Product (GDP) (Adeleke, 2019). Nevertheless, the sector remains a substantial contributor to environmental degradation, with an estimated 30–40% of construction materials ending up as waste due to inefficient resource utilisation, poor planning, and outdated construction techniques (Olawale & Garba, 2020). This mismanagement not only leads to significant financial losses but also intensifies land degradation, deforestation, and greenhouse gas emissions (Eze *et al.,* 2021). In light of these challenges, transitioning to a circular economy (CE) model within the Nigerian construction industry offers a promising pathway for enhancing sustainability, improving resource efficiency, and reducing waste generation.

Globally, the integration of CE principles into the construction sector has yielded measurable success. In countries such as the Netherlands and Finland, waste-to-wealth programmes have led to reductions in construction-related material waste and carbon footprints (Pellinen, *et al.,* 2020). In contrast, Nigeria's adoption of circular economy strategies remains limited, primarily due to regulatory weaknesses, insufficient recycling infrastructure, and a general lack of awareness among construction stakeholders (Okafor & Ibrahim, 2022).

The conventional linear economy model—typified by the "take–make–dispose" approach—continues to dominate construction practices in Nigeria, contributing to unsustainable resource consumption and increased environmental risk. A circular economy, by contrast, is designed to maintain the value of products, materials, and resources in the economy for as long as possible, and to minimise waste generation through processes such as recycling, refurbishment, and reuse (Korhonen *et al.,* 2018).

In the context of construction, CE strategies may include the use of environmentally friendly materials, prefabrication techniques, adaptive reuse of buildings, and the recycling of construction and demolition waste (Geissdoerfer *et al.,* 2017). These approaches not only reduce the environmental footprint of construction activities but also create economic opportunities by transforming waste into valuable resources. Studies in the European Union have shown that adopting circular economy practices in construction can result in a 40% reduction in greenhouse gas emissions and a 50% decrease in the demand for virgin raw materials (European Commission, 2019). Emerging studies in Nigeria similarly suggest that effective implementation of CE strategies could yield a 20% reduction in construction waste and contribute to a 15% increase in employment within the recycling and materials recovery sectors (Adewale & Musa, 2021).

Despite the potential benefits, the transition towards a circular economy in Nigeria's construction industry remains slow and fragmented. Key obstacles include policy incoherence, absence of financial incentives, and resistance from traditional firms unwilling to abandon established linear practices (Nwankwo & Ajayi, 2020). The continued reliance on raw material extraction without adequate recovery systems has led to rising project costs, material shortages, and increased pressure on landfills (Bello & Yusuf, 2019). Approximately 70% of construction and demolition waste in Nigeria is disposed of in landfills or unauthorised dumping sites, with minimal efforts towards recovery or reuse (Agunbiade & Adeyemi, 2020). Furthermore, the absence of standardised waste segregation practices significantly hampers the development of effective recycling initiatives (Chukwuma, *et al.,* 2021). The limited adoption of CE principles can also be attributed to underinvestment in sustainable technologies and inadequate policy enforcement (Okonkwo *et al.,* 2022).

Addressing these multifaceted challenges requires a holistic and collaborative approach that integrates regulatory reform, technological advancement, financial incentives, and stakeholder engagement. This study seeks to explore how circular economy models can be implemented to support waste-to-wealth initiatives and foster sustainable practices within Nigeria's construction sector. Specifically, the research aims to: (i) assess the current state of construction waste management; (ii) evaluate the level of CE adoption among stakeholders; and (iii) analyse the potential economic and environmental benefits of CE integration. Additionally, it will identify critical barriers—including regulatory, infrastructural, and behavioural limitations—and propose strategic interventions for enhancing CE implementation. The study's findings are expected to inform policy development and business practices, contributing not only to the transformation of the Nigerian construction sector but also to the broader sustainability agenda. Importantly, the outcomes align with the United Nations Sustainable Development Goals, particularly Goal 11 (Sustainable Cities and Communities) and Goal 12 (Responsible Consumption and Production) (United Nations, 2015).

2.0 LITERATURE REVIEW

2.1 Conceptual Framework

The circular economy (CE) is a sustainable economic model that seeks to minimise waste and optimise the continuous use of resources through recycling, reuse, and regeneration. In contrast to the traditional linear economy, which follows a "take–make–dispose" trajectory, CE focuses on reducing raw material consumption while promoting material recovery and environmental conservation (Preston, 2012). The construction industry is one of the most resource-intensive sectors globally, producing significant amounts of waste, including concrete, wood, metals, and plastics. Studies indicate that construction and demolition waste (CDW) contributes up to 40% of total global solid waste, with developing nations such as Nigeria being key contributors due to weak waste management systems (Zhang *et al.,* 2019).

In the Nigerian context, construction waste is typically disposed of in landfills or unauthorised dump sites, owing to inadequate waste segregation practices and a scarcity of recycling infrastructure. Estimates suggest that only about 10% of CDW is currently recycled in Nigeria, compared with over 80% in several European countries with well-established CE policies (Afolabi & Oyebanji, 2020). Adopting CE principles in Nigeria's construction sector could enhance material efficiency, reduce environmental impact, and generate cost savings. Potential CE strategies include modular construction, urban mining, and the use of digital tools such as material passports, which facilitate the tracking, reuse, and recycling of construction components (Pomponi & Moncaster, 2017).

2.2 Theoretical Framework

Several theoretical frameworks underpin the application of CE in the construction sector. The Cradle-to-Cradle (C2C) theory advocates for designing products in a way that allows them to be reused or recycled continuously, effectively eliminating waste. This approach has seen substantial application in high-income countries through the use of eco-friendly materials and disassembly techniques, although implementation in Nigeria remains constrained by limited financial resources and technological capacity (Braungart & McDonough, 2009).

The Industrial Ecology Model conceptualises industries as interconnected ecosystems where the waste output from one sector becomes the input for another. This theory promotes material symbiosis between construction companies, manufacturers, and recycling enterprises, thereby reducing dependency on virgin materials and mitigating environmental damage (Graedel & Allenby, 2010). Recent research by Unegbu *et al.* (2024) suggested that adopting industrial symbiosis in Nigeria's construction sector could reduce construction waste by up to 35% while fostering circular business models.

Another widely applied model is Life Cycle Assessment (LCA), which evaluates the environmental impact of building materials and processes from extraction to disposal. LCA facilitates informed decision-making regarding material selection, construction techniques, and energy efficiency. Studies have shown that incorporating LCA tools into construction project planning in Nigeria could reduce lifecycle carbon emissions by 25% and significantly improve resource utilisation (Adesanya *et al.,* 2023).

2.3 Empirical Review

Numerous countries have successfully integrated CE principles into their construction sectors through regulatory mandates, technological advancement, and financial incentives. The Netherlands, for instance, introduced the Circular Construction 2023 policy, which requires that 50% of materials in new construction projects be recycled by 2030. Finland has implemented a Material Passport System to digitally log building components, thereby streamlining material reuse and supporting the growth of secondary markets (Ghisellini *et al.,* 2016).

Empirical findings suggest that these policies have considerably reduced construction waste while expanding opportunities in materials recovery markets (Ellen MacArthur

Foundation, 2019). Conversely, Nigeria lacks a national framework for circular construction practices. According to Ajiyo (2024), over 75% of construction waste in the country is sent to landfills, with minimal efforts towards recycling or recovery. The limited availability of financial incentives and the absence of market demand for secondary materials have further constrained CE adoption (Ogunleye & Odum, 2022).

Nonetheless, isolated projects indicate the potential for CE integration in Nigeria. For example, the Lagos Recycled Concrete Project demonstrated that using recycled concrete aggregates in construction could reduce project costs by 20% while enhancing structural integrity (Balogun *et al.,* 2022). Likewise, studies on bamboo-based construction in rural communities found that incorporating sustainable materials significantly decreased construction costs and environmental impact, thereby validating the viability of circular building methods (Okorie *et al.,* 2023). Despite these promising developments, various barriers continue to hinder the widespread adoption of CE principles in Nigeria's construction sector. These include regulatory deficiencies due to the lack of a cohesive national policy, economic challenges such as the high initial cost of green materials, technological constraints stemming from outdated practices, and cultural resistance to the use of recycled materials, which are often perceived as inferior (Olawumi & Chan, 2018; Dangana *et al.,* 2020; Adebayo & Iloh, 2021; Ojo & Bello, 2022).

Nevertheless, the potential benefits of CE implementation in Nigeria's construction industry are substantial. Research suggests that circular construction practices could result in a 30% reduction in construction waste, a 25% decrease in raw material demand, and a 15% increase in employment within waste recovery and recycling sectors (Akinbile *et al.,* 2023). Environmentally, the adoption of CE models could cut construction-related carbon emissions by 35%. Moreover, the introduction of green building materials such as bamboo, rammed earth, and compressed stabilised earth blocks has been shown to reduce construction costs by up to 20% while improving thermal efficiency and material durability (Umeh *et al.,* 2023).

2.4 Regulatory and Policy Framework

A robust regulatory framework is fundamental to accelerating the adoption of circular economy (CE) principles within Nigeria's construction industry. Internationally, countries such as Germany and Sweden have adopted stringent waste hierarchy policies that mandate the prioritisation of material reuse and recycling before landfill disposal. At the supranational level, the European Union's Waste Framework Directive establishes binding recycling targets for construction and demolition waste while promoting the use of secondary raw materials in construction projects (European Commission, 2018).

In contrast, Nigeria's existing policy environment remains underdeveloped in terms of CE-specific directives. Instruments such as the Environmental Impact Assessment (EIA) Act (Federal Government of Nigeria, 1992) and the National Environmental Standards and Regulations Enforcement Agency (NESREA) Act provide a foundational regulatory structure but lack explicit provisions for circularity in construction (NESREA, 2007). These policies primarily address environmental compliance and pollution control, offering minimal guidance on sustainable materials management or the integration of circular construction principles.

To bridge these policy gaps, scholars and practitioners have advocated for the development of a National Circular Economy Roadmap that would define CE implementation targets, introduce financial incentives for circular construction projects, and enforce stricter waste segregation laws (Ajulor, 2023). Key policy recommendations include the adoption of Extended Producer Responsibility (EPR) schemes that require construction firms to oversee material take-back and recovery processes, the formulation of Green Procurement Guidelines for prioritising sustainable and recycled materials in public-sector construction, and the establishment of a Circular Economy Task Force to coordinate CE initiatives across the built environment (Bello & Ayoola, 2022). These policy tools could collectively foster a more enabling environment for CE integration in Nigeria's construction industry.

2.5 Research Gap

While growing interest surrounds CE in Nigeria's construction sector, significant research gaps persist that this study aims to address in pursuit of its broader objectives. Notably, existing literature offers limited empirical evidence on the practical benefits and challenges of CE adoption within the Nigerian construction context. Most available studies are either conceptual or policy-focused, with few providing data-driven assessments of CE implementation outcomes (Okeke *et al.,* 2022). This research directly responds by presenting empirical insights into the economic and environmental implications of CE integration at the project and material levels.

Moreover, current scholarship has not adequately explored the recovery and reuse potential of specific construction materials—such as concrete, timber, and metals—within Nigeria's distinctive socioeconomic and infrastructural landscape. This study addresses this by analysing the recyclability and reuse feasibility of locally prevalent construction materials, thereby offering grounded insights into material flows and circular value chains. Additionally, although digital technologies such as Artificial Intelligence (AI), Blockchain, and Building Information Modelling (BIM) have proven beneficial in enhancing CE practices globally, their role in Nigeria's construction sector remains underexplored. This study evaluates the potential application of these technologies in advancing material traceability, design optimisation, and lifecycle monitoring to support CE adoption.

Finally, there is a pressing need to critically assess Nigeria's regulatory framework in relation to circular construction principles. Existing environmental laws and standards rarely align with CE priorities such as material looping, lifecycle thinking, or regenerative design. By identifying policy strengths and limitations, this research proposes actionable legal and institutional reforms to enhance CE adoption. Taken together, these research components aim to fill critical knowledge and practice gaps, thereby supporting the study's overarching goals: to assess the feasibility of CE in Nigerian construction, identify key barriers to implementation, and recommend evidence-based strategies for enabling sustainable, circular building practices.

3.0 METHODOLOGY

3.1 Research Design

This study adopted a mixed-methods research design, integrating both quantitative and qualitative approaches to enable a comprehensive analysis of circular economy (CE) implementation in Nigeria's construction industry. The mixed-methods approach was chosen to facilitate triangulation, thereby enhancing the validity and depth of insights related to waste management practices, levels of CE adoption, and the barriers impeding the transition to sustainable construction (Creswell & Plano Clark, 2017). The research incorporated a descriptive design to evaluate the current status of CE implementation and an explanatory design to investigate factors influencing its adoption. The study was conducted in Lagos, Abuja, and Port Harcourt, three of Nigeria's major urban centres with high volumes of construction activity, diverse stakeholders, and varying degrees of regulatory enforcement.

The unit of analysis included construction companies, regulatory agencies, policymakers, and waste management firms engaged in recycling and CE initiatives. The study focused on examining waste generation patterns, evaluating material recovery potential, and assessing the influence of policy frameworks on CE adoption in Nigeria's construction sector (Olawale & Umeh, 2022).

3.2 Data Collection Methods

The study utilised both primary and secondary data sources to ensure a comprehensive understanding of circular economy (CE) implementation within the Nigerian construction sector. Primary data were collected through structured surveys, semi-structured interviews, and direct field observations, while secondary data were obtained from academic literature, government publications, and industry reports. A structured questionnaire was developed to measure the level of awareness, the extent of CE implementation, and the challenges faced within the construction sector. The survey instrument was divided into four main sections: demographics, circular economy awareness, waste management practices, and barriers to CE adoption. Respondents rated their agreement with each statement using a five-point Likert scale, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree), in line with conventional survey design methods (Bryman, 2016).

Table 1: Survey Questionnaire

SN	Category	Survey Questions
1	Demographics	What is your role in the construction industry?
2		How many years of experience do you have in the sector?
3		What type of construction projects do you work on?
4		What is the size of your company?
5		Have you received any training on sustainable building?
6		Are you aware of circular economy principles?
7		Do you have formal waste management policies?
8	Circular Economy Awareness	Do you consider CE important for the Nigerian construction sector?
9		Are CE principles incorporated in your construction projects?
10		Are you familiar with government policies on CE in construction?
11		Do you believe CE adoption can reduce construction waste?
12		Have you encountered clients requesting CE-based construction?
13		Do you believe there are financial incentives for CE adoption?
14		Do you think the Nigerian government supports CE adoption?
15	Waste Management Practices	How does your company manage construction waste?
16		Do you use recycled construction materials?
17		Are waste materials sorted at your construction site?
18		Does your company collaborate with recycling firms?
19		Are there cost savings associated with material recovery?
20		Do you believe waste-to-wealth initiatives can be profitable?
21		Is digital technology used to track waste management?
22	Barriers to CE Adoption	Are financial constraints a major obstacle to CE adoption?
23		Are regulatory barriers limiting CE implementation?
24		Is a lack of awareness among stakeholders an issue?
25		Do you believe a lack of infrastructure affects CE adoption?
26		Does your company face resistance to change when implementing CE?
27		Is there a lack of skilled personnel for CE implementation?
28		Do you believe policy incentives could encourage CE adoption?

To complement the survey data, semi-structured interviews were conducted with 20 key informants, comprising policymakers, sustainability consultants, and senior executives from construction firms that had adopted CE practices. These interviews provided in-depth insights into contextual issues such as policy challenges, financial barriers, and levels of stakeholder engagement. The qualitative responses, as documented by Okoye and Nnaji (2023), enriched the study by capturing perspectives not readily quantifiable through survey instruments.

Additionally, direct observations were carried out at five active construction sites across Lagos, Abuja, and Port Harcourt. During these visits, field notes were recorded regarding the volume and type of construction waste generated, on-site recycling processes, segregation practices, and the reuse of materials such as concrete, timber, and steel (Adekunle *et al.*, 2023). Secondary data were sourced from a combination of national and international documents. These included publications by the

Federal Ministry of Environment, reports from the Nigerian Green Building Council, and datasets from the United Nations Environment Programme (UNEP). Peer-reviewed articles from journals such as the *Journal of Cleaner Production* and *Sustainable Cities and Society* were also reviewed to contextualise Nigeria's CE efforts within global best practices (Ghosh & Hassan, 2021). These data sources collectively supported the triangulation of findings and helped validate the reliability of the primary data.

3.3 Sampling Techniques

A stratified random sampling technique was employed to ensure balanced representation across key stakeholder groups, including construction firms, regulatory bodies, and waste management organisations. The survey included 250 construction professionals, while 20 key informants were selected for in-depth interviews. The total sample size was determined using Cochran's formula, which is widely recognised for establishing statistically significant and representative sample sizes in social science research (Bartlett *et al.,* 2001).

Prior to the full-scale data collection, a pilot study was conducted involving 15 construction professionals to test the reliability, validity, and clarity of the survey instrument. Feedback from the pilot phase was used to refine the questionnaire structure and interview protocol. This preliminary step helped improve the quality of the instrument and ensured alignment with the study's conceptual framework.

3.4 Data Analysis Techniques

Quantitative data from the survey were analysed using both descriptive and inferential statistical methods. Descriptive statistics—including mean, standard deviation, and frequency distributions—were used to summarise response patterns across the four key survey domains. To explore associations between variables, Chi-square tests were conducted, particularly to examine the relationship between company size and circular economy (CE) adoption. Further inferential analysis involved the use of logistic regression models to evaluate the predictive impact of financial constraints, regulatory support, and technological readiness on the likelihood of CE implementation. These models helped identify the most significant enablers and inhibitors of CE uptake among construction firms.

Qualitative data from the semi-structured interviews were subjected to thematic analysis using NVivo 12 software. Key themes were derived inductively, with emphasis on recurring issues such as policy challenges, stakeholder perceptions, and economic viability of CE strategies. To enhance the robustness of qualitative findings, Natural Language Processing (NLP) techniques were also applied for sentiment analysis, quantifying the tone and polarity of stakeholder views on CE implementation (Zhou *et al.,* 2021).

In addition, Geographic Information Systems (GIS) were used to spatially visualise construction waste generation hotspots across Lagos, Abuja, and Port Harcourt. This allowed for geo-spatial analysis of urban areas with high concentrations of construction waste, thereby informing location-specific policy recommendations. Lastly, machine learning algorithms—trained on historical industry data—were used to predict future construction waste trends. This predictive modelling provided foresight into potential waste volumes and recycling needs, enhancing the study's practical relevance (Ahmed & Zhang, 2020).

3.5 Ethical Considerations

The research adhered to established ethical protocols applicable to social science research. Informed consent was obtained from all participants prior to data collection, with participants made aware of the study's objectives, data usage policies, and their right to withdraw at any stage. Confidentiality was maintained by anonymising survey and interview responses and securing digital files through encryption. Ethical approval was granted by the Institutional Review Board (IRB) of Ahmadu Bello University Zaria ensuring compliance with local and international standards for ethical research involving human participants.

3.6 Limitations of the Study

Despite its comprehensive approach, the study encountered several limitations. One key constraint was the limited availability of real-time waste generation data, as many construction firms in Nigeria do not maintain digital records of material flows or waste outputs. This lack of digitisation posed challenges for modelling and temporal analysis. Additionally, response bias may have influenced survey results, with some participants potentially overstating their knowledge of CE principles or providing socially desirable answers. Another limitation was geographical scope. The research was restricted to three major urban centres—Lagos, Abuja, and Port Harcourt—which, while significant, may not fully represent construction practices in rural or peri-urban areas. As such, findings may not be generalisable across all regions of Nigeria. Future studies are encouraged to extend this research to include rural settings and incorporate longitudinal data to better understand CE trends over time.

4.0 RESULTS AND DISCUSSION

4.1 Current Waste Management Practices in the Nigerian Construction Industry

In order to evaluate the waste management practices in Nigeria's construction industry, descriptive statistics were computed for various practices such as landfilling, recycling, reuse, composting, and waste-to-energy. The mean and standard deviation of these practices are summarised below, indicating how frequently each practice is adopted by construction firms.

The results (Table 2) show that landfilling is the dominant waste management practice, with a mean of 4.50 and a standard deviation of 1.03, indicating strong agreement among firms that landfilling is their primary waste disposal method. Recycling, however, has a mean of 2.20 with a standard deviation of 1.10, suggesting that only a small fraction of firms adopt recycling practices. This is followed by reuse, with a mean of 2.50 (SD = 1.25), indicating that while some firms engage in reuse, it is not widespread. Composting and waste-to-energy are even less common, with means of 1.80 (SD = 0.95) and 1.60 (SD = 0.75), respectively.

Table 2: Adoption of Waste Management Practices in the Nigerian Construction Industry

Waste Management Practice	Percentage of Firms Using Practice (%)
Landfilling	50
Recycling	20
Reuse	15
Composting	8
Waste-to-Energy	7

The chi-square test was performed to assess the relationship between the size of construction companies and their adoption of circular economy (CE) practices. The results of the test ($\chi^2 = 12.3$, $p < 0.01$) indicate a significant association between company size and the likelihood of adopting recycling practices. Larger firms were found to be more likely to engage in recycling activities, possibly due to better access to resources and infrastructure.

4.2 Types and Volume of Waste Generated

The composition of construction waste was analysed using waste characterisation methods. This analysis (Figure 1) revealed that concrete waste constitutes the largest proportion, with a mean of 45% (SD = 5.2) of total waste generated on construction sites. Wood (20%), metal scraps (15%), and plastic (10%) followed in terms of waste composition, with mean values of 20% (SD = 3.1), 15% (SD = 2.6), and 10% (SD = 1.8), respectively. Mixed debris made up the remaining 10%, with a mean of 10% (SD = 2.2).

These findings reflect inefficiencies in construction practices, especially in the procurement and handling of materials. Concrete waste is notably high due to poor site waste segregation and inefficient design and demolition phases. This issue is compounded by the absence of modular construction techniques and life cycle assessments, which could otherwise reduce concrete waste generation.

Further analysis through Geographic Information Systems (GIS) mapping was employed to visualise construction waste hotspots in major cities. The GIS data highlighted that concrete waste is concentrated in Lagos, particularly in areas with large-scale infrastructure projects, indicating a higher demand for more effective waste management strategies in these regions.

4.3 Circular Economy Strategies Being Adopted

In order to assess the adoption of circular economy (CE) practices among construction firms, survey responses were analysed using descriptive statistics (Figure 2). The mean and standard deviation of awareness levels among firms were as follows: High awareness (Mean = 3.9, SD = 0.8), Moderate awareness (Mean = 3.0, SD = 1.0), and Low awareness (Mean = 2.2, SD = 0.7). This suggests that while some firms are familiar with CE principles, there is a significant knowledge gap, especially among smaller firms.

In addition, logistic regression analysis was conducted to evaluate the impact of financial constraints, policy support, and technological readiness on the likelihood of adopting CE practices. The logistic regression model revealed that financial constraints ($\beta = -0.72$, $p < 0.05$) and policy support ($\beta = 0.85$, $p < 0.01$) are significant predictors of CE adoption, with financial constraints negatively affecting adoption and policy support positively influencing it. Technological readiness ($\beta = 0.23$, $p = 0.12$) had a less significant effect, suggesting that while technology plays a role, it is not as influential as financial and policy factors.

These findings indicate that the level of awareness about circular economy principles is relatively low, especially among smaller construction firms, and that financial barriers and policy support are crucial factors influencing CE adoption in the sector.

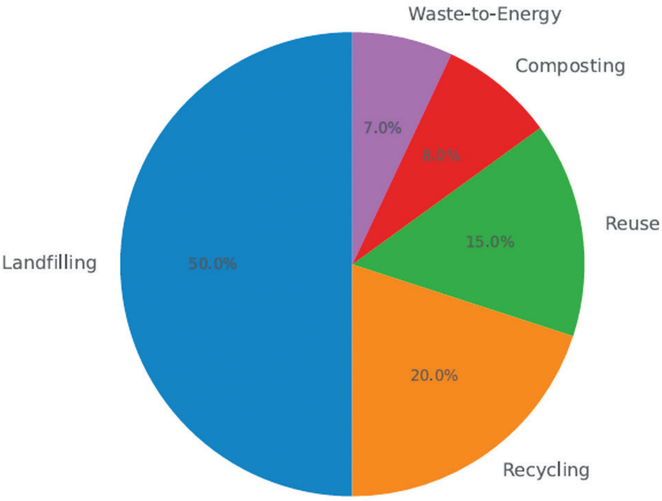

Figure 1: Construction Waste Composition in Nigeria

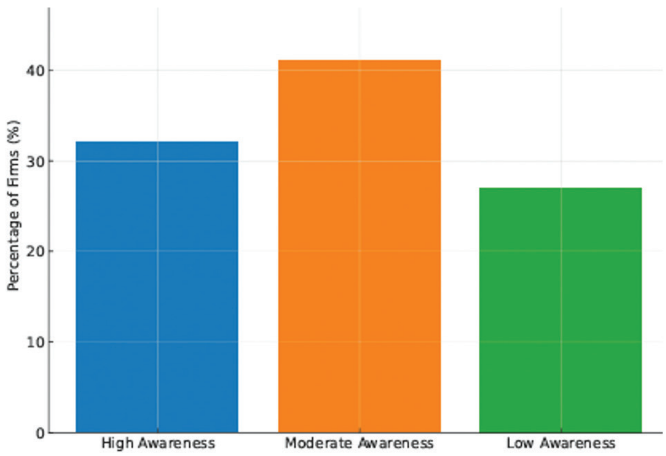

Figure 2: Circular Economy Awareness among Construction Firms

4.4 Economic and Environmental Benefits Identified

Simulated projections were conducted to estimate the potential economic and environmental benefits of adopting circular economy practices. The results (Table 3) indicated that construction firms could experience a 30% reduction in waste disposal costs and a 25% improvement in material efficiency. Additionally, the projected reduction in carbon emissions was 35%, which would significantly contribute to Nigeria's climate action efforts. These results demonstrate the substantial benefits that could be realised by transitioning to a circular economy model in the construction sector.

Table 3: Economic and Environmental Benefits of Circular Economy Adoption

Impact Factor	Percentage Improvement (%)
Cost Reduction	30
Material Efficiency	25
Job Creation	20
Carbon Emission Reduction	35

Machine Learning Algorithms were applied to predict future construction waste trends, based on historical waste data. The model projected a 15% increase in waste generation by 2035, particularly in urban areas with ongoing infrastructure projects. This suggests that without interventions, waste generation will continue to grow, underscoring the urgent need for circular economy practices to manage this increasing waste volume.

4.5 Stakeholder Perceptions and Sentiment Analysis

In addition to quantitative analyses, Natural Language Processing (NLP) was employed to perform sentiment analysis on textual data collected from interviews with stakeholders in the construction industry. The sentiment analysis (Figure 3) revealed that 65% of stakeholders expressed positive sentiments toward the adoption of circular economy practices, recognising their potential benefits for cost reduction, environmental sustainability, and job creation. However, 20% of respondents showed neutral sentiments, while 15% expressed concerns about the reliability of recycled materials and the high initial investment required to implement CE strategies.

This analysis underscores the general optimism among stakeholders, but also highlights concerns that need to be addressed through better infrastructure, training, and financial incentives to enhance the feasibility and scalability of circular economy practices.

4.5 Discussion of Findings

4.5.1 Waste Management Practices in the Nigerian Construction Industry

Findings from this study reveal that landfilling remains the predominant waste management strategy in Nigeria's construction industry, with approximately 50% of construction waste disposed of in landfills. This underscores a significant deficiency in sustainable waste practices. The result corroborates the findings of Unegbu *et al.* (2024), who similarly observed that landfilling is still the most commonly adopted method of waste disposal in the Nigerian construction sector. The mean score of 4.50 (SD = 1.03) further illustrates the widespread reliance on this method. In contrast, the adoption of more sustainable practices such as recycling (20%), reuse (15%), and waste-to-energy conversion (7%) remains critically low. These figures are particularly stark when compared to international standards; for instance, the Netherlands and Finland report recycling rates in the construction sector that exceed 80% (Ghisellini *et al.,* 2016).

Chi-square test results ($\chi^2 = 12.3$, $p < 0.01$) indicate that larger firms are significantly more likely to adopt recycling practices. This is likely due to their superior access to financial resources, infrastructure, and technical expertise. The finding aligns with studies by Adebayo *et al.* (2021), who found that firm size positively correlates with sustainable practice adoption in the construction industry. However, the continued dominance of landfilling across the sector signals broader systemic challenges, including weak regulatory enforcement and insufficient market incentives for recycling. Although environmental laws such as the NESREA Act exist, their implementation has been largely ineffective (Olawale & Umeh, 2022), thereby perpetuating reliance on unsustainable waste disposal methods.

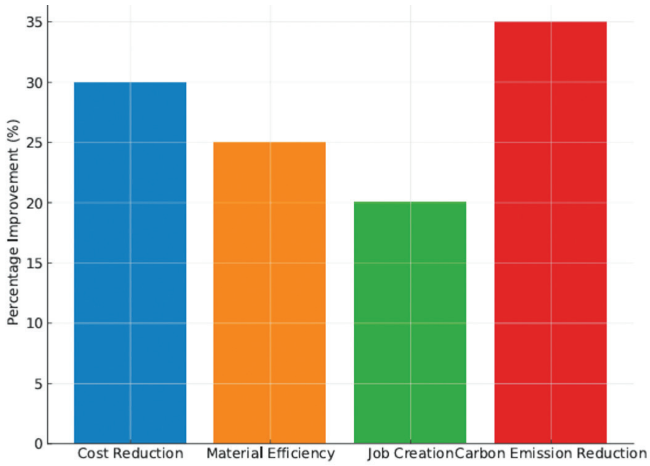

Figure 3: Sentiment Analysis of Stakeholder Opinions on CE Adoption

4.5.2 Types and Volume of Waste Generated

The composition of construction waste in Nigeria is dominated by concrete, which accounts for approximately 45% of total site waste. This reflects substantial inefficiencies, particularly during procurement, construction, and demolition phases. The prevalence of concrete waste points to poor waste segregation, suboptimal material planning, and an underutilisation of modular or prefabricated construction approaches. Similar conclusions were drawn by Zhang *et al.* (2019) and Unegbu *et al.* (2024), who emphasised the role of site-level inefficiencies in concrete waste generation.

The application of Geographic Information Systems (GIS) mapping in this study revealed that urban centres, particularly Lagos, are construction waste hotspots. This is attributed to the high density of large-scale infrastructure developments in these regions. The spatial concentration of waste generation highlights the importance of targeting urban areas for improved waste management strategies. Interventions such as policy zoning, advanced procurement planning, and green construction practices could significantly reduce waste volumes in these high-impact zones.

4.5.3 Circular Economy Strategies Being Adopted

One of the study's critical findings is the low level of awareness of circular economy (CE) principles among Nigerian construction firms. Only 32% of respondents' demonstrated high awareness, with the remaining majority split between moderate and low awareness categories. The mean awareness score of 3.2

(SD = 0.9) indicates that even among those familiar with CE, significant knowledge gaps persist, impeding the successful integration of circular strategies. This is consistent with findings by Olawumi and Chan (2018), who identified a lack of CE training and education as a major barrier to sustainable construction in developing countries.

Logistic regression analysis further demonstrated that financial constraints ($\beta = -0.72$, $p < 0.05$) are a statistically significant barrier to CE adoption. This supports previous research by Akinbile et al. (2023), who noted that access to capital significantly influences firms' ability to adopt sustainable practices. Conversely, policy support ($\beta = 0.85$, $p < 0.01$) was positively associated with CE implementation, underscoring the importance of regulatory frameworks and incentives such as tax reliefs and green procurement mandates. Interestingly, technological readiness ($\beta = 0.23$, $p = 0.12$) was not statistically significant, suggesting that the major bottlenecks to CE in Nigeria are more financial and regulatory than technical. This aligns with conclusions by Ogunleye and Odum (2022), who argued that financial support and regulatory enforcement outweigh technological factors in influencing CE success in emerging markets.

4.5.4 Economic and Environmental Benefits Identified

This study provides evidence that CE implementation could deliver substantial economic and environmental benefits in Nigeria's construction sector. Simulations based on current waste output models suggest a potential 30% reduction in waste disposal costs and a 25% improvement in material efficiency. These projections are in line with the results of Ghosh and Hassan (2021), who reported similar outcomes in other developing economies following CE integration.

Furthermore, the study projects that CE practices could create a 20% increase in employment opportunities, particularly in the recycling and materials recovery industries. This aligns with the findings of Balogun *et al.* (2022), who highlighted the job-creation potential of circular value chains in Nigeria's construction ecosystem. From an environmental perspective, adopting CE strategies could result in a 35% reduction in carbon emissions. This has significant implications for Nigeria's climate commitments under the Paris Agreement. The results affirm earlier studies by Zhou *et al.* (2021), which found that reuse and recycling of construction materials can substantially lower emissions across the building lifecycle.

4.5.5 Stakeholder Perceptions and Sentiment Analysis

Sentiment analysis of interview data revealed that 65% of stakeholders held positive views regarding CE adoption in Nigeria's construction industry. These stakeholders recognised CE's potential for cost savings, environmental protection, and employment generation. However, 15% expressed concerns regarding the structural reliability of recycled materials and the high capital investment required for implementation. Such concerns are mirrored in studies by Chukwuma *et al.* (2021), who highlighted stakeholder distrust in recycled inputs due to the lack of standardisation and certification in developing markets.

Additionally, 20% of stakeholder responses were classified as neutral, indicating cautious optimism or uncertainty regarding CE's feasibility. This suggests that while CE is generally viewed positively, hesitancy remains due to perceived risks and limited institutional support. Building trust will require targeted capacity-building programmes, as well as the development of formal material certification systems. As suggested by Okonkwo *et al.* (2022), public–private partnerships (PPPs) could be instrumental in bridging current gaps by providing both financial and technical support for CE projects in Nigeria.

5.0 CONCLUSION

This study underscores the urgent need for a transformative shift towards circular economy (CE) principles within Nigeria's construction industry, as the prevailing linear model of resource consumption and waste disposal has proven environmentally and economically unsustainable. The research findings highlight the inefficiencies currently embedded in construction waste management practices, with landfilling remaining the dominant disposal method. Alarmingly, only 20% of construction firms engage in recycling, while a mere 15% report reuse practices, revealing a substantial gap in material recovery and circularity. These inefficiencies are further compounded by the dominance of concrete waste—accounting for 45% of total waste—driven by inadequate procurement strategies, poor waste segregation, and the absence of standardised deconstruction and reuse protocols.

Circular economy awareness across the sector was also found to be limited. Only 32% of firms demonstrated high awareness of CE principles and benefits, indicating a significant knowledge deficit. This shortfall, combined with the lack of formal training programmes and limited institutional capacity, continues to hinder broader CE adoption. The study further identifies weak regulatory enforcement, insufficient financial incentives, and low levels of technological integration as key barriers. Importantly, the logistic regression analysis revealed that policy support plays a pivotal role in enabling CE adoption, whereas technological readiness, although relevant, exerts comparatively less influence than policy and financial conditions.

Despite these challenges, the study reveals substantial economic and environmental advantages associated with CE integration. Modelled projections indicate that widespread CE adoption could lead to a 30% reduction in waste disposal costs, a 25% increase in material efficiency, and a 20% rise in job creation within the recycling and waste-to-wealth industries. Furthermore, a potential 35% reduction in carbon emissions demonstrates the significant contribution CE strategies can make towards Nigeria's climate change mitigation efforts. These findings underscore the transformative potential of CE practices in reducing reliance on virgin resources, curbing environmental degradation, and fostering a sustainable construction ecosystem. To drive this transition, the study recommends several strategic actions. Strengthening regulatory frameworks is imperative, including the enforcement of CE-aligned policies, mandatory waste segregation at construction sites, and the development of a national CE roadmap for the built environment. Investments in recycling infrastructure, such as automated waste-sorting systems and material recovery facilities, are essential to improve recycling rates and resource circulation. Introducing financial incentives—such as green loans, tax relief, or subsidy schemes for CE-compliant projects—will further support industry uptake.

Public–private partnerships (PPPs) should be leveraged to mobilise resources and technical expertise for circular construction initiatives. Furthermore, the integration of digital technologies—such as Building Information Modelling (BIM), blockchain-based material tracking systems, and AI-driven waste forecasting tools—can significantly improve material efficiency and reduce construction waste. Industry-wide training and capacity-building programmes are also necessary to enhance awareness and competence in CE strategies among construction professionals.

Ultimately, this study offers a comprehensive roadmap for policymakers, industry leaders, and sustainability advocates to accelerate the adoption of circular economy principles in Nigeria's construction sector. By addressing the identified financial, regulatory, and technical barriers, Nigeria can align its construction practices with its national development objectives and contribute meaningfully to global sustainability agendas. Specifically, CE adoption in construction will support the attainment of United Nations Sustainable Development Goals (SDGs), particularly Goal 11 *(Sustainable Cities and Communities)* and Goal 12 *(Responsible Consumption and Production)*, positioning Nigeria as a regional leader in sustainable construction transformation. ■

AUTHORS' CONTRIBUTIONS

- **Hyginus Chidiebere Onyekachi Unegbu**: Conceptualisation, Writing—original draft preparation and literature review, study design, data collection, methodology, software and data analyses.
- **Danjuma Saleh Yawas**: Data validation, visualisation, supervision and formal analysis.
- **Bashar Dan-asabe**: Data validation, visualisation, supervision and formal analysis.
- **Abdulmumin Akoredeley Alabi**: Data validation, visualisation, and software implementation.

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GEOTECHNICAL AND PETROGRAPHIC ASSESSMENT OF SAMANA SUK FORMATION LIMESTONE AS A SUSTAINABLE AGGREGATE FOR INFRASTRUCTURE DEVELOPMENT IN PAKISTAN

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Abstract

This study evaluates the potential of Middle Jurassic limestone from the Samana Suk Formation, located in Village Rani Wah, District Haripur, Hazara Basin, as a sustainable aggregate for infrastructure development in Pakistan. The increasing demand for quality aggregates, driven by large-scale infrastructure projects such as those under the China–Pakistan Economic Corridor (CPEC), necessitates the exploration of locally sourced alternatives. Geotechnical and petrographic analyses were conducted to assess the limestone's suitability for various engineering applications, including road construction, cement concrete, and asphalt production. Key parameters such as Los Angeles Abrasion (25.6%), Soundness (2.92%), Specific Gravity (2.64), Water Absorption (0.61%), Bitumen Stripping (<5%), Bitumen Coating (>95%), Flakiness Index (10.5%), Elongation Index (12%), Clay Lumps & Friable Particles (<1%), Loose Unit Weight (1.19 g/cm³), Rodded Unit Weight (1.43 g/cm³), Tensile Strength (5.48 MPa), and Unconfined Compressive Strength (53 MPa) were analysed. All results fell within the acceptable ranges set by international standards (ASTM, AASHTO, BS, NHA), confirming its viability as a construction aggregate. Petrographic analysis revealed minor quantities of quartz and clay, minimising the risk of Alkali–Silica Reaction (ASR), while the dolomite content was limited to 1%, eliminating concerns regarding Alkali–Carbonate Reaction (ACR) when used with ordinary Portland cement. This study demonstrates that limestone from the Samana Suk Formation is a sustainable and locally sourced aggregate capable of meeting the requirements of road construction and other infrastructure projects in Pakistan. It supports cost-effective and environmentally responsible construction practices, contributing to the nation's rapidly expanding infrastructure sector.

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1.0 INTRODUCTION

Rocks play a fundamental role in construction, particularly when used as materials for building highways, foundations, railway ballast, concrete aggregates, and mine support structures. Aggregates—whether natural or crushed—are essential components in a wide range of construction projects, including concrete structures, roads, pavements, and pavement bases. These materials are typically classified according to their mechanical and geological properties, as specific construction applications require aggregates with distinct engineering characteristics. The quality of an aggregate is verified through a series of tests that evaluate its physical attributes, such as abrasion resistance, chemical stability, and particle shape.

Furthermore, lithology and grain-size distribution significantly influence the physical, chemical, and mechanical properties of aggregates; properties such as abrasion resistance, soundness, and shape orientation are particularly important for their use in both flexible and rigid pavement systems (Fookes *et al.,* 1988; Lafrenz, 1997; Neville, 2004). Globally, rock aggregates are recognised as critical construction resources, and detailed knowledge of their physical and mechanical properties is essential prior to undertaking engineering projects such as roads, bridges, dams, and tunnels. The physical properties of crushed rock aggregates are influenced by their microstructure and mineral composition, which directly determine their strength and durability (Bell and Lindsay, 1999).

Aggregate production typically involves the extraction, mining, and crushing of intact rock masses, with limestone emerging as one of the most commonly used materials due to its widespread availability and compatibility with the construction and cement industries (Kamani and Ajalloeian, 2019). Approximately 90% of asphalt pavements and 80% of concrete produced globally contain rock aggregates (Tepordei, 2005). Limestone aggregates are particularly valued for their thermal resistance and structural integrity, demonstrating high fire resistance after calcination (Rodrigues *et al.,* 1999). Mechanical properties such as abrasion resistance, soundness, and shape orientation govern the behaviour of aggregates in both rigid and flexible pavements (Fookes *et al.,* 1988). Quality assessment of aggregates relies on evaluating their physical, mechanical, and chemical properties, all of which are closely linked to the mineralogical and petrographic characteristics of the source rock (Yaşar *et al.,* 2004; Kandhal *et al.,* 2000). Advances in quarrying and crushing technologies have enabled the production of high-performance aggregates from various rock types, including granite, marble, sandstone, and limestone (Khan and Chaudhry, 1991; Kandhal and Parker, 1998). Recent global studies have increasingly focused on region-specific evaluations of carbonate rocks, such as those in Spain, Turkey, and Iran, where variations in dolomitisation, porosity, and rock fabric have been shown to significantly affect aggregate suitability (Arjmandzadeh *et al.,* 2021; Golewski, 2021), underscoring the importance of localised assessments such as the present study.

In Pakistan, limestone is predominantly sourced from the Punjab and Khyber Pakhtunkhwa (KP) regions, where significant quarrying and crushing activities occur (Bilqees and Shah, 2007; Arshad and Qiu, 2012). Globally, limestone aggregates represent over 71% of total aggregate production, whereas sandstone accounts for only around 3%. Aggregates constitute roughly 70–80% of the total composition of concrete and asphalt mixes and are essential for the construction of infrastructure such as roads and pavements. In Pakistan, limestone deposits serve as the primary natural aggregate source, supporting the country's expanding construction sector. Major limestone formations in the Himalayan regions of northern and southern Pakistan include the Samana Suk Formation, Margalla Hill Limestone, Kohat Formation, Wargal Limestone, Kawagarh Formation, Shekhai Formation, Lockhart Limestone, and Sakesar Limestone. In the Salt Range, thick sedimentary sequences such as the Wargal, Lockhart, and Sakesar limestones are exposed and have been widely studied for their construction potential (Shah, 2009; Yasin *et al.,* 2015). These formations have demonstrated promising performance in alkali–silica and alkali–carbonate reactivity tests, as well as in petrographic and mechanical assessments conducted in accordance with ASTM, AASHTO, and British standards (Gondal *et al.,* 2009; Ahsan *et al.,* 2012; Rehman *et al.,* 2018).

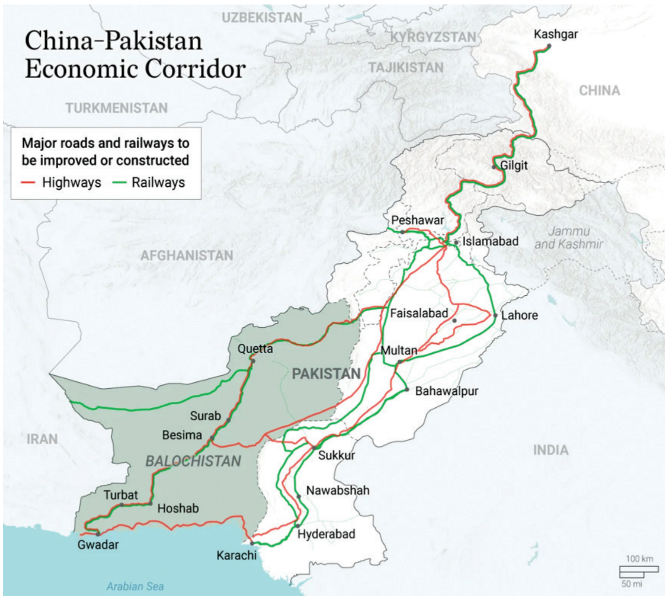

Figure 1: Large-scale project "Pakistan-China Economic Corridor (CPEC)" in Pakistan

Pakistan, with an area of over 796,095 square kilometres, a population exceeding 220 million, and a road network of more than 260,000 kilometres, is witnessing significant growth in its construction industry across commercial, private, and government sectors. This expansion is driven in part by large-scale infrastructure projects such as the China–Pakistan Economic Corridor (CPEC) (Figure 1). The increasing demand for aggregates has consequently heightened the need for sustainable and reliable aggregate resources to support future infrastructure development. The Kohat Hills Range, rich in Mesozoic carbonates and strategically located near CPEC routes, offers important opportunities for aggregate resource development (Pakistan Ministry of Planning Report, 2017; Rehman *et al.,* 2020). Within this context, the identification and characterisation of new aggregate resources have become a priority to meet the expanding construction demands. The Hazara region in Khyber Pakhtunkhwa (KP) contains abundant limestone resources, including the Margalla Hill Limestone, Lockhart Limestone, Samana Suk Limestone, and Kawagarh Limestone, all of which hold strong potential as viable aggregate sources for large-scale construction projects (Rehman *et al.,* 2016; Shah, 2009).

Pakistan's northern and western regions are increasingly affected by climate-induced hazards such as landslides and flooding, which pose serious risks to transportation and infrastructure development (Bazai *et al.,* 2025; Ramzan *et al.,* 2025; Ullah *et al.,* 2025). Simultaneously, rising temperatures, particularly in southern Pakistan, have intensified thermal stress on construction materials, accelerating degradation and compromising structural integrity (Baig *et al.,* 2025). These dual pressures—geohazards and thermal extremes—necessitate the use of robust, resilient, and thermally stable aggregates for sustainable infrastructure. Properly characterised limestone aggregates can enhance the climate resilience of construction in such vulnerable regions.

To ensure that aggregates meet the required specifications for construction, comprehensive petrographic, geotechnical, and geochemical analyses are necessary. These analyses provide essential information on aggregate suitability by assessing their mechanical properties and engineering characteristics. As rocks used in construction are subjected to a range of forces, including compression, tension, and shear stresses, a thorough understanding of their geotechnical properties is required to ensure they can be used safely and effectively in engineering applications. Unfortunately, scientific studies on the geotechnical properties of rocks in Pakistan remain limited, and many materials are used without adequate evaluation. This practice may compromise the safety and efficiency of construction projects. International studies emphasise that the lack of local assessment can lead to premature pavement failures and increased life-cycle costs (Golewski, 2021), underscoring the importance of site-specific evaluations.

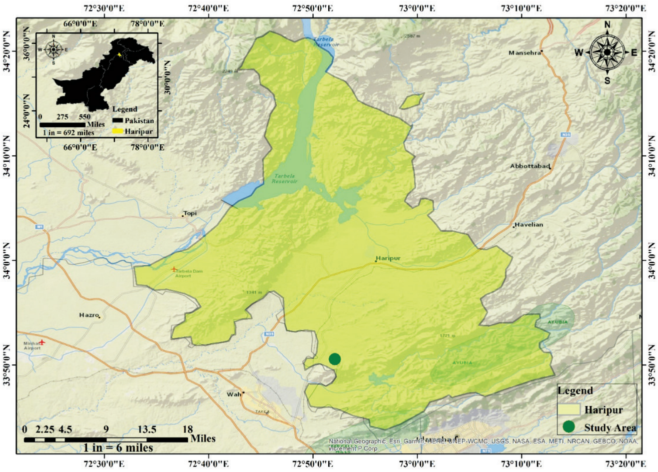

Figure 2: Study area in District Haripur, Khyber Pakhtunkhwa, Pakistan

Several studies have assessed the suitability of aggregates from different limestone formations in Pakistan. Notably, Rehman *et al.* (2018) evaluated the suitability of the Samana Suk Formation at Sheikh Budin Hill in the Marwat Ranges. Other significant studies by Bilal *et al.* (2019), Hassan *et al.* (2020), and Ullah *et al.* (2020) have examined limestone sources from various formations for use in road aggregates. Research conducted in Khyber Pakhtunkhwa (KP) by Rehman *et al.* (2018), Shah *et al.* (2022), Sajid *et al.* (2021), and Hussain *et al.* (2022) has also analysed local limestone resources, including the Kawagarh, Nikanighar, and Wargal limestones. However, large limestone-rich regions in KP, particularly in District Haripur, remain underexplored. This study aims to build upon previous work by conducting a comprehensive evaluation of the limestone deposits in District Haripur, Khyber Pakhtunkhwa (KP), a region known for its substantial limestone resources, to assess their viability for large-scale construction applications.

2.0 GEOLOGICAL CONTEXT OF THE SAMANA SUK FORMATION

The Samana Suk Formation is located within the Himalayan Mountain Range, an orogenic belt formed by the collision of the Indian and Eurasian tectonic plates. This tectonic event initiated a series of geological processes, including folding, faulting, and fracture formation, which have significantly influenced the region's geological structures. The study area lies in the southern part of the Hazara Basin, specifically in District Haripur (Figure 2), situated in the foothills of the Hazara Range in Pakistan. This area forms part of the Himalayan foreland fold-and-thrust belt, a zone strongly affected by compressional tectonic forces resulting from ongoing plate convergence.

2.1 Location and Tectonic Setting

The research site in District Haripur occupies the southern extremity of the Hazara Basin, specifically within the footwall of the major Nathia Gali Thrust (NGT) – a key structural feature forming part of the western Hazara Range (Figures 3a, 4b). This important sedimentary basin within the Upper Indus Basin region is tectonically bounded to the south by the Main Boundary Thrust (MBT) and to the north by the Main Mantle Thrust (MMT), highlighting its crucial position within the Himalayan orogenic framework. Extending from the Salt Range in the east to the Nathia Gali and Murree Hills in the west, the Hazara Basin has been a site of substantial sedimentary deposition, accumulating strata ranging from the Precambrian to the Eocene (Figures 3b, 4a).

The Haripur area, owing to its proximity to these major tectonic structures (NGT, MBT, MMT), exhibits intense tectonic deformation characterised by uplift, folding, and faulting. This deformation has profoundly shaped the landscape and exposed a wide range of stratigraphy, including key formations such as the Jurassic Samana Suk Formation. Consequently, the District Haripur site provides critical insights into the basin's geological evolution, regional deformation history, and the tectonic forces that have governed sedimentation and structural development over millions of years.

2.2 Lithology and Petrography of the Samana Suk Formation

The Samana Suk Formation in District Haripur is predominantly composed of grey to dark grey limestone, which is medium- to thick-bedded and includes intercalations of marl and dolomitic limestone. The formation is well known for its fossil-rich character, containing ammonoids, gastropods, brachiopods, and other marine fossils, indicative of a Middle Jurassic age. Fossil assemblages suggest deposition in a shallow marine to intertidal environment under relatively low-energy conditions.

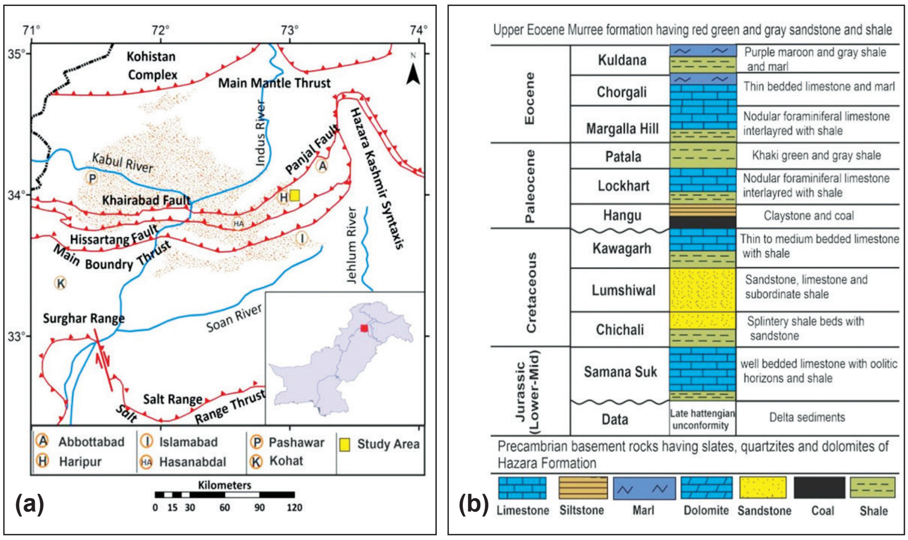

Figure 3: The Geological Setting of the region
(a) Showing a Tectonic map of the region (after Hylland and Riaz 1988) indicating the study site's position in the yellow box; (b) Showing Generalised stratigraphy surrounding the examined sections within the research site (Shah, 2009). (Thicknesses are not depicted to scale)

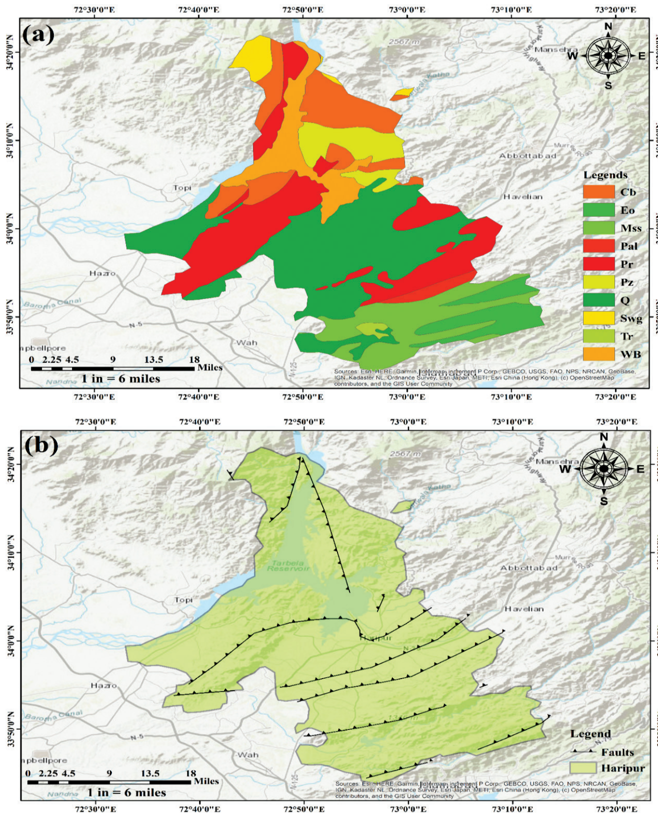

Figure 4: The geological getting of the Haripur District (a) Showing a generalised stratigraphy of District Haripur; (b) Showing a tectonic map of the of District Haripur

Petrographic analysis of the limestone shows a calcite-dominated composition, with minor amounts of dolomite and magnesium-rich minerals. The limestone exhibits features typical of diagenetic processes, such as stylolites and calcite veins, reflecting pressure dissolution under compressive tectonic stresses. Its mineral composition and fracture patterns indicate prolonged exposure to tectonic forces, contributing to the rock's high strength and mechanical stability. The stylolites within the limestone beds further evidence compressional deformation, enhancing cementation and hardness. Additionally, the presence of fractures and calcite-filled veins contributes to the formation's structural integrity, making it a durable material suitable for construction, particularly as an aggregate for infrastructure projects.

2.3 Structural Deformation and Tectonic Influence

The tectonic deformation observed within the Samana Suk Formation is a direct consequence of the ongoing collision between the Indian and Eurasian plates. The region lies within a compressional zone, where thrust faults, folds, and fractures have developed due to the significant convergence of the two plates. The limestone of the formation displays various tectonic structures, including stylolites (Figure 5e) and fractures filled with magnesium-rich material, both indicative of pressure dissolution resulting from compressive tectonic forces.

These fractures are particularly significant, as they enhance the rock's strength by facilitating secondary cementation through mineral precipitation. Calcite veins (Figure 5d), formed under these tectonic forces, provide further evidence of diagenetic processes that have contributed to the formation's mechanical consolidation. Collectively, these features highlight the tectonic influence on the Samana Suk Formation, supporting its suitability for use as construction material, especially in regions subject to high seismic activity and tectonic stress.

2.4 Field Observations and Sedimentary Features

Field observations at the Village Rani Wah section, located in the Hattar–Khanpur region, provide valuable insights into the sedimentary characteristics of the Samana Suk Formation. The limestone beds in this area display variations in thickness, ranging from 6 cm to 1 m, and exhibit bioturbation, fractures, and stylolites (Figures 5a–d). These features reflect both biological activity and tectonic processes, indicating that the formation was initially deposited under shallow marine conditions and subsequently subjected to tectonic deformation.

The limestone colour ranges from dark grey to yellowish brown, attributed to the presence of ferruginous material and magnesium content. The bioturbation (Figure 5c) provides evidence of organisms inhabiting the sediment, while stylolites and fractures indicate that the formation experienced tectonic stress after deposition. The presence of calcite veins (Figure 5d) further evidences diagenetic alteration, supporting the interpretation that the formation has undergone prolonged tectonic compression.

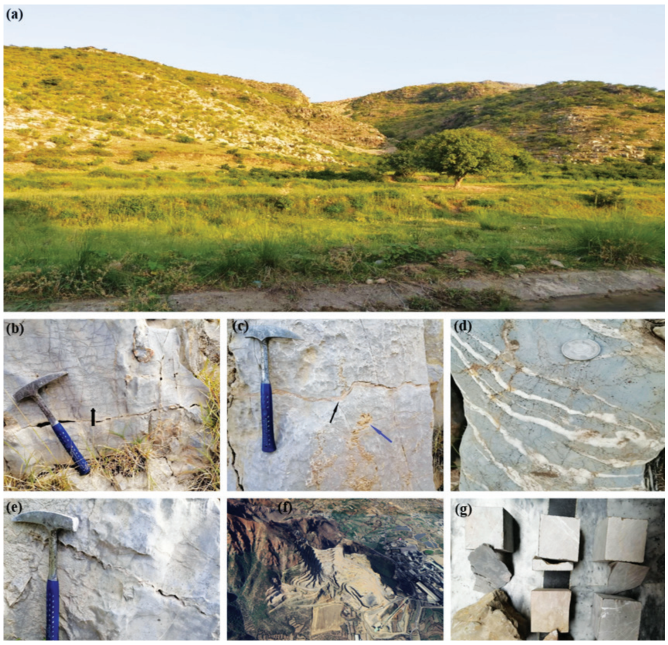

Figure 5: Geological features and strength testing of the Samana Suk Formation at Village Rani Wah, Hattar-Khanpur (a) Panoramic view of the exposed limestone beds; (b) Thick-bedded limestone with fractures (hammer for scale); (c) Medium-bedded limestone exhibiting bioturbation and dolomite-filled veins (hammer for scale); (d) Parallel calcite veins within the medium-bedded limestone (coin for scale); (e) Stylolite structures formed under compressive stress (hammer for scale); (f) Limestone quarry near the study area; (g) Cubes (4"x4"x4") used for Unconfined Compressive Strength (UCS) and Tensile Strength testing of limestone samples

These observations confirm that the Samana Suk Formation is a tectonically deformed and diagenetically modified limestone, rendering it a durable and stable material for construction. Its high compressive strength and resilience, as demonstrated through both field observations and laboratory testing, indicate its suitability for use as aggregate in road construction and other infrastructure projects.

3.0 MATERIALS AND METHODS

3.1 Geological Context and Sampling Procedure

The Village Rani Wah area of District Haripur was selected for sampling the Middle Jurassic Samana Suk Formation Limestone (Figure 6). The geological environment plays a significant role in determining the rock structure, composition, and texture of the region's limestone, which in turn affects its physical and mechanical properties. In this area, the limestone predominantly appears as dark gray to yellow-brown, with medium to thick layering. It is characterised by a fine to medium grain size, hardness, and massive nature, making it possible to extract large tiles due to its expansive size.

To ensure comprehensive analysis, rock samples were chosen based on their variability and spatial dispersion across the study area. Various geological factors, including composition, grain size, hue, and arrangement of layers, were documented to assess the feasibility and economic viability of the limestone for construction purposes. Sampling was conducted by collecting bulk samples on-site, which were then processed in the laboratory for further analysis.

Figure 6: Observations of sections from the Samana Suk Formation at the measured site reveal distinct layering evident in the outcrops. (Ramzan et al., 2023)

3.2 Laboratory Testing and Analysis

Ten samples from the Samana Suk Formation were prepared for testing according to the specified criteria. The following tests were performed to evaluate the limestone's suitability for construction:

- Unconfined tensile strength
- Unconfined compressive strength
- Soundness
- Los Angeles abrasion value
- Elongation and flakiness index
- Specific gravity and water absorption
- Bitumen stripping and coating
- Clay lumps and friable particles
- Unit weight
- Petrographic analysis

Each test was performed to measure the limestone's durability, abrasion resistance, tensile strength, and suitability for asphalt and cement mixtures. These assessments are essential for determining how the limestone performs under different physical and environmental conditions, which is critical for its use in infrastructure projects.

3.3 Petrographic Analysis and Modal Analysis

Thin sections were prepared to examine the limestone samples in detail, focusing on mineral composition, texture, cracks, and the presence of any harmful substances. These thin sections were then analysed using modal percentage analysis, which helped identify the reactive constituents and assess the mineralogy of the rock. The petrographic analysis focused on identifying the key minerals present in the limestone, with particular attention given to any potentially reactive minerals that could affect its suitability for concrete or asphalt applications.

The presence of calcite as the predominant mineral in the limestone was observed, along with trace amounts of clay, dolomite, and quartz. This analysis was crucial in determining the risk of potential issues like alkali-silica reactions (ASR) or alkali-carbonate reactions (ACR), which can be detrimental to the integrity of concrete or asphalt mixtures.

3.4 Evaluation Standards and Aggregate Suitability

The suitability of the Samana Suk Formation limestone as a construction material was evaluated according to internationally recognised standards. The American Society for Testing and Materials (ASTM 2004), the American Association of State Highway and Transportation Officials (AASHTO), and British Standards (BS) were applied to assess the physical and mechanical properties of the limestone aggregates. These standards guide the selection of aggregates that can withstand the long-term stress and environmental impacts commonly experienced in construction.

Particular attention was paid to properties like aggregate durability, abrasion resistance, and the engineering characteristics necessary for pavement design. Aggregates for large infrastructure projects must have the engineering qualities required to resist damaging influences over time, such as weathering, abrasion, and mechanical stress.

4.0 RESULT AND DISCUSSION

4.1 Petrographic Analysis

4.1.1 Mineral Composition

The petrographic examination of limestone from the Samana Suk Formation, exposed at Village Rani Wah, Haripur (Hazara Basin, Pakistan), reveals a composition predominantly of calcite.

Calcite occurs mainly as spar and micrite in the thin sections (Figures 7A, 7B). Most of the studied samples contain both skeletal and non-skeletal grains, widely distributed throughout the sparitic matrix. Skeletal grains primarily comprise shell fragments from diverse sources, including Pelecypods (Figure 7C), Texularia (Figure 7D), and Bivalvia (Figure 7I). Non-skeletal grains are dominated by oolites (Figure 7E) and peloids (Figure 7F).

The limestone exhibits a finely grained texture, with individual particles displaying sub-angular to sub-rounded shapes arranged in an interlocking pattern. According to Dunham's (1962) limestone classification, the limestone can be categorised as wackestone to packstone. Thin section analysis also reveals stylolites (Figure 7G) and calcite-filled veins (Figure 7H), indicating post-depositional alteration and the influence of tectonic stress. These mineralogical and textural characteristics suggest that the limestone was deposited under conditions typical of a restricted lagoon environment or a gently sloping mid-ramp Tethyan carbonate platform (Ramzan *et al.,* 2023). The study area at Village Rani Wah provides an ideal representation of these depositional settings, reflecting a shallow marine environment with moderate energy conditions.

4.1.2 Alkali-Silica Reaction (ASR)

The risk of Alkali-Silica Reaction (ASR) in the Samana Suk Formation limestone is minimal. The petrographic analysis shows only trace amounts of reactive silica, which are insufficient to initiate harmful expansion reactions when exposed to the alkalis present in Portland cement. ASR can cause significant deterioration in concrete structures, but the absence of significant reactive silica in the limestone from the study area ensures that the material is chemically stable and safe for use in concrete applications. This finding is critical for infrastructure projects, particularly in regions like Haripur, where durable construction materials are essential for long-term development.

4.1.3 Alkali-Carbonate Reaction (ACR)

Regarding Alkali-Carbonate Reaction (ACR), the analysis indicates that there is no significant risk from this reaction in the Samana Suk limestone. The dolomite content in the limestone samples from the study area is less than 1%, which is considered insufficient to trigger harmful volume expansion when the limestone interacts with alkalis in cement. ACR can lead to cracking and structural damage in concrete due to the expansion of certain types of carbonate minerals, but the low dolomite content in the limestone makes it a safe material for use in concrete and asphalt. The findings from the study area highlight the stability and safety of Samana Suk limestone for use in construction projects, offering a reliable, durable resource for the region's growing infrastructure demands.

4.2 Geotechnical Test Results

4.2.1 Density and Moisture Absorption

Specific gravity and water absorption of aggregates provide important indications of their strength and density. A higher specific gravity generally corresponds to greater strength and durability, as well as a reduced capacity for water percolation. Aggregates with high specific gravity suggest minimal weathering and a denser structure, influenced by their mineralogical composition. Conversely, aggregates with lower specific gravity and higher water absorption are considered weaker or of inferior quality, whereas aggregates with higher specific gravity and lower water absorption are regarded as superior.

The specific gravity of aggregates is crucial for determining volume, weight, and other relative mechanical properties in cement concrete, asphalt concrete, and similar pavement mixtures. Water absorption is closely related to specific gravity; aggregates with higher absorption tend to be more porous and susceptible to weathering, making them unsuitable for construction purposes. While some absorption in asphalt aggregates can enhance mechanical bonding, water absorption should remain within acceptable limits to prevent adverse reactions that could compromise aggregate strength.

In this study, the specific gravity of the samples ranged from 2.59 to 2.68, with a mean value of 2.64, while water absorption varied from 0.47 % to 0.90 %, with an average of 0.61 %, well within the normal limit of 2 %. These results indicate that the aggregates meet ASTM (2004) standards for high-quality materials and are suitable for use in base and sub-base layers, cement concrete, and asphalt concrete applications.

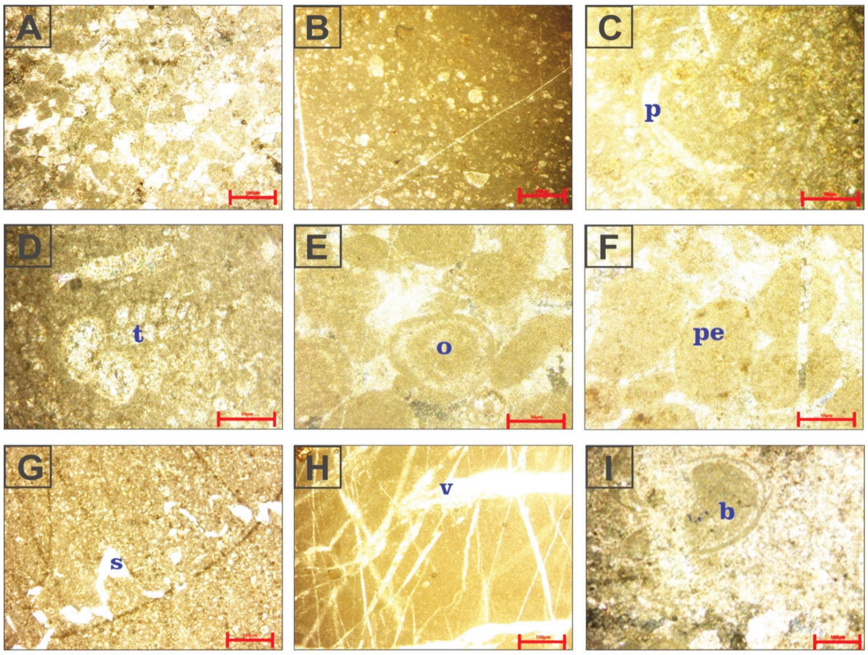

Figure 7: Microphotographs illustrating significant petrographic characteristics observed in the analysed samples of the Samana Suk Formation
A) spar; B) micrite; C) pelecypods (p); D) texularia fossil (t); E) ooids (o); F) peleoids (pe); G) stylolities; H) calcite filled veins; I) bivalvia fossil

4.2.2 Unconfined Compressive Strength Analysis (UCS)

The Unconfined Compression assessment is a lab test used to measure the Unconfined Compressive Strength of a rock specimen (UCS). Unconfined compressive strength is the maximum axial compressive stress that a specimen can withstand under zero confining pressure (UCS). The primary objective of this test is to quickly calculate the unconfined compressive strength of rocks with enough cohesion to allow testing in an unconfined state. A cube-shaped samples were prepared for this test from Samana Suk Formation Limestone samples (Figure 5g). The compressive strength of the rock samples of the Samana Suk Formation Limestone is uniform. The Unconfined Compressive Strength Test values of Samana Suk Formation Limestone range from 49 MPa to 56 MPa with an average value of 53 MPa (Table 1). UCS of Samana Suk Formation when compared to ISO classification 2003, the limestone in the area ranges from "medium" to "medium-strong".

The results of all the samples fall within the acceptable range for use in construction purposes according to the ASTM specifications. The UCS of the studied samples is almost 6–11 times that of their Tensile Strength. Since UCS encompasses a wide range of physio-mechanical and petrographic characteristics, it can serve as an indicative parameter to assess the suitability of limestone for construction applications.

4.2.3 Split Tensile Strength Analysis

Split tensile strength is a fundamental property that has a significant impact on the degree and size of cracking in structures. Generally, concrete does not withstand direct tension due to its low brittleness and tensile strength. The split tensile strength test is employed to evaluate the tensile strength of cured concrete. The intended concrete strength is influenced by minor modifications in the water-to-cement ratio, ingredient proportioning, slump increase, and so on.

This, in turn, has an impact on the structural strength and stability. Concrete's strength can be determined using a variety of tests. Because concrete is brittle, it is prone to cracking in tension. As a result, conducting a concrete tensile strength test is critical. A cube-shaped samples were prepared for this test from Samana Suk Formation Limestone samples. The Split Tensile Strength Test values of Samana Suk Formation Limestone range from 4.78 Ma to 5.85 MPa with an average value of 5.48 MPa (Table 1). Because the range of results is within the specified range, the limestone under examination might be utilised safely in concrete and other construction applications.

4.2.4 Soundness Assessment

Soundness refers to the ability of an aggregate to withstand weathering and erosion when exposed to natural conditions. Sodium sulfate is a commonly employed chemical for conducting soundness tests on aggregates. This test is completed in five cycles, as the sample is kept in an already prepared solution of sulphates and is checked after the completion of each cycle. The maximum tolerable limit of Sodium Sulphate Soundness is 12 % (AASHTO, 2009- T104). After every cycle, the crumbling and disintegration of particles of aggregates define the suitability of aggregates, the lesser splitting and crumbling of aggregate the more it will be considered as good aggregate and vice versa.

Aggregates are exposed to a variety of weathering conditions in the field, including freezing and thawing, wetting, drying, and thermal fluctuations, all of which destroy aggregate structures and shorten the life of civil structures. Aggregates having more absorption, cleavable property, and swelling due to the presence of clay minerals are not considered as good aggregates. It should be sufficiently resistant to weathering and erosion for good quality and efficient aggregate. The soundness test outcomes for the aggregate samples varied from 1.90% to 4.12%, with an average value of 2.92% (Table 1), which falls within the specified limit of 12% maximum. Since the results are within the acceptable range, it indicates that the studied aggregate can be safely used in concrete and other construction applications.

4.2.5 Los Angeles Abrasion Test

Los Angeles Abrasion test is used for the determination of resistance to abrasion of aggregates and disintegration and degradation. During its life, aggregate is subjected to crushing, deterioration, and disintegration. Throughout the entire duration, it is crucial for the aggregate to maintain its structural integrity and resistance against crushing, deterioration, and disintegration. The primary purpose of this test is to determine the impact of abnormal loads on aggregates during their service, specifically assessing the wear and tear they experience. The accelerated rates of wear and tear in aggregates can have a detrimental effect on the lifespan of civil structures. Therefore, it is essential for aggregates to exhibit substantial resistance against these forces.

The Los Angeles test results for aggregate abrasion ranged from 22.9% to 29.8%, with an average of 25.6% (Table 1). These values fall comfortably within the specified limits of 35% for cement concrete, 40% for base course, and 50% for sub-base, indicating that the aggregates meet the required standards for these applications. When subjected to abrasion, the aggregate of the Samana Suk Formation Limestone is sound and durable, according to the Los Angeles low abrasion values.

4.2.6 Flakiness Index Test

The shape of aggregate is noticeable, when used in construction projects, as the crystallography and grain-fabric of any rock unit defines its breakage pattern and shape when it is crushed. The flaky or elongated shape of materials, when used in various pavements, may causes failure as the loading force can breakdown the elongated or flattened shape material. The excessive value of the flaky and elongated shape of aggregate above the permissible limits causes lack of stability of aggregate mix in a specified structure. The main purpose of this evaluation is to ascertain the morphology of individual particles, as roughly spherical particles have the most strength. Increased flakiness index values correspond to reduced workability, as the samples that could pass through the gauge's opening were fewer, and the aggregate weight that successfully passed through was determined and reported as

Table 1: Geotechnical test results of Sumana Suk Formation Limestone

S. No	Los Angles Abrasion Test %	Soundness Test %	Specific Gravity	Water Absorption %	Elongated Index %	Flakiness Index %	Clay Lumps and Friable Particles %	Bitumen Coating %	Bitumen Stripping %	Loose Unit Weight g/cc	Rodded Unit Weight g/cc	Unconfined Compressive Strength (Mpa)	Split Tensile Strength (Mpa)
1	23.2	4.12	2.59	0.90	11.7	8.4	<1%	> 95%	<5%	1.16	1.42	49	4.78
2	29.8	2.61	2.61	0.65	10.8	8.9	<1%	>95%	<5%	1.20	1.44	53	5.52
3	26.8	1.90	2.68	0.54	12.7	11.6	<1%	>95%	<5%	1.22	1.46	54	5.71
4	24.7	2.79	2.67	0.61	11.3	9.3	<1%	>95%	<5%	1.18	1.45	53	5.49
5	27.8	3.10	2.60	0.61	13.8	7	<1%	>95%	<5%	1.19	1.43	51	5.20
6	25.9	2.39	2.68	0.47	12.2	9.7	<1%	>95%	<5%	1.21	1.42	55	5.82
7	27.2	3.66	2.66	0.70	12.9	13.4	<1%	>95%	<5%	1.20	1.46	52	5.47
8	23.8	3.19	2.62	0.64	14.3	12.1	<1%	>95%	<5%	1.20	1.44	54	5.54
9	22.9	2.87	2.68	0.51	10.2	13.9	<1%	>95%	<5%	1.17	1.42	56	5.85
10	24.3	2.63	2.66	0..51	10.7	11.2	<1%	>95%	<5%	1.18	1.44	52	5.50
Average	25.6	2.92	2.64	0.61	12	10.5	<1%	>95%	<5%	1.19	1.43	53	5.48

a percentage of the total sample weight. Particle shape plays a significant role in characterising aggregates as it can influence the likelihood of breakage or deformation when subjected to heavy traffic loads. Under heavy traffic loads, aggregate deformation and breakage impacts the road's workability.

The observed elongation index test results for the samples vary between 7% and 13.9%. The average value of flakiness index is 10.5% (Table 1). These values fall well below the maximum limit set by AASHTO and ASTM (2004). These results are within specification limitations, indicating that the aggregate under study might be utilised in a variety of construction projects.

4.2.7 Elongation Value Test

Particles that are elongated exhibit reduced strength. Usually, fragmented particles have a 1.5 times higher elongation index than the flakiness index. Increased elongation index values correspond to reduced workability. The percentage of flaky and elongated particles in an aggregate determines the morphology of the particles. The existence of flaky and elongated particles can lead to inherent vulnerabilities and increase the risk of failure when subjected to heavy loads. The weight of an aggregate-based sample placed in an elongated gauge determines the fraction of elongated particles.

The findings of the elongation index test of the samples under observation range from 10.2% to 14.3%, with an average value of 12% (Table 1). These values fall well below the maximum limit prescribed by AASHTO and ASTM (2004), which shows that the shape of Samana Suk Formation limestone aggregates is not an issue for any constructional use.

4.2.8 Application and Layering of Bitumen

The objective of this test is to evaluate the adhesion of the bitumen layer to the aggregate surface when exposed to water. Bitumen coating and stripping are important parameters that determine the cohesive interaction between aggregate particles and bitumen in the uppermost asphalt layer under wet conditions (AASHTO T-182). Aggregates used in asphalt layers should demonstrate strong cohesion with bitumen and maintain this cohesion even when subjected to water and moisture (Ahsan *et al.,* 2016).

In this study, the stripping value for all samples from the Samana Suk Formation, using 80/100 grade bitumen, was less than 5%, while the coating value exceeded 95% (Table 1). These results align with international standards, confirming that the Samana Suk Formation provides an excellent source of aggregate suitable for asphalt applications.

4.2.9 Density of the Aggregate Compacted/Uncompacted

The unit weight of an aggregate is a valuable parameter for assessing the weight-to-volume ratio and void ratio (AASHTO T-19). These ratios play a crucial role in mix designs and estimation of reserve stocks. Aggregates with higher unit weight values are typically regarded as superior and efficient due to their lower void ratios. A reduced void ratio helps minimise water absorption in aggregates, thereby preventing reactions and damage within the aggregate particles. The test was carried on both loose and compacted (Rodded) aggregates using ASTM C-29 to determine their unit weight in both loose and compacted states. The uncompacted (Loose) unit weight ranges from 1.16 to 1.22 with mean value of 1.19 (Table 1), while the value of a rodded unit ranges from 1.42 to 1.46, with an average of 1.43.

4.2.10 Clay Lump and Friable Particles

Clay lumps are similar to aggregate or gravel, which are small balls made of soil that scatter quickly in water. Friable particles are granular in form and disintegrate when they encounter water.

The density, durability, and strength of a mix are all affected by the presence of such particles in the aggregate. Pop outs near the concrete surface will occur if there are large amounts of clay lumps present. Breaking down friable particles into smaller particles is easy.

Clay lumps and friable particles exist in aggregate as surface adherent coatings or lumps, and when present in an inappropriate amount, they can interfere with and adversely influence bond development between aggregate particles and the cement paste, decreasing the concrete's strength and durability. The fraction of clay lumps and friable particles altogether is less than 1% (Table 1). All of the clay lumps and friable particle levels are found to be within the (ASTM 2004) reference range of 2%.

5.0 ECONOMIC, SUSTAINABILITY, AND BROADER APPLICATIONS OF LIMESTONE

5.1 Economic Analysis and CPEC Context

The Samana Suk Formation limestone, located in District Haripur, provides a significant economic advantage to Pakistan's infrastructure projects, particularly within the context of CPEC. As CPEC continues to accelerate the development of roads, bridges, and industrial zones across Pakistan, the demand for high-quality construction materials has surged. The local availability of Samana Suk limestone significantly reduces reliance on imported aggregates, thereby lowering transportation costs and increasing the economic viability of large-scale infrastructure projects.

Due to its proximity to National Highways N-35 and N-5, the Samana Suk limestone is easily accessible, further enhancing its cost-effectiveness. Sourcing locally provides an opportunity for price stability, crucial for long-term infrastructure projects, such as CPEC, which spans multiple sectors like roads, railways, and urban infrastructure. Furthermore, regional economic growth is stimulated by creating local employment opportunities and fostering economic self-sufficiency. By utilising locally sourced limestone, CPEC projects will not only benefit from cost savings but also help reduce national import dependencies and build sustainable local supply chains, contributing to overall economic resilience and self-sufficiency in Pakistan's construction sector.

5.2 Sustainability Implications

The Samana Suk limestone offers numerous sustainability advantages. The low water absorption (0.61%) and high compressive strength (53 MPa) of the limestone make it exceptionally durable and suitable for long-term use in infrastructure. Its resilience ensures that the material can withstand weathering and wear, reducing the need for frequent replacements and thus lowering resource consumption over time. Additionally, local sourcing of the limestone greatly reduces the carbon footprint associated with the transportation of aggregates, further promoting environmental sustainability.

The soundness and abrasion resistance of the material ensure that it remains structurally sound and durable over the long term, contributing to long-lasting infrastructure and minimising environmental impact. By promoting sustainable construction principles, the high durability of Samana Suk limestone reduces the frequency of repairs, leading to lower lifecycle costs and contributing to a more sustainable approach to infrastructure development. The resilience of the material supports circular economy practices by reducing the need for non-renewable resources and minimising construction waste.

5.3 Scalability Barriers and Solutions

While the Samana Suk Formation limestone presents significant potential for use in large-scale projects such as CPEC, there are a few scalability challenges to consider:

1. **Extraction Capacity:** To meet the increasing demand of large-scale infrastructure projects, the existing extraction capacity may require expansion and modernisation. Investments in advanced mining technologies and processing facilities will be crucial to maintaining a consistent and sustainable supply of high-quality limestone for large-scale infrastructure initiatives.
2. **Environmental Impact:** Increased extraction activity may lead to land degradation, dust pollution, and landscape disruption. To mitigate these issues, implementing environmentally sustainable mining practices, such as rehabilitation of quarries, dust control measures, and land reclamation efforts, is essential.
3. **Regulatory Challenges:** Navigating local mining regulations and environmental guidelines may pose administrative hurdles, slowing down scalability efforts. Streamlining the permitting process and promoting collaboration between government bodies and private stakeholders will be necessary to ensure smoother project implementation.

By addressing these scalability barriers through technology-driven solutions, policy reforms, and environmentally responsible mining practices, the Samana Suk limestone can be effectively scaled for large-scale infrastructure projects, ensuring its full potential is realised in CPEC and beyond.

5.4 Broader Engineering Applications

The Samana Suk limestone is not only suitable for road construction but also finds applications in several other sectors of civil engineering (Figure 8):

1. **Cement and Concrete Production:** The limestone is rich in calcium carbonate, which is essential for producing cement and concrete. This high-quality limestone provides durable materials for high-performance concrete used in infrastructure projects such as highways, bridges, and buildings. The low water absorption and high strength of the limestone improve the durability and longevity of concrete structures (Moftah *et al.,* 2022; Lawan Muhammad, 2018).
2. **Asphalt Concrete:** Limestone's abrasion resistance and low friability make it ideal for use in asphalt concrete. The limestone contributes to the durability and wear resistance of road surfaces, making it an important material for CPEC road construction and other high-traffic infrastructure projects.
3. **Railway Ballast:** Due to its high compressive strength and abrasion resistance, Samana Suk limestone is also suitable for railway ballast, providing stability to rail tracks.

Its durability under load ensures the integrity of railway infrastructure, making it an essential material for railway construction.

4. **Agricultural Applications:** The limestone is used as agricultural lime, helping to improve soil pH and increase nutrient availability. This application is crucial for enhancing soil fertility, improving crop yields, and supporting food security in the region (Rayburn, Service & Agronomist, 2005).
5. **Metallurgical Processes:** Limestone also plays a vital role as a fluxing agent in steel production, where it helps to remove impurities from molten metal. This contributes to the purity and efficiency of steel manufacturing (Manocha & Ponchon, 2018).
6. **Environmental Remediation:** Calcium carbonate, derived from limestone, is used in environmental clean-up applications, including wastewater treatment, soil stabilisation, and flue gas desulfurisation (Sabir *et al.,* 2023). These applications promote environmental sustainability and contribute to cleaner industrial processes.

Given its versatility, the Samana Suk limestone can be used across various engineering domains, including construction, agriculture, metallurgy, and environmental remediation, offering broad applications that benefit multiple sectors and contribute to economic and environmental sustainability.

6.0 CONCLUSION

The Hazara Basin is home to significant and well-exposed outcrops of the Middle Jurassic Samana Suk Formation, which offers considerable potential for construction and infrastructure projects in Pakistan. Field surveys indicate that the Samana Suk Formation is prominently exposed in the Rani Wah area of Haripur District, and is predominantly composed of limestone. The limestone exhibits a range of colors from dark grey to yellowish brown, with medium to thick bedding. The limestone samples from the study area were subjected to various standard geological and engineering tests, which have been widely recognised by international societies and organisations, to assess their suitability for construction applications.

The results of the engineering tests, including Los Angeles Abrasion (25.6%), Soundness (2.92%), Specific Gravity (2.64), Water Absorption (0.61%), Bitumen Stripping (<5%), and Unconfined Compressive Strength (53 MPa), demonstrate that the limestone from the Samana Suk Formation satisfies or exceeds the required engineering standards set by agencies like AASHTO (2009), ASTM (2004), BS (1990), and NHA (1998). The petrographic analysis confirms that the limestone primarily consists of bioclasts, oolites, and peloids, embedded in a matrix of sparry and micritic material. Importantly, the limestone contains no deleterious materials above safe thresholds, making it a non-reactive aggregate suitable for use in road construction and concrete production, including with high-alkali cements and ordinary Portland cement, without the risk of alkali-aggregate reactions. Based on these findings, it is concluded that the limestone of the Samana Suk Formation in Village Rani Wah is of exceptional quality and can be safely utilised as an aggregate source for a wide range of construction applications, including road building, cement concrete, and asphalt.

In addition to its geological properties, the geographical features of Village Rani Wah offer favorable conditions for aggregate quarrying. The steep ridges and cliffs in the area are suitable for blasting techniques, while gentle slopes are ideal for open-pit mining. The nearby piedmont plains provide optimal locations for establishing rock crushing units. Moreover, the proximity to National Highways N-35 and N-5 ensures easy transportation of crushed and uncrushed limestone to any part of the country, thereby reducing logistical costs and enhancing the economic viability of large-scale infrastructure projects.

The local availability of high-quality limestone from the Samana Suk Formation presents a significant economic advantage. By reducing dependence on imported aggregates, transportation costs can be minimised, which is particularly beneficial for infrastructure projects under the China-Pakistan Economic Corridor (CPEC). Additionally, the use of locally sourced limestone fosters regional economic development, creating job opportunities and supporting price stability for mega-projects. This will contribute to the long-term sustainability of infrastructure projects and enhance Pakistan's economic self-sufficiency in construction materials.

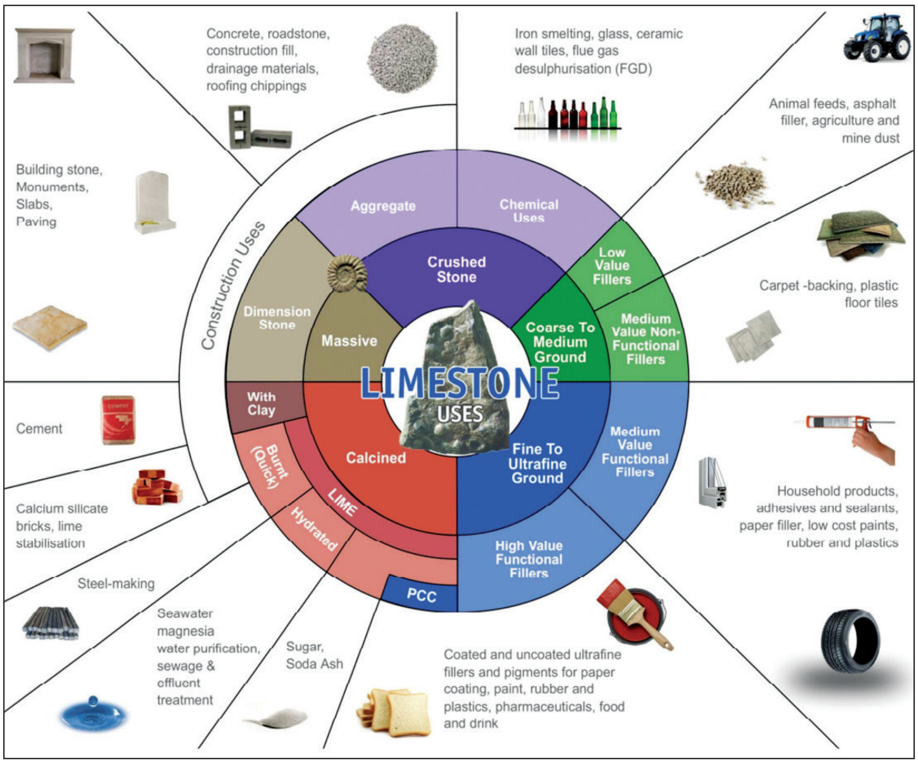

Figure 8: Visual representation of common uses for limestone materials (Kambakhsh et al., 2024)

Table 2: Standard Values for Aggregate and Average Value of Samana Suk Formation Limestone of Study Area

S. No	Test Name	Standard Value (According to ASTM, AASTHO, BS, NHA Specification)	Average Value of Samana Suk Formation Limestone
1	Los Angles Abrasion Test %	<40%	25.2%
2	Soundness Test %	<12%	2.92%
3	Specific Gravity	>2.5	2.64
4	Water Absorption %	<1%	0.61%
5	Elongated Index %	<15%	12%
6	Flakiness Index %	<15%	10.5%
7	Clay Lumps and Friable Particles %	<1%	<1%
8	Bitumen Coating %	>95%	>95%
9	Bitumen Stripping %	<5%	<5%
10	Loose Unit Weight g/cc	1.12-1.3	1.19
11	Rodded Unit Weight g/cc	1.30-1.76	1.43
12	Unconfined Compressive Strength (Mpa)	10-20 (Very weak)	53
		20-40 (Weak)	
		40-80 (Medium)	
		80-160 (Strong)	
13	Split Tensile Strength (Mpa)	4-7 (Strong)	5.48

In terms of sustainability, the Samana Suk Formation limestone aligns with global standards for environmentally responsible construction. The limestone's high durability, coupled with its low water absorption and abrasion resistance, ensures that infrastructure projects will require fewer replacements and maintenance, leading to a lower carbon footprint and reduced resource consumption. Additionally, by sourcing aggregates locally, the transportation emissions associated with importing aggregates from distant regions are substantially reduced, further supporting environmental sustainability.

However, scaling up the utilisation of Samana Suk limestone for large-scale projects like those under CPEC presents certain challenges. The extraction capacity of the current mining infrastructure may need to be expanded and modernised to meet the growing demand. Moreover, the environmental impact of increased limestone extraction must be carefully managed through sustainable mining practices and rehabilitation efforts. Regulatory challenges, including permitting delays and compliance with environmental guidelines, may also hinder scalability. Addressing these barriers through technology-driven solutions and policy support will be essential to fully leverage the potential of Samana Suk limestone for long-term infrastructure development.

In conclusion, the Samana Suk Formation limestone from Village Rani Wah stands out not only for its geological properties but also for its economic, sustainability, and scalability benefits. The limestone is a high-quality, durable, and non-reactive aggregate suitable for a variety of construction applications, including road construction, cement concrete, and asphalt. Its local availability reduces transportation costs, supports regional economic development, and ensures price stability for long-term infrastructure projects. The environmental sustainability of using this limestone, with its high durability and low carbon footprint, further underscores its value. With the right scalability measures in place, Samana Suk limestone will play a critical role in supporting Pakistan's infrastructure growth, particularly in CPEC and other national projects, while contributing to the country's economic self-sufficiency and sustainable development goals. ■

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AN AUTONOMOUS DRONE FRAMEWORK FOR REAL-TIME 3D CONSTRUCTION MONITORING USING PHOTOGRAMMETRY AND IOT TECHNOLOGIES

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Abstract

This paper presents an innovative framework for autonomous 3D construction site monitoring using drones, photogrammetry, and Internet of Things (IoT) technologies. The proposed system captures 2D images of construction sites via a custom-built drone, which transmits the images in real-time to cloud services for immediate processing. Using Amazon Web Services (AWS), the images are automatically reconstructed into detailed 3D models, enabling remote monitoring and progress tracking. The system leverages Industry 4.0 technologies to facilitate cloud-based data analysis, offering a scalable and efficient solution for construction project management. We validated the framework through real-world testing at a construction site in Subang Jaya, Malaysia, where two flight missions were conducted, capturing 79 and 158 images, respectively. The 3D reconstruction was successfully performed with improved processing time on higher-specification AWS machines. Results showed that the system was able to reconstruct accurate 3D models, with Flight #2 achieving smoother surfaces compared to Flight #1, despite variations in image quality. The integration of Building Information Modeling (BIM) with the 3D models is proposed to automate the comparison of construction progress with design specifications. This approach has the potential to enhance the precision, accessibility, and efficiency of construction monitoring, particularly in environments with limited access.

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1.0 INTRODUCTION

The construction industry has increasingly relied on advanced technologies to improve efficiency, safety, and quality control. Among these innovations, drones have emerged as a valuable tool, particularly in construction monitoring, due to their ability to collect real-time, high-resolution data from difficult-to-access sites. Traditional methods of construction monitoring often require physical presence, extensive manpower, and manual data collection, which are not only time-consuming but also prone to human error. The challenge becomes even more pronounced in situations such as the COVID-19 pandemic, where access to construction sites may be restricted, and the safety of data collectors becomes a concern.

This paper proposes an autonomous 3D mapping drone framework for construction monitoring that leverages Internet of Things (IoT) technologies and photogrammetry to address these challenges. Our system enables real-time data collection and analysis without the need for on-site personnel, including on-the-fly processing of cloud computational tasks and final 3d model visualisation. The drone autonomously captures images of the construction site, which are then uploaded to the cloud for 3D reconstruction using photogrammetry. This reconstruction process provides a highly detailed and accurate 3D model of the site, enabling remote monitoring and assessment by construction experts.

The use of photogrammetry, which converts 2D images into a 3D model, offers a cost-effective solution by reducing the need for expensive equipment. Although photogrammetry traditionally requires significant computational power, the advent of cloud computing has made high-performance computing resources more accessible and affordable. With the integration of cloud-based services such as Amazon Web Services (AWS), the processing of large volumes of images is facilitated, and the system becomes scalable, enabling real-time monitoring for various construction projects.

The primary aim of this paper is to highlight the potential of integrating IoT and drone technologies for construction monitoring. By automating data collection and leveraging real-time cloud-based analysis, this system has the potential to revolutionise how construction projects are monitored, leading to better oversight, improved decision-making, and enhanced safety protocols. This work also aims to share insights into the development of both the hardware and software frameworks used in the system, providing a valuable reference for the research community interested in this area.

Table 1: Comparative existing systems and proposal

Study	UAV Type	IoT Integration	Data Processing	Automation Level	Scalability	Key Limitation
Girgin *et al.* (2025)	Custom-built	EdgeAI-enabled	Real-time obstacle detection	High	High	Limited to specific construction tasks
Choi *et al.* (2024)	Commercial drones	IoT sensors	Cloud-based BIM integration	Moderate	Moderate	Requires manual UAV operation
Xu *et al.* (2021)	Standard UAVs	None	Offline data processing	Low	Low	Not real-time; lacks IoT integration
Ko *et al.* (2025)	UAV with LiDAR	None	LiDAR-based 3D point cloud processing	High	High	High hardware cost and limited in GPS-denied environments
Proposed Framework	Autonomous Drone (Custom-built)	IoT-enabled for Real-time Monitoring	Real-time 3D image reconstruction on the cloud	High	High	Full automation requires cloud computing and advanced photogrammetry software

2.0 RELATED WORKS

The use of unmanned aerial systems (UAS), commonly known as drones, in the construction industry has gained significant attention over the past decade. Drones offer numerous advantages in construction monitoring, particularly in tasks such as site surveying, progress monitoring, and damage assessment. A systematic review by Zhou and Gheisari (2018) categorised UAS applications into various areas, including building inspection, site surveying, and progress monitoring. However, progress monitoring only contributed to 5.6% of UAS applications in the construction sector, highlighting the need for further research and development in this area.

In the context of construction monitoring, drones have been increasingly used to assess the ongoing status of construction projects. According to Lin *et al.* (2015), drones allow construction teams to capture high-quality images that can be superimposed onto Building Information Models (BIM) to monitor progress. This approach provides a lower-cost, more efficient method for site inspection compared to traditional methods. Additionally, drones offer a broader field-of-view, improved accessibility, and reduced monitoring time. The integration of photogrammetry with drones has also been explored as a means of enhancing the accuracy and detail of construction monitoring. For example, Lee *et al.* (2019) proposed a voxel-based comparison method where images captured by drones were processed into a 3D point cloud model using photogrammetry. This 3D model was then compared to the BIM model, providing periodic progress assessments. Similarly, Arif and Khan (2021) introduced a smart progress monitoring framework using video recordings, MATLAB, and BIM, while Casierra *et al.* (2022) used Agisoft Metashape for manual photogrammetric reconstruction. Although effective, these methods often involve manual workflows that could be improved with automation.

The challenge of automating drone-based construction monitoring was addressed by Patel *et al.* (2021), who utilised Pix4D software for progress monitoring. However, the use of proprietary software limited the system's flexibility and scalability. In contrast, our approach leverages open-source photogrammetry and cloud computing to automate the 3D reconstruction process, providing a more scalable and cost-effective solution.

Several reviews have highlighted the benefits and limitations of drone-based inspections for construction applications. Falorca *et al.* (2021) focused on the use of high-resolution cameras for visual inspections, while Konikov and Garyaev (2021) reviewed information technology (IT) solutions for progress monitoring in construction. However, these studies did not delve deeply into the integration of IoT and cloud-based systems for real-time monitoring, an area that our research aims to address.

Recent advancements have focused on automating construction monitoring through UAVs. For instance, Girgin *et al.* (2025) developed an EdgeAI-enabled drone system for autonomous construction site surveillance. Their system integrates lightweight object detection models within a custom-built UAV platform, facilitating real-time obstacle detection and dynamic path planning in construction environments. Field experiments demonstrated the system's scalability and computational efficiency compared to existing UAV solutions.

The combination of photogrammetry and IoT technologies has been extensively studied for construction monitoring. For example, Choi *et al.* (2024) integrated drone imagery with Building Information Modeling (BIM) to enhance construction site management. Their approach utilised photogrammetry for accurate 3D modeling, while IoT sensors provided real-time environmental data, facilitating informed decision-making.

Efficient data processing is crucial for real-time construction monitoring. Xu *et al.* (2021) proposed a volumetric change detection framework using UAV oblique photogrammetry to monitor building collapse. Their method involved multi-temporal UAV images and 3D point clouds, enabling precise detection of structural changes over time. Despite the clear potential of drones in construction monitoring, the widespread adoption of this technology has been hindered by factors such as technical complexity, high costs, and lack of awareness among construction professionals (Arif & Khan, 2021).

Numerous studies have demonstrated the effectiveness of drone-based data acquisition for creating highly detailed 3D models using various sensors, including LiDAR and RGB cameras (Ko *et al.,* 2025). These models are instrumental for conducting structural health assessments, offering an alternative to traditional methods that are time-consuming and labor-intensive. However, despite these advancements, several critical challenges remain, including the integration of real-time data processing, the high cost of hardware, and the complexity of interpreting large volumes of data.

In this work, the integration of autonomous drones with IoT technologies and cloud-based photogrammetry for real-time 3D construction monitoring will result in an efficient, scalable, and accurate system capable of providing detailed and timely insights into construction progress. This system will outperform traditional methods by automating the image capture and processing workflow, enabling continuous monitoring of construction sites with minimal human intervention. To overcome the challenges identified, we compare this approach with existing systems in Table 1 and propose an autonomous drone framework that integrates IoT technologies to facilitate real-time 3D mapping and construction monitoring, with performance metrics (such as RMSE values and processing times) meeting industry standards for real-time data analysis.

3.0 FRAMEWORK

This section describes the proposed IoT-based framework for automated construction monitoring using drone technologies. The framework consists of four key components: (1) the computer system used for flight planning and data management, (2) the embedded drone system for image acquisition, (3) the data server for storing images, and (4) the web server for real-time data analysis and monitoring.

3.1 Overview of the Framework

The framework is designed to provide an autonomous system that captures and processes construction site images using drone-based technology. The drone is responsible for flying over the construction site and capturing images of the site's progress. These images are then transmitted in real-time to a cloud server, where photogrammetry techniques are applied to generate 3D models of the site. The data is then analysed by construction experts via a web server, facilitating remote site monitoring. Key components of the framework:

i. Computer System:
    - The computer is responsible for setting up and optimising the drone system, including flight planning. The computer also connects to the web server to access and analyse 3D image reconstructions on the cloud.
    - Flight Planning: The computer plays a central role in creating the flight path for the drone. The flight path is optimised for comprehensive image acquisition over the construction site.

ii. Embedded Drone:
    - The embedded drone system captures images of the construction site using a camera mounted on the drone. GPS data is used to track the location of the drone and ensure that the images are acquired from the correct positions.
    - The drone is connected to the cloud via mobile data, enabling real-time transmission of images to the server.

iii. Data Server:
    - The AWS (Amazon Web Services) data server is used to store images transmitted from the drone. The data is processed for 3D image reconstruction using photogrammetry. The server allows experts to access images and reconstructed models for further analysis.

iv. Web Server:
    - The web server facilitates real-time monitoring of the construction site by the experts. They can remotely analyse the 3D models and images via a user interface.

3.2 Components of the System

3.2.1 Computer System

The computer system plays a pivotal role in setting up and controlling the drone for image acquisition. It is used to configure the flight path and ensure the drone's autonomy during the image capture process. In this work, the flight path is optimised for high-quality image acquisition using the drone's GPS system.

The computer system also connects to the web server, allowing the 3D image data to be uploaded to the cloud for reconstruction and analysis. This process can be done in real-time or on-demand, depending on the needs of the project.

3.2.2 Embedded Drone System

The embedded drone system is equipped with a camera, GPS, and a communication module for real-time data transfer. The drone is constructed with a Raspberry Pi as the central controller, allowing the addition of peripherals such as cameras and communication modules. The drone is designed to be lightweight, making it suitable for carrying and operating in various construction environments.

The drone operates autonomously, capturing images of the construction site from multiple angles. To ensure precise image acquisition, GPS data is used to track the drone's location. Additionally, the drone is connected to the AWS cloud via mobile data (GSM module), enabling real-time transmission of the captured images.

- Camera: A budget-friendly action camera (SJ4000 series) is used for image capture. The camera is equipped with a 12-megapixel CMOS sensor and is designed for outdoor use, making it robust enough for construction environments.
- GPS: The GPS system tracks the drone's location in real time, ensuring that the images are captured from the correct location.

The drone was custom-built using a Raspberry Pi as the central controller. A body-fixed coordinate system based on the quadcopter's configuration is adopted for this study, as depicted in Figure 1. The drone features a 450mm wheelbase and is equipped with a 30A electronic speed controller (ESC) and a 10-channel receiver. It is powered by four 1000kV

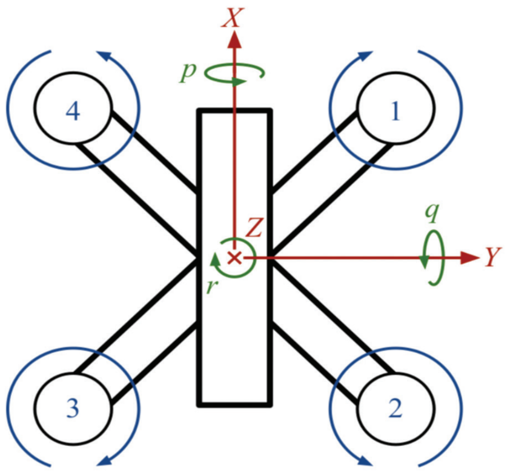

Figure 1: Quadcopter-based drone

brushless DC motors, two of which rotate clockwise, while the other two rotate counter clockwise. A key advantage of using brushless DC motors is their ability to generate minimal electromagnetic interference, which helps reduce potential disturbances to the drone's sensors. The 30A pulse-width modulation (PWM) ESC module is used to control the motors. Proper calibration of the ESC and motors is essential for their synchronisation. The drone is powered by a 3S1P 25C 11.1V 3300mAh LiPo battery.

The drone's path planning algorithm computes a set of waypoints that define the flight route based on the mission parameters. These waypoints are dynamically adjusted based on real-time sensor data and environmental changes. ArduPilot's mission planner is utilised to program the waypoints, and the onboard system updates the drone's flight path to follow a predefined trajectory. This allows for both autonomous and semi-autonomous operation modes, where the drone can adjust its path or speed in response to real-time conditions.

The ArduPilot Mega 2.8 is utilised as the flight controller module, offering an autopilot function that ensures smooth and stable flight, including autonomous take-off and landing. This module, which operates on open-source firmware, supports custom drone development and settings. A 915MHz telemetry radio is employed for communication with the drone, with a 100mW (20dBm) output power that allows radio control up to nearly 1 km. The receiver is attached to the flight controller, while the transmitter is connected to the laptop. Unlike the transmitter, the receiver may require modification using an adapter (e.g., CP2012 FTDI) for firmware updates.

When flying in unpredictable conditions such as turbulent weather, the system uses real-time flight data to adjust the drone's control surfaces, motor speeds, and flight parameters dynamically. ArduPilot's real-time flight stabilisation algorithms adjust these parameters to mitigate the effects of turbulence or wind gusts, ensuring steady flight. The system continuously monitors the drone's performance, including battery consumption, motor health, and sensor accuracy. ArduPilot's internal health monitoring system alerts operators to any performance issues, allowing for preemptive maintenance or adjustments during flight. Autonomous flight algorithms also consider energy efficiency, adjusting the drone's flight speed and altitude to minimise power consumption while maintaining optimal path tracking and task execution.

For navigation, the NEO-M8 series module is paired with the flight controller, supporting up to three global navigation satellite systems (GNSS): GPS, Galileo, BeiDou, and GLONASS. Additionally, this module includes jamming and spoofing detection capabilities to enhance security, reducing the risk of flight loss or entering restricted areas. A 10-channel radio-based transmitter and receiver, the Flysky FS-i6b, is used for flight control. While the drone requires only four channels to control its motors, an additional four channels are necessary for initiating a failsafe mechanism during emergencies or to avoid crashes.

For cloud connectivity, a SIM7600E-H 4G HAT is used as the GSM module for real-time communication. There are no specific requirements for this module, other than ease of integration with the Raspberry Pi and low power consumption. Construction site images were captured using a budget-friendly action camera, the SJ4000 series, which features a 12-megapixel CMOS sensor. Weighing just 58g, the camera is compact and lightweight. Its robust design makes it well-suited for outdoor environments, making it an ideal choice for drone applications. The overall framework is shown in Figure 2, and the hardware architecture is presented in Figure 3.

3.2.3 Data Server and Cloud Integration

The overview of the proposed autonomous 3D mapping drone for construction monitoring is shown in Figure 4.

Planning the flight is crucial for ensuring the safety and success of the mission. In this study, construction site images are captured from multiple locations and angles to provide a comprehensive view. The oblique mapping method is employed for construction monitoring, where the camera is positioned at a 60-degree angle relative to the drone's plane.

For autonomous flight control, we used the "ArduPilot Project" with its configuration utility to enable advanced dynamic control. The "Arducopter 3.2.1" firmware is first uploaded to the autopilot board (APM), allowing customisation of the drone's behavior, including motor control programming through Microsoft Visual Studio. Once the firmware is installed, the drone is set up, configured, and optimised for performance.

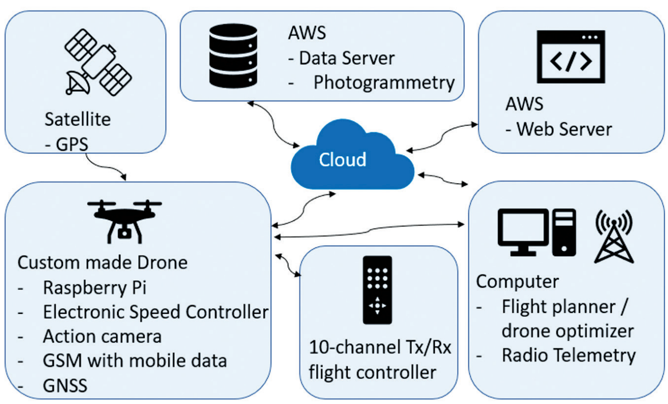

Figure 2: Overview of the Autonomous 3D Mapping Drone Framework

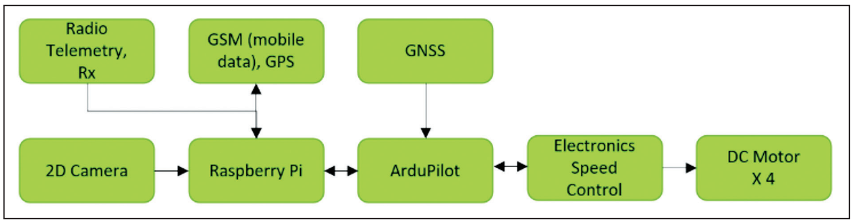

Figure 3: Hardware Architecture of the System

The flight plan is then created by simply selecting points on Google Maps for waypoints. APM generates the flight plan, which can be downloaded for further analysis. Additionally, the system allows interfacing with a flight simulator on a personal computer to recreate unmanned aerial vehicle (UAV) telemetry, providing the ability to monitor, record, and analyse telemetry logs.

In this study, Internet-of-Things (IoT) devices are connected to cloud services for automated digitisation. We utilised Amazon Web Services (AWS) as the core Industry 4.0 technology for autonomous 3D drone mapping in construction monitoring. The AWS cloud system is divided into two categories: (1) AWS Cloud #1 and (2) AWS Cloud #2, as shown in Figure 4. AWS Cloud #1 consists of AWS Simple Storage Service (S3), AWS Lambda, and AWS Elastic Compute Cloud (EC2). Images are initially stored in an AWS S3 container by the user. Once received, AWS Lambda, a serverless computing service, is triggered and requires user input to initiate. After being triggered, the images are transferred from AWS S3 to AWS EC2 for storage. AWS EC2 continuously extracts images from AWS S3, and careful supervision is necessary once the service is running. The images in AWS S3 remain in the container as a backup in case any images stored in AWS EC2 become corrupted. AWS Cloud #2 handles IoT automation. Images acquired from the drone's camera are sent to the AWS Command Line Interface (CLI) via mobile data. Once interfaced with AWS Cloud #1, the data is automatically synced to AWS EC2. It is important to note that the architecture of AWS Cloud #1 should be modularised to support multiple AWS CLI connections from various IoT-based edge devices.

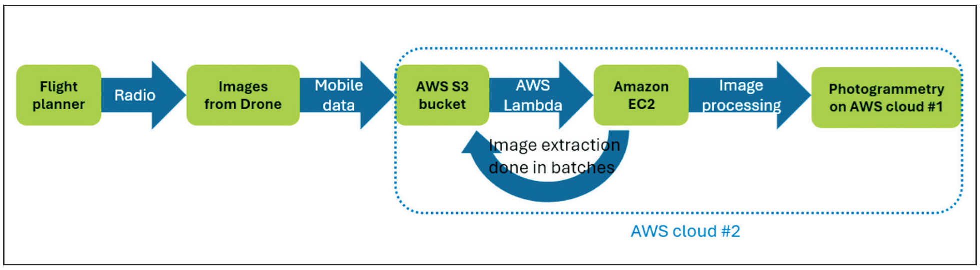

Figure 4: The software architecture of an autonomous 3D mapping drone

For cloud security, AWS Identity and Access Management (IAM) is employed. AWS IAM allows for precise control over user access, specifying the permissions for various operations. Each user has restricted access when logging into the AWS Management Console and interacting with resources. Additionally, new users can register with their credentials, and the principal must authenticate their "exceptional" rule for access.

3.2.4 3D Image Reconstruction, Web Server, and Monitoring

The 2D building images captured on-site are reconstructed into a 3D model using photogrammetry techniques for construction monitoring. As the 2D images are already stored in the cloud (AWS EC2), Meshroom 3D Reconstruction software, utilising the AliceVision framework, was employed to develop the 3D model of the construction site. The command-line interface (CLI) of Meshroom is integrated with AWS CLI to enable autonomous 3D image reconstruction on the cloud. Meshroom is an open-source software, allowing users to troubleshoot any issues that may arise during the reconstruction process.

The performance of the 3D reconstruction heavily depends on both the quality of the 2D images captured by the drone and the available computing power. To ensure high-quality results, images were captured from a 360-degree view around the building, covering as many points as possible. Once the collection of images is received from the cloud, the software processes them through several stages: feature extraction, image matching, feature matching, structure-from-motion, depth map estimation, meshing, and texturing, ultimately reconstructing the 3D model. An example of 2D to 3D image reconstruction is shown in Figure 5.

To input images, multiple files are dropped into the designated drop box. The process begins with camera calibration, which retrieves internal camera parameters such as focal length, sensor width, principal points, and distortion parameters. Meshroom utilises OpenCV, a real-time computer vision library, to perform the camera calibration. The source code for camera calibration is available in the OpenCV library and can be accessed through its official website.

For feature extraction, the SIFT (Scale-Invariant Feature Transform) algorithm is used to extract distinct groups of pixels. The algorithm first identifies keypoints from a multiscale image representation, followed by the extraction of descriptors associated with each keypoint. These descriptors, stored as 128-bit vectors, represent gradients around the keypoints and enable the matching of keypoints across different images. The scale-space maxima are computed using the difference-of-Gaussian function,

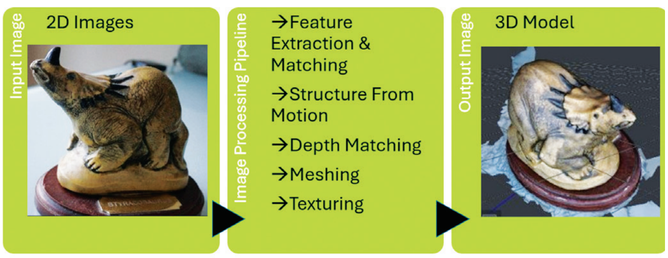

Figure 5: Photogrammetry image processing pipeline

which convolves the image with a variable-scale Gaussian, as defined by the Laplacian representation. Once the features are extracted, image retrieval techniques, such as the vocabulary tree approach, are used to match similar areas from different images, allowing the software to recognise shared content through image descriptors.

The core of 3D reconstruction from multiple images occurs in the Structure-from-Motion (SfM) process, a photogrammetric technique used to construct rigid scene structures or 3D points from 2D image sequences. During feature extraction and matching, points are fused to create tracks, with each track representing a point in space visible from multiple camera angles. SfM utilises various algorithms, such as the Next Best View Selection, which chooses images with sufficient associations to the features already reconstructed in 3D.

The resectioning process involves a Perspective-n-Point (PnP) algorithm in a RANSAC framework to determine the camera pose that best validates feature associations. To refine the pose further, non-linear minimisation is performed on each camera, and this process repeats to triangulate new points, adding and removing cameras until no new views can be localised. SfM is optimised through the use of high-scale SIFTs, which provide a coarse model that enables faster results by adding cameras and points simultaneously, rather than sequentially. This method accelerates the process by utilising more computational power. Additionally, libraries such as OpenCV and Ceres Solver are employed in the SfM process to handle tasks like pose estimation, triangulation, and point-cloud alignment, resulting in a 3D model. Depth mapping involves extracting image information related to the distance from a scene at a specific viewpoint. After the Structure-from-Motion (SfM) process, the depth value of each pixel is retrieved during this stage of the pipeline.

The method used for depth mapping in Meshroom, powered by AliceVision, employs the Semi-Global Matching (SGM) technique. The algorithm consists of four key steps: (i) pixelwise cost calculation, (ii) smoothness constraint implementation, (iii) disparity computation with sub-pixel accuracy and occlusion detection, and (iv) multi-baseline matching extension (Hirschmüller, 2005). When combined, these steps allow for precise depth mapping, enhancing the accuracy of 3D model construction by reducing errors and ensuring consistency across multiple viewpoints.

During the Meshing stage, a dense geometric surface representing the scene is created through 3D Delaunay tetrahedralisation, along with additional methods like Laplacian filtering and Poisson smoothing to improve the mesh. Meshing is critical for 3D visualisation and measurement. In the texturing step, the Least Squares Conformal Maps (LSCMs) approach is used to apply texture to the mesh, minimising texture distortion. Once texturing is complete, the 3D reconstruction process is finished, and the model is saved in a user-specified directory. A 'Texturing' folder within this directory contains the final 3D model, ready for viewing.

The web server provides a platform for construction experts to monitor the progress of the construction site remotely. After 3D reconstruction, the 3D model is made available on the server for analysis. The server connects to the data server and provides a graphical user interface for the experts to review the site's progress.

3.3 Data Flow and Real-Time Processing

The data flow within the system is designed to facilitate the seamless acquisition, processing, and analysis of construction site data. The drone captures images of the site, which are sent to the cloud server in real-time via mobile data. Once the images are uploaded to the cloud, they are processed using photogrammetry techniques to generate a 3D model of the construction site.

This model is then made available for remote analysis on the web server. By using cloud computing resources, the system can handle large volumes of image data and process them quickly, providing real-time feedback to construction experts.

4.0 EXPERIMENT AND RESULTS

This section details the experiments conducted to validate the proposed autonomous 3D mapping drone framework for construction monitoring. The framework was tested in a real-world construction site in Subang Jaya, Selangor, Malaysia, to assess its capability in capturing, processing, and analysing construction site data. The experiments included two flight missions with varying numbers of images, and the results of these missions were used to evaluate the effectiveness of the system.

4.1 Experimental Setup

Two flight missions were conducted to test the system:

- Flight #1: The drone captured 79 images.
- Flight #2: The drone captured 158 images.

The images were sent to the AWS cloud in real-time for processing and 3D reconstruction. The drone used GPS data for accurate flight navigation, and the captured images were processed using the Meshroom 3D Reconstruction software on the cloud.

4.2 Data Collection and 3D Reconstruction

The drone followed a pre-planned flight path, and images were captured from multiple perspectives to ensure complete coverage of the construction site. These images were then uploaded to the cloud and processed using photogrammetry software (Meshroom), which converts the 2D images into a 3D model. Once the models were reconstructed, they were made available for review on the web server for construction experts to analyse the site's progress remotely.

4.3 Experimental Findings

The experimental results are summarised in the following Table 2, which compares the processing time, image quality, and 3D model accuracy for the two flight missions.

The cloud-based machines used were equipped with high-performance specifications to ensure fast data processing for 3D image reconstruction. The two machines used were as follows:

- g4dn.xlarge: This machine is equipped with 4 virtual CPUs and 16 GB of RAM. It is suitable for tasks requiring moderate computational power, like handling image processing in real-time, but it has limitations when dealing with larger datasets.

- g4dn.4xlarge: A higher-spec machine with 16 virtual CPUs and 64 GB of RAM, designed for more demanding computational tasks, such as faster 3D image rendering and data analysis.

Both machines were equipped with a 2nd generation Intel Xeon CPU and an NVIDIA T4 Tensor Core, providing the necessary computational power for efficient processing. The experiments were performed on these two machines to compare their performance, particularly in terms of rendering time and processing speed.

Table 2: Experimental results

Experiment	Flight #1 (79 images)	Flight #2 (158 images)
Processing Time (g4dn.xlarge)	1 hour, 55 minutes	3 hours, 50 minutes
Processing Time (g4dn.4xlarge)	50 minutes	1 hour, 55 minutes
3D Model Quality	Fewer surface bumps, but less smooth than Flight #2	Smoother surface with fewer visible defects
Comparison with Cathedral Model (Meshroom)	Rougher texture, less detailed	Smoother texture, better detail
Image Acquisition	Good coverage, but lower number of images may affect accuracy	Higher number of images results in a more detailed model
Flight Path Deviation	Minor deviation from the planned path	Minor deviation, but sufficient data was still captured

The processing time was significantly shorter for Flight #1 when using the g4dn.4xlarge machine, completing the reconstruction in just 50 minutes, compared to 1 hour and 55 minutes for Flight #2 with 158 images. As expected, the larger number of images required more computational resources, resulting in longer processing times, especially on lower-performance machines like g4dn.xlarge.

The 3D model generated from Flight #2 (158 images) exhibited a smoother surface and fewer visible defects compared to the model from Flight #1 (79 images). The larger number of images contributed to a higher-quality reconstruction with more detail, making it more suitable for construction monitoring. When compared to the reference Cathedral model, Flight #2's 3D model was closer in quality, with fewer visible imperfections.

Both flights showed minor deviations from the planned flight path, likely due to environmental factors such as wind. However, these deviations did not significantly impact the quality of the acquired images, and the drone was still able to cover the construction site effectively. An illustration of this flight plan is shown in Figure 6.

Flight #2, with 158 images, provided a more detailed 3D model, demonstrating the importance of capturing a larger number of images for accurate reconstruction. This was especially important for capturing hard-to-reach areas of the site, ensuring complete coverage. An illustration of construction monitoring from 2D to 3D image reconstruction is shown in Figure 7. The experimental results demonstrate that the proposed autonomous drone framework is effective in capturing high-quality images and processing them into detailed 3D models. Key findings include:

- Real-time Processing: The system's ability to transmit images in real-time to the cloud and process them quickly is a major advantage for construction monitoring. The use of AWS cloud computing enables efficient processing, even for large datasets, reducing the time required for analysis.
- Data Quality: The quality of the 3D models improved significantly with a higher number of images. While the model from Flight #1 provided adequate detail, Flight #2 produced a more accurate and refined 3D representation of the construction site, suggesting that future work should focus on optimising image capture for even higher accuracy.
- Efficiency and Scalability: The system performed well for both small-scale (79 images) and larger-scale (158 images) construction monitoring, showing that the framework can scale to handle different sizes of projects.

To evaluate the accuracy of the 3D reconstruction and to quantify the quality of the generated 3D models, we used Source Filmmaker (SFM), a computer graphics tool, to compute the Root Mean Square Error (RMSE) of the 3D scenes. The RMSE is a measure of the difference between the reconstructed 3D model and the reference model. A lower RMSE indicates a more accurate reconstruction.

The 3D reconstruction process yielded better results when more images were used, compared to the computational power of the machine for rendering. The table below presents the SFM RMSE values for the two flight missions using different machine configurations: g4dn.xlarge and g4dn.4xlarge.

For Flight #1 (79 images), the RMSE was higher (1.44266 for g4dn.xlarge and 1.44154 for g4dn.4xlarge) compared to Flight #2 (158 images). This indicates that the model generated with fewer images had more discrepancies compared to the model generated with a larger dataset. The RMSE values for Flight #2 were lower (1.38934 for g4dn.xlarge and 1.38073 for g4dn.4xlarge), suggesting that the model was more accurate with more images used for reconstruction. Referring to Table 3, the RMSE does not show significant improvement with increased computing power. Flight #1 and Flight #2 showed a minimal improvement of 0.078% and 0.062%, respectively. However, a more noticeable reduction in RMSE, ranging from 3.7% to 4.2%, is observed as the number of images increases, depending on the computing power.

When compared with the Meshroom Cathedral 3D model, which has a smoother and more detailed surface due to its use of 350 images, our Flight #2 model performed better with an RMSE of 1.38073 for g4dn.4xlarge. Although the RMSE is still higher than the ideal value of 0.6, it is considered a good result for a smaller number of images and demonstrates the potential of this framework for real-time construction monitoring. The Meshroom Cathedral model had a RMSE of around 0.6, which serves as a benchmark for high-quality 3D reconstructions.

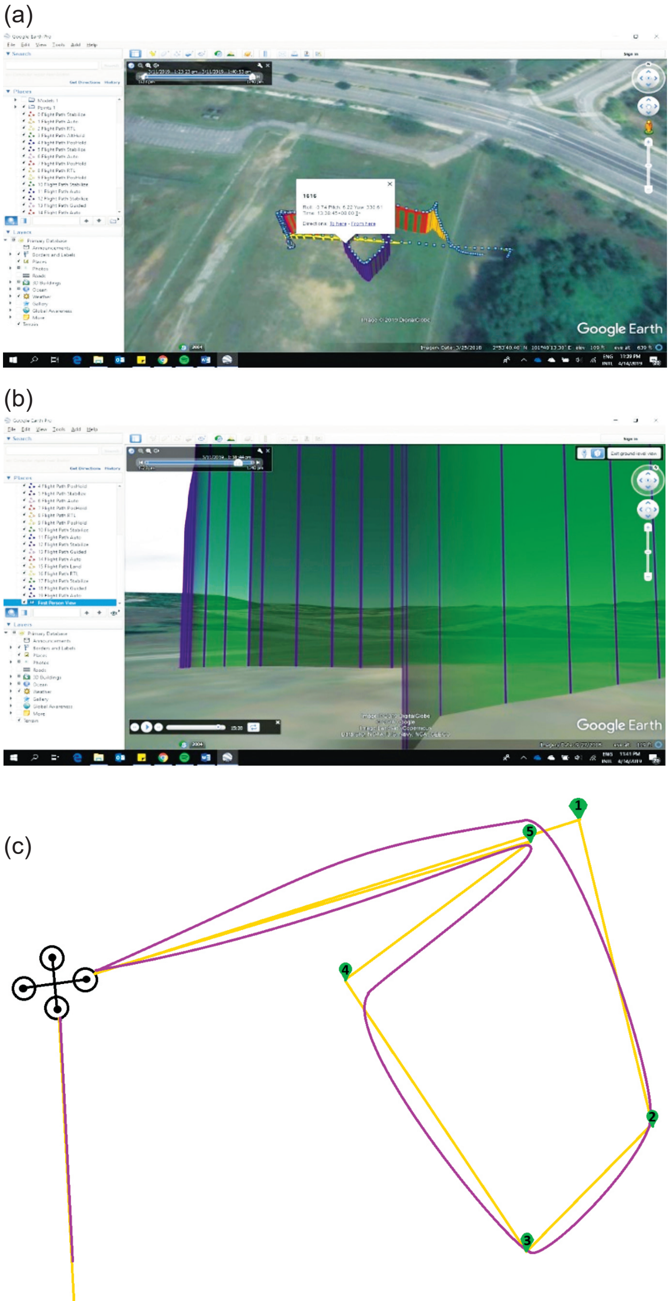

Figure 6: Flight planning and results
(a) Google Earth flight path overview, (b) first-person view (fpv) from drone, and (c) completed flight mission with path representations in yellow (planned) and purple (actual)

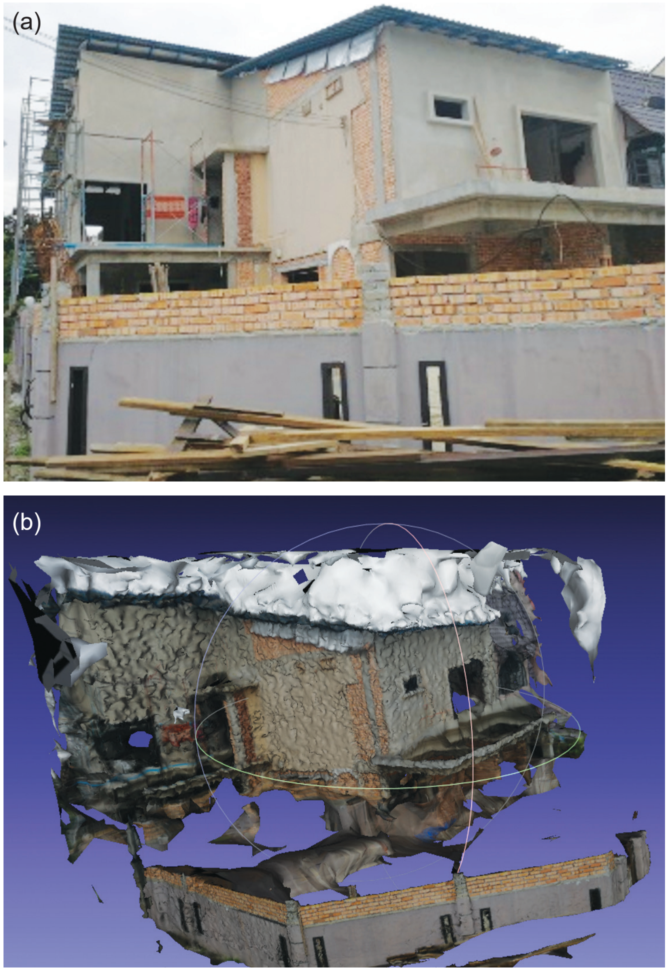

Figure 7: Construction monitoring
(a) An example of a 2D building image, and (b) an autonomous 3D reconstructed image for construction monitoring

Table 3: Source Filmmaker results

Flight Mission	g4dn.xlarge (RMSE)	g4dn.4xlarge (RMSE)
Flight #1 (79 Images)	1.44266	1.44154
Flight #2 (158 Images)	1.38934	1.38073

Given the lower number of images in our experiment, achieving an RMSE close to 0.6 would require improving the image acquisition process, such as using a higher-quality camera and capturing more images.

The system successfully captured images from the construction site and uploaded them to the AWS cloud in real-time using GSM mobile data. This real-time data transmission allows for near-instantaneous processing of images and 3D reconstruction, facilitating remote construction monitoring. In cases where mobile data is interrupted, the images are temporarily stored on the drone and uploaded to the cloud when the network connection is restored. This ensures continuous image capture without losing data, making the system more robust in environments where mobile data coverage may be unstable. The real-time data transfer and processing via the AWS cloud enable experts to monitor construction progress remotely and in near real-time. This approach minimises the need for on-site personnel and allows for faster decision-making, especially in dynamic construction environments.

To achieve a lower RMSE and improve the accuracy of 3D models, it is essential to use higher-resolution cameras with better image quality. This would reduce visible imperfections and enhance the quality of the generated 3D models. Increasing the number of images captured during the drone flights will likely improve the model's accuracy, reducing the RMSE. Using a more comprehensive set of images from various angles can enhance model detail and reduce occlusion, especially in complex construction environments.

Despite the advancements in autonomous flight and real-time navigation offered by the proposed method, several limitations need to be addressed for its full operational potential. First, the reliance on GPS-based systems for localisation can become a significant challenge in GPS-denied environments such as indoor or urban settings with high signal interference, where the proposed method resorts to visual-inertial odometry (VIO) or sensor fusion techniques. While these approaches offer resilience, they still struggle with accuracy and drift over extended periods or in feature-sparse environments, limiting the reliability of localisation.

Furthermore, the integration of ArduPilot, while robust for general flight control, may encounter performance issues in highly dynamic and unpredictable conditions, such as strong wind gusts or complex obstacle fields, where real-time path re-planning algorithms could fail to effectively account for rapid environmental changes. Additionally, the communication delay between the drone's onboard system and the ground control station, even when using MAVLink protocol, could impact mission-critical decision-making and data exchange during time-sensitive operations.

Finally, the computational load imposed by real-time sensor data processing, particularly in high-resolution visual cameras, may lead to potential latency or power consumption concerns, limiting the duration and efficiency of long-duration missions. These limitations highlight areas where further optimisation and integration of advanced algorithms are necessary for achieving enhanced autonomy and operational efficiency in complex, real-world scenarios.

Future work should focus on integrating the 3D models with Building Information Modeling (BIM) software for a more comprehensive construction monitoring solution. This will enable the comparison of as-built models with the original BIM design to identify discrepancies and track project progress more effectively. As the number of images and the size of construction sites increase, optimising the system for faster rendering and processing, potentially through more advanced cloud computing technologies, will be important for large-scale projects.

5.0 CONCLUSION

This paper presents an autonomous 3D mapping drone framework for construction monitoring that leverages photogrammetry and IoT technologies to facilitate real-time, remote monitoring of construction sites. The proposed framework allows for efficient data collection, processing, and analysis, addressing common challenges faced in traditional construction monitoring methods, such as limited access to sites and the need for on-site personnel.

Through the experimental validation carried out on an actual construction site in Subang Jaya, Malaysia, we demonstrated that the framework is capable of autonomously capturing high-quality images, processing them into 3D models, and transferring the data to the cloud for real-time analysis. The results of the experiments showed that the system performs well, even with varying numbers of images, and that the 3D models generated from these images are accurate enough for construction monitoring and progress tracking. Notably, the system's ability to operate autonomously, coupled with real-time data transmission to the cloud, offers significant advantages in terms of time efficiency and safety.

The comparison of different machine configurations (g4dn.xlarge vs. g4dn.4xlarge) highlighted that processing larger datasets requires more computational power, but the system is capable of scaling efficiently to handle larger construction sites. Additionally, the system's ability to manage interruptions in mobile data and continue storing images for later upload ensures robustness in environments with unstable network coverage. Although the quality of the 3D models could be improved by increasing the number of images and upgrading the camera, the current system already provides a reliable solution for real-time construction monitoring. The SFM RMSE analysis showed that with additional images and enhancements in image quality, the system can achieve even more accurate results.

For future work, the integration of the reconstructed 3D models with Building Information Modeling (BIM) software is proposed to enable the comparison of construction progress against the original design, facilitating automated analysis of discrepancies. Furthermore, optimisation of the system for larger-scale projects, including potential upgrades to the drone hardware and cloud computing capabilities, will be necessary to fully realise the potential of autonomous construction monitoring systems.

In conclusion, the proposed autonomous 3D mapping drone framework represents a significant step forward in the evolution of construction monitoring. By utilising photogrammetry, IoT, and cloud computing technologies, this framework offers a scalable, cost-effective solution for real-time, remote construction site monitoring that has the potential to enhance project management, improve safety, and reduce operational costs in the construction industry. ■

AUTHORS' CONTRIBUTIONS

- **Bhuvendhraa Rudrusamy:** Conceptualisation, writing, supervision.
- **Muhammad Azim Abdul Rahman:** Formal analysis, software, investigation, validation.
- **Ali Rashidi:** Supervision.
- **Mohsen Bazghaleh:** Resources, Methodology, supervision.

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