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STRENGTH PROPERTIES OF LIGHTWEIGHT FOAMED CONCRETE WITH STEEL FIBRE

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Abstract

The advancement in lightweight cementitious composite strength enhancement has promoting the usage of lightweight material across modern construction industry. Likewise, lightweight foamed concrete (LFC) was introduced as an alternative material in the construction industry due to its properties including good thermal and sound insulation, lighter in weight and cost-effectiveness. In corresponded to LFC strength issue which often found to be diminished due to its lower density and porous structures. Studies have shown that the incorporation of steel fibre into concrete can recover the diminished strength of lightweight foamed concrete. Hence, this research focusses on the strength properties of LFC incorporate with 30 kg/m^3 of steel fibre. Three types of LFC were prepared in this study including a trial mix of LFC (LFC-TM), a control mix of LFC (LFC-CTR), and LFC with 30 kg/m^3 steel fibre (LFC-30SF). The LFC-CTR and LFC-30SF were cast based on the obtained optimum water-to-cement ratio from the plotted performance index graph, which was 0.56 for both mixes. The fresh properties of LFC-CTR and LFC-30SF were determined based on the result obtained from fresh density, flow table and inverted slump tests. Besides, the strength properties studied for LFC-CTR and LFC-30SF were compressive strength, splitting tensile strength and flexural strength at 7, 28 and 56 days after curing. From the test results obtained, the compressive, splitting tensile and flexural strength of LFC was found to be improved by adding the steel fibre into the mix. As for the fresh properties of LFC, the stability was found to decrease after the steel fibre was added into the mix, while the flowability and consistency was observed with an improvement subject to fibre addition. In short, incorporating steel fibre can improve the strength properties of LFC, which driving their usability and encouraging wider adoption across modern industries.

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Compressive Strength, Flexural Strength, Lightweight Foamed Concrete, Splitting Tensile Strength, Steel Fibre

1.0 INTRODUCTION

As one of the major components in construction sector, concrete behaviours are highly dependent on the mixing proportions of raw materials and the type of raw materials used. Other than that, concrete can be categorised base on density into ordinary normal weight concrete, heavyweight concrete, and lightweight concrete. Likewise, lightweight concrete refers to low density concrete produce through artificial modification on its matrix, which normally has a density value ranges from 300 to 2000 kg/m^3 (Hedjazi, 2019). The lightweight concrete can be produced using lightweight aggregate, artificial entrained air, or a foaming agent, and is commonly used in construction because it is thermally and acoustically insulating, lighter, and more cost-effective.

Lightweight foamed concrete (LFC) is a cellular concrete made by entraining the foam into cement mortar using a suitable foaming agent (Brady, Watts, and Jones, 2001). The foam can be formed by mixing the foaming agent gently in the plastic cement mortar, or it can be formed by aerating the foaming agent before being added to the mixture (Alonge and Ramli, 2013). Around 20% volume of foamed concrete contains entrapped air pores caused by the entrained foam in mortar slurry. However, coalescence can result in much larger voids, especially at the top of pours, thus making the LFC high-strength development more challenging. The application of LFC is commonly found in the construction industry nowadays. Therefore, LFC is useful in the construction industry as it brings many benefits. There are several advantages of LFC, i.e. LFC is lighter than ordinary concrete. Artificially incorporating foam into plastic mortar reduces concrete density. The density has decreases because the amount of concrete has increases (Swati, 2020). The LFC is a highly porous microstructure (Elrahman *et al.,* 2021). This microstructure has caused the LFC to be light in weight, so the adjacent sub-structure is not subjected to much vertical stress. LFC has lower heat conductivity than ordinary concrete. This is due to microscopic air voids inside having low thermal conductivity. Hence, LFC can reduce the heat conducted through it and lower the temperature of a building. The LFC also has better fire resistance and good sound insulation compared to normal cement. Sound waves cannot pass through a void medium. Consequently, sound wave energy may become trapped within voids or empty areas (Lim *et. al,.* 2021). LFC has water retention properties. The LFC contains multiple air bubbles, which cause a high percentage of porosity. LFC also has a low permeability coefficient. Next, LFC has high resistance to freezing and thawing. The microscopic air bubbles have caused void structures in hardened concrete. The concrete's internal stress is reduced during the freezing and thawing. As a result, the cracking of concrete will not occur easily. LFC is more economical than the normal concrete. The cost of manufacturing LFC is lower because the foam entrained into plastic mortar will increase the volume of concrete. Besides, the construction cost will decrease as the material used is decreased. On top of that, the LFC is easier to transport and handle than normal concrete. Hence, the transportation fees will be economical.

The usage of fibre as an additive to concrete is increasing nowadays. Fibre reinforcement concrete (FRC) is utilised extensively in construction due to its characteristics and application. The inclusion of fibre in concrete has brought advantages to its properties. Fibre-reinforced concrete has more crack and shrinkage resistance than conventional concrete. As a matter of fact, the fibres in concrete are distributed throughout the concrete at relatively small spacing, which provide uniform resistance in all directions (Rao and Rao, 2014). On top of that, fibre-reinforced concrete will have higher ductility due to the uniform distribution of fibre in concrete (Yao, Li, and Wu, 2003). Besides, some fibres also increased the mechanical strength of concrete. Fibre act as a reinforcement component when incorporated into concrete to improve its performance. Fibres are commercially accessible and made from steel, plastic, glass, and other natural materials (Behbahani, Nematollahi and Farasatpour, 2013). Steel fibre is one type of the fibre that widely used in the production of fibre reinforced concrete. In the manufacturing of fibre-reinforced concrete, steel fibre is a common type of fibre. There are a few types of steel fibre, such as corrugated steel fibre, twisted steel fibre, hooked-end steel fibre and straight fibre (Larsen and Thorstensen, 2020). Steel fibres are available in various shapes and sizes, with lengths ranging from 0.25 in. to 2.5 in. (0.6 cm to 6.4 cm) and diameters ranging from 0.02 in. to 0.04 in (0.05 cm to 1.0 cm). In producing steel fibre-reinforced concrete (SFRC), the amount of fibre used is often expressed as a percentage or volume fraction. The different volume fractions of steel fibre will produce different behaviour in SFRC.

In this research, the steel fibres used are discrete, short, with an aspect ratio range of 20 to 100. The added steel fibre in fresh concrete can improve the shear resistance, toughness and assist in crack control (Chanh, 2015). Hence, the introduction of steel fibre into LFC was expected to recover the diminished strength in LFC.

The optimum water to cement ratio of LFC-CTR and LFC-30SF were obtained by selecting the peak performance index from the compressive strength tests on LFC-TM. Besides, the engineering strength properties of LFC-30SF, regarding compressive strength, splitting tensile strength and flexural strength, were investigated through standardize testing method. While the influence of steel fibre on the fresh properties of lightweight foamed concrete, including its flowability and stability were examined as well.

2.0 MATERIALS AND METHODOLOGY

2.1 Materials

The materials used in this research including Orang Kuat Ordinary Portland Cement, fine aggregates passing (600 μm), water, SikaAER-50/50 foaming agent, STAHLCON hooked-end type steel fibre and silica fume.

2.2 Ordinary Portland Cement (OPC)

In this study, the Orang Kuat Ordinary Portland Cement - CEM I 52 N manufactured by YTL Cement Sdn. Bhd. was used as the OPC cement. It was certified by MS ISO 9001, MS ISO 14001, OHSAS 18001 and MS EN 197-1:2014. The Orang Kuat Ordinary Portland Cement was being sieved through a 300 μm sieve to avoid hydrated cement clinker during the production of LFC. After sieving, the sieved OPC was stored in an air-tight container to avoid dampness.

2.3 Fine Aggregates

This research utilises sand as fine particles for filler material in producing LFC. To eliminate the moisture content within sand which will affecting the W/C ratio, it was subjected to oven drying at a temperature of 100°C for a duration of 24 hours. The particles size of sand was controlled within 600 μm by passing through a 600 μm sieve. Eventually, a sieve analysis was conducted to determine the grading of sand which obtaining the fineness modulus at 2.89.

2.4 Water

In accordance with ASTM C1602 (ASTM, 2006), tap water was selected as the mixing water for all lightweight foamed concretes in this research. Likewise, all lightweight foamed concretes were cast using tap water presented with a specific gravity of 1.0. Identically, the same water was employed during the curing process of LFC, while it was stored in the enclosed curing tank to prevent excessive moisture loss during the hydration process. The water temperature in the curing tank was kept at a room temperature of 25 ºC.

2.5 Foaming Agent

By utilising a foam generator, the foaming agent were combined with water and compressed air to generate foam bubbles. The compressed air was pressurised and maintained at 5 kg/m^3. The foaming agent used in this study was SikaAER-50/50 in compliance with ASTM C796 (ASTM, 2009). The foaming agent produced stable foam, which has a density of 45 kg/m^3 with a tolerance limit of ± 5 kg/m^3.

2.6 Steel Fibre

This study employed hooked-end steel fibre branded by STAHLCON as the reinforcement fibre. It consists of a diameter of 0.55 mm and a length of 35 mm and made by cold-drawn wire in compliance with BS EN 14889 Part 1 (British Standards Institution, 2006).

2.7 Silica Fume

The micro silica supplied by Scancem Materials Sdn. Bhd. was added during the production of LFC as a pozzolana to enhance its strength properties.

2.8 Mix Proportions

In this study, the absolute volume method was applied in designing the mix proportions of both LFC-CTR and LFC-30SF as shown in Table 1. Noted that cement to sand ratio was 1:1 and the silica fume dosage refer to 10 % by mass of cement.

Besides, the foam percentage is based on the weight of dry mix, i.e. cement and sand weight.

2.9 Specimens Preparation and Testing Methods

In this study, a total of 150 specimens were prepared while 60 of them were trial mixes. All the trial mixes were undergone a compressive strength test to determine the optimum water to cement ratio. The rest of 90 specimens were the control mix (LFC-CTR) and steel fibre mix (LFC-30SF). For each type of mix, 15 cube specimens, 15 cylindrical specimens and 15 prism specimens were prepared for the compressive, splitting tensile and flexural strength tests, respectively. Besides, the fresh properties tests, namely the flow table test, inverted slump test and fresh density test, were carried out before casting.

2.10 Fresh Density Test

The fresh density test was performed in compliance with ASTM C138 (ASTM, 2009). Fresh density test calculates the weight of bulk or compacted aggregates per cubic meter. The apparatus required consist of a container with one liter capacity and a weighing machine. First, the well mixed fresh concrete was filled into the container, and the excess foamed concrete was struck off. Afterward, the filled container was weighted on the weighing machine to assess its fresh density. The process can be repeated by adding foam into the well mixed concrete mixture until the desired concrete density was reached.

2.11 Flow Table Test

In line with ASTM C230 (ASTM, 2009), the consistency of LFC-TM, LFC-CTR, and LFC-30SF was tested using a flow table test. The apparatus involved in the flow table test was a flow table and mould. The freshly mixed foamed concrete was poured into the mould positioned at the centre until it is fully filled. The mould was lifted and removed slowly, leftover concrete was raised and dropped on the flow table for a maximum of 25 times. The amount of drop in the flow table was recorded, and the slump spread diameter was measured.

2.12 Inverted Slump Test

The inverted slump test was performed to study the workability of concrete in compliance with ASTM C1611 (ASTM, 2009). The result of the inverted slump test was obtained by measuring the spread diameters of the fresh concrete. A slump cone and a base plate were used to perform the test. Firstly, the slump cone was placed inversely on the centre of the base plate. Then, hold the slump cone tightly on the base plate to avoid leaking concrete mix from the bottom. Next, the freshly mixed LFC was poured into the inverted slump cone until it was fully filled. The excess concrete was removed to provide a flat top surface. Lastly, the slump cone was raised vertically and slowly at about 1 ft. The slump spread diameter was measured and recorded.

2.13 Compression Test

In this study, the compressive strength test accordance to BS EN 12390-3 (British Standards Institution, 2019) was conducted on LFC-TM, LFC-CTR, and LFC-30SF. Cubic specimens (100 mm x 100mm x 100mm) of LFC-TM, LFC-CTR and LFC-30SF were prepared for compressive strength test at 7 days, 28 days, and 56 days. The test was carried out using the concrete compression machine with a loading rate of 1 kN/s.

2.14 Splitting Tensile Test

The splitting tensile strength test carried out for LFC-CTR and LFC-30SF was in accordance with BS EN 12390-6 British Standards Institution, 2010). A concrete compression machine was used to conduct the splitting tensile strength test. Cylindrical specimens of LFC-CTR and LFC-30SF were prepared for splitting tensile strength test at 7, 28 and 56 days. Firstly, the surface of the cylindrical specimen and the platform of the concrete compression machine were cleaned to ensure no debris present. Next, the cylindrical specimen was then positioned in a steel mould. The bearing strips were placed at the upper and bottom of the concrete specimen to uniformly distribute the load along the longitudinal axis of cylindrical specimen. Then, the steel mould was adjusted to the centre of the loading machine and the specimen was loaded at the loading rate of 0.5 kN/s until it failed and cracked appear on its surface.

2.15 Flexural Test

The flexural strength test was carried out for LFC-CTR and LFC-30SF in accordance with BS EN 12390-5 (British Standards Institution, 2019). The prism specimens (40 mm x 40 mm x 160 mm) were prepared for the flexural strength test. A Shimadzu Universal Testing Machine was used to conduct the flexural strength test in accordance with BS EN 12390-5 standard. A three-point flexural test was used in conducting the flexural strength test of LFC-CTR and LFC-30SF. Two loading lines were marked at 20 mm from each edge of the prism specimen. The prism specimen was loaded at 0.2 mm/min until it failed and cracked appear on its surface.

Table 1: Mix proportions

Specimen	W/C Ratio	Material (kg/m^3)						Foam Percentage (%)
		Cement	Sand	Water	Foam	SF	Silica Fume	
LFC-CTR	0.56	562.50	625.00	350.00	8.45	0	62.50	0.68
LFC-30SF	0.56	549.00	610.00	341.60	9.21	30.00	61.00	0.74

Note: The mix proportions are based on 1m^3 concrete volume using absolute method.

3.0 RESULTS AND DISCUSSION

3.1 Compression Test (Trial Mix)

To evaluate the optimum W/C ratio, both LFC-CTR and LFC-30SF compressive strength was complied with various W/C ratio to obtain the performance index graph at different curing age. In this research, the W/C ratio of the trial mix proportions range from 0.52 to 0.68 with an incremental interval of 0.04, whereas for both LFC mix, the W/C ratio with highest performance index was indicated as the optimum W/C ratio. Likewise, all W/C ratio achieved acceptable average hardened densities, range within 1600 ± 50 kg/m^3. For the performance index, it was governed by both compressive strength and density, which defined as MPa per 1000 kg/m^3. From Figure 1 below, a W/C ratio of 0.56 was observed with the highest performance index at both 7 and 28 days. Thus, it can be concluded that the optimum W/C ratio for LFC-CTR was 0.56. Identically from Figure 2, 0.56 W/C ratio achieved the highest performance index at 7 and 28 days. Therefore, the optimum W/C ratio for LFC-30SF was 0.56 as well.

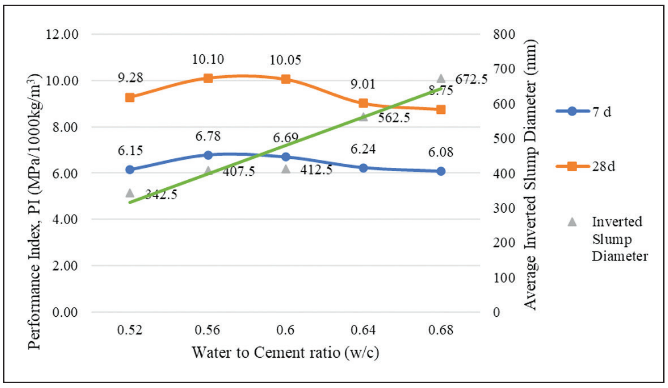

Figure 1: Performance index of trial mixes (LFC-CTR)

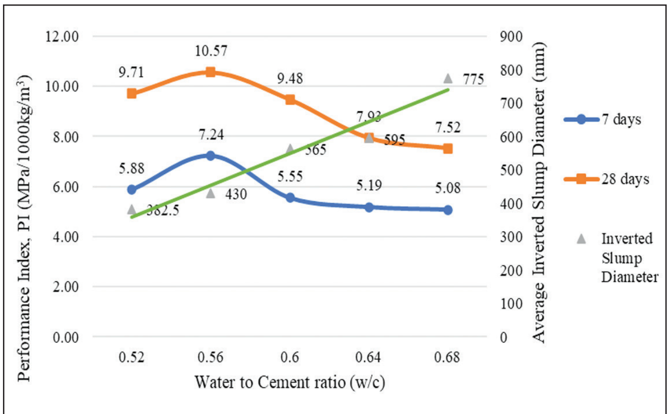

Figure 2: Performance index of trial mixes (LFC-30SF)

3.2 Fresh Properties

In this research, fresh properties tests including fresh density test, flow table test and inverted slump test were carried out to examine the flowability, consistency and stability of LFC. The fresh density test is carried out to ensure LFC density maintained at 1600 ± 50 kg/m^3. Besides, the LFC-CTR and LFC-30SF specimens were cast at lower range of acceptable density, as to avoid the unstable air bubbles from bursting during the hardening process, which tends to increase the LFC hardened density. The consistency was defined as the fresh to target density ratio, a consistency close to unity indicates a well-balanced mixture as per designed proportion which is convenient for proper handling and placement. Besides, the stability was defined as fresh to hardened density ratio, a stability close to unity refer to a stable mixture where air and water content of LFC remain largely unchanged during the hydration process, thus a minimal shrinkage and settling effect correspond to a consistent and predictable product. From Table 2, the fresh density of LFC-CTR and LFC-30SF were maintained within the acceptable range. Based on the result obtained from the flow table test, the flowability of the mortar mix for LFC-30SF was higher than that of LFC-CTR. Besides, the spread diameter of the LFC-30SF was larger than that of control mix, this might be due to the high specific gravity of the steel fibre increased the gravitational force of the LFC-30SF, thus obtained smaller flow table drop number and larger spread diameter than that of the control mix. On the other hand, the stability of LFC-30SF was found to be slightly lower than LFC-CTR but the effect was no significant. Any instability phenomenon which are very common in lightweight foamed concrete was associated with the bubble rising towards the top of the specimen due to buoyancy force, which may slightly change the LFC matrix properties (Jones, Ozlutas and Zheng, 2016). Therefore, the stability test was carried out to show that the absence of this instability phenomenon, and the unity check of 0.96 indicate the LFC matrix become denser after hydration process.

3.3 Compression Test

Figure 3 shows the comparison of compressive strength for LFC-CTR and LFC-30SF at different curing age. Overall, both LFC shows an increasing trend of compressive strength from 7 to 56 days of curing. The compressive strength of LFC-CTR was 10.18 MPa, 12.86 MPa and 13.71 MPa at testing age of 7, 28 and 56 days, respectively. Likewise, LFC-30SF was observed with compressive strength of 10.40 MPa, 15.30 MPa and 15.56 MPa at testing age of 7, 28 and 56 days. From the results, LFC-30SF achieve overall higher compressive strength than LFC-CTR at all testing age. While concrete compressive

Table 2: Fresh properties of LFC-CTR and LFC-30SF

Sample	Fresh Density (kg/m^3)	Flow Table Spread, (number of drop)	Average Inverted Slump Diameter (mm)	Consistency	Stability
LFC-CTR	1556.000	27	405.000	0.973	0.972
LFC-30SF	1566.070	23	436.750	0.979	0.968

strength progressively increases with longer period of hydration process, LFC-30SF can achieve compressive strength of 13.49 % higher than LFC-CTR after 56 days of curing. Overall, the results proved that the inclusion of steel fibre will enhance the compressive strength of LFC. Steel fibre embedded within the LFC provide reinforcement for the cellular matrix which able to holds the structure together (Awang and Ahmad, 2012). Besides, the steel fibre within LFC-30SF act as stress distributor to reallocate developed internal stress by bridging across cracks when subject to external loadings.

3.4 Splitting Tensile Test

Figure 4 shows the splitting tensile strength of LFC-CTR and LFC-30SF at 7-, 28- and 56-days testing age. Both LFC were cast in cylindrical specimens of 100 mm diameter and 200 mm height to carry out the splitting tensile strength test. Prior to testing, the specimens at 7-days testing age were over dried for 4 hours before testing, while specimen at 28- and 56-days testing age will go through 24-hours oven dry process. Likewise, the splitting tensile strength of both LFC-CTR and LFC-30SF increased from 7 to 56 days of curing. The splitting tensile strength of LFC-CTR was 5.67 MPa, 7.90 MPa and 18.14 MPa at 7-, 28- and 56-days testing age, respectively. While the splitting tensile strength of LFC-30SF was 6.48 MPa, 9.91 MPa and 10.38 MPa, respectively at 7-, 28- and 56-days testing age. For comparison, the LFC-30SF achieve overall higher splitting tensile strength than LFC-CTR at all testing age. Additionally, LFC-30SF achieve splitting tensile strength of 27.52 % higher than LFC-CTR after 56 days of curing. In general, the steel fibre bridging effect able to distribute loads and stresses evenly across the concrete. As a result, stress concentration at stress critical point diminished which tends to inhibit cracks formation and propagations. Moreover, the discrete and short steel fibre tends to have a uniform dispersion across the LFC matrix, thus result in a homogenous LFC mixture reinforced by steel fibre in all parts of concrete specimen. Overall, the addition of steel fibre can enhance the LFC splitting tensile strength and cracks resistance.

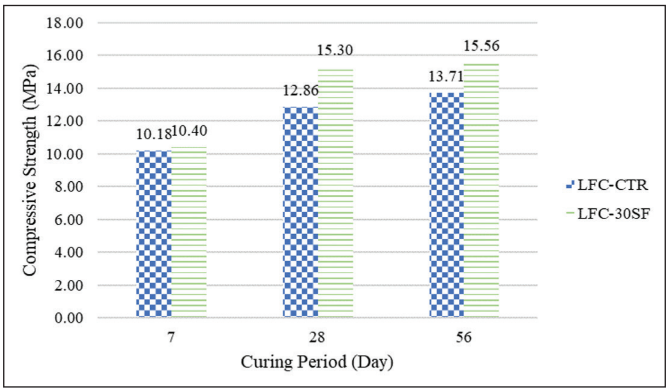

Figure 3: Compressive strength of LFC-CTR and LFC-30SF

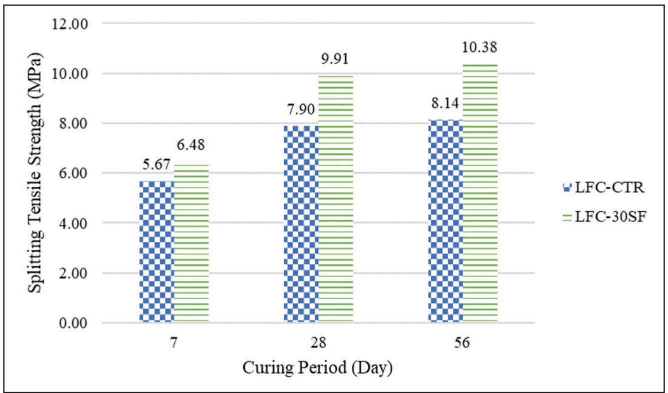

Figure 4: Splitting tensile strength of LFC-CTR and LFC-30SF

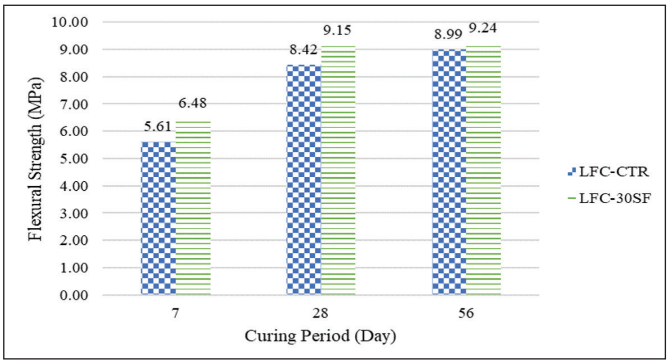

Figure 5: Flexural strength of LFC-CTR and LFC-30SF

3.5 Flexural Test

Figure 5 shows the flexural strength of LFC-CTR and LFC-30SF at 7-, 28- and 56-days testing age. LFC were cast in prism specimen of dimension 40 mm (width) x 40 mm (height) x 160 mm (length) for the flexural strength test. The flexural strength of LFC-CTR was 5.61 MPa, 8.42 MPa and 8.99 MPa at 7-, 28- and 56-days testing age, respectively. While LFC-30SF achieved flexural strength of 6.48 MPa, 9.15 MPa and 9.24 MPa, respectively at 7-, 28- and 56-days testing age. Identically, flexural strength of both LFC have the same trend of strength improvement along increasing curing age. According to the result, the overall flexural strength of LFC was slightly improved with the addition of steel fibres. The flexural strength of LFC-30SF was higher than LFC-CTR by 2.78 % after 56 days of curing. Overall, the testing result data reveal that the steel fibre has lower degree of influence on flexural strength enhancement when incorporating into LFC. The bridging effect by the steel fibre can be observed from the failure mode as shown in Figure 6.

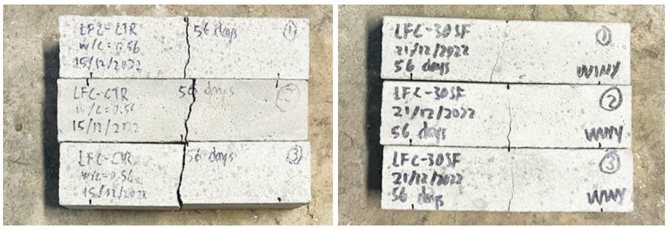

Figure 6: Failure mode of LFC-CTR and LFC-30SF

By comparing the failure mode between LFC-CTR and LFC-30SF. The LFC-CTR specimen failed by formation of deep crack at the specimen central critical point and catastrophically breaks into two parts. While the LFC-30SF specimen observed with gentler failure mode, whereby concrete first yield at the central of prism, followed by gradually cracks propagation along force action line and manage to hold tightly together by steel fibre after failure. As discussed, the role of the steel fibre is to provide the bridging effect to hold the LFC from separate apart under loading.

4.0 CONCLUSION

Based on the result data obtained from fresh and hardened concrete test, the aim and objectives of this research was accomplished. Lightweight foamed concrete (LFC-CTR) and lightweight foamed concrete incorporated with 30 kg/m^3 steel fibre (LFC-30SF) were produced at 1600 ± 50 kg/m^3 of fresh and hardened density with an optimal W/C ratio of 0.56. Within the scope of work of research, the following conclusion were made:

(1) The fresh properties tests, namely flow table test, inverted slump test and fresh density test, were carried out. The flowability and consistency of LFC was enhanced after adding the steel fibre. However, the stability of LFC was reduced after adding the steel fibre.

(2) The incorporation of steel fibre improved the engineering strength properties of LFC. The compressive strength of LFC-30SF was higher than LFC-CTR. Besides, the splitting tensile strength of LFC was significantly improved after adding the steel fibre into the mix. Although the incorporation of steel fibre in LFC do not possess significant improvement in terms of flexural strength, the effect of steel fibre was proven through the examination of the LFC specimen failure mode after the flexural test.

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PROFILES

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A NEW CAPACITY MODEL FOR MALAYSIAN URBAN ROADS USING MACROSCOPIC FUNDAMENTAL DIAGRAM AND MULTIPLE LINEAR REGRESSION APPROACH

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Abstract

The existing manuals used to estimate urban road capacity have limitations. Adapting these manuals to compute the road capacity at urban roads reduces estimation accuracy. This study attempts to develop a capacity model to characterise urban road capacity. Twenty-two sites consisting of the collector/distributor roads and local roads in the Cheras-Kajang area in Klang Valley are selected for traffic data collection during the morning peak hour from 8 a.m. to 9 a.m. Site video camera recording is carried out, and the traffic data is extracted from the video footage. The speed-density and flow-density curves of the macroscopic fundamental diagram are fitted with the traffic data extracted. The capacity value is then derived from these curves. The urban road capacity model, termed the UrbanCap model, is developed in this study using the multiple linear regression approach. The results show that the urban road capacity depends on the type of road and carriageway and speed limit. The comparison of the capacity values produced from the UrbanCap model with other manuals justifies that it has a better estimate than the existing manuals used in Malaysia. The results also signify a need to develop a manual/guideline to quantify the urban road capacity in Malaysia for road design and analysis.

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1.0 INTRODUCTION

Road capacity is the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given period under prevailing roadway, traffic, and control conditions (TRB, n.d.). Understanding the road capacity is crucial as it facilitates road design, planning, and performance assessment. The road capacity is well established with a handful of research studies and technical manuals/guidelines that define the values. The Highway Capacity Manuals (HCM 2000 and HCM 2010) (TRB, n.d.) provide details on estimating the capacity for basic freeway segments, multi-lane highways, and two-lane highways. However, most of these manuals focus on deriving the capacity value for expressways and highways. There are limited studies on urban roads, i.e., arterial roads, collector/distributor roads, and local roads, especially in Malaysia.

Nevertheless, the traffic impact assessment (TIA) requires the road performance assessment that needs the road capacity value. Most of the time, the types of roads investigated in the TIA are not expressways and highways where the capacity values can be estimated from the manual. Adopting the capacity charts shown in HCM 2000, HCM 2010, or Malaysia Highway Capacity Manual (MHCM 2011) (HPU, 2011) to assess the urban road has the following limitations: (1) the free flow speed of the highway starts from 60 km/hr on the speed-volume relationship, while most of the collector/local roads have a free flow speed below 60 km/hr, extrapolation is performed to derive the capacity value. This extrapolation approach requires further engineering judgment; (2) there are no or limited theoretical findings to support that the multi-lane highway's speed-volume chart could be extrapolated to the speed below 60 km/hr; (3) the driver behavior on highway/expressway and urban roads tend to be different due to different road geometry and environment. Urban roads tend to be narrower with roadside parking or/and bus stops; hence, the capacity value derived might not be appropriate; (4) the existence of median/divider might have impact on the urban road capacity.

The objectives of this study come in twofold, i.e. (1) to develop a new capacity model for urban roads, termed the UrbanCap model, and (2) to determine the factors that influence the urban road capacity. Traffic data is collected from the sites selected before extracting the traffic parameters required for the model development. The speed-density and flow-density curves are estimated from the data. Then, the capacity value is calculated with the macroscopic fundamental diagram (MFD) approach. The UrbanCap model is then developed by relating the capacity value obtained with several independent variables that classify the urban road, i.e., the type of carriageway and road and speed limit using the regression analysis. A comparison of the capacity values derived from the model with those extracted from the guidelines/manuals is carried out. The results show that the UrbanCap model is reliable and appropriate for capacity estimation for urban roads.

The paper's organisation is as follows: the introduction section provides the background and objectives of the study, followed by the literature review section highlighting the existing studies. Then, the methodology adopted to conduct this study is presented, which includes data collection, extraction, processing, and model development. An analysis follows it by comparing the capacity values obtained from the UrbanCap model and those used in practice and some other guidelines in abroad countries. Lastly, the findings are concluded, and recommendations are made.

2.0 RELATED EXISTING STUDIES

The most important reference of road capacity in traffic engineering studies is the Highway Capacity Manual (2000, 2010) published by the Transportation Research Board, USA. The manual is a vital reference in estimating the level of service and the capacity for basic freeway segments, multi-lane highways, and two-lane highways. Charts and tables are provided to assist the users in referring to the manual. The Malaysian Highway Capacity 2011 version adapted the HCM 2000 to the Malaysian local condition. Sets of procedures, charts, and tables are provided to estimate the level of service and capacity for the three facilities mentioned above. The significant difference between MHCM and HCM is the consideration of motorcycle traffic in the estimation procedure. The road capacity estimation using MHCM 2011 could be referred for roadway with free flow speed higher than 60 km/hr. Besides, the Road Traffic Volume Malaysia (RTVM) (Ministry of Works Malaysia, 2020) has indicated a formula to estimate the capacity for single and dual carriageways. It indicates the ideal capacity for a multi-lane carriageway (per lane per direction) and a two-lane single carriageway (both directions), and the model considers the roadway and traffic reduction factor in the capacity estimation.

Internationally, there are published guideline for urban roadway capacity estimation. The UK TA79/99 Guideline (The Highway Agency, 1999), the Indian Guideline IRC: 106-1990 (Indian Roads Congress, 1990), and the Austroads Guideline (Austroads, 2017) are established guidelines that provide references for urban road capacity. The UK TA 79/99 Guideline (The Highway Agency, 1999) classified urban roads into five types, i.e., urban motorways (UM) and urban all-purpose (UAP1, UAP2, UAP3, and UAP4), based on their features that distinguish the roads, which include speed limit, the existence of side roads, the access to roadside development, parking and loading facility availability, pedestrian crossings, and bus stop availability. The urban motorways have the highest hierarchy in the urban roads with the highest speed limit and lowest accessibility, and UAP4 is vice versa. Besides the road classification, the carriageway type, the number of lanes, and the carriageway width are considered in determining the capacity. The Indian Guideline IRC:106-1990 (Indian Roads Congress, 1990) defined eight carriageway types: one-way and two-way, divided and undivided carriageway. These carriageways are classified into three categories, i.e., arterial, sub-arterial, and collector. The Australian Guidelines (Austroads, 2017) defined the urban road capacity based on lane type (i.e., inner lane, middle lane, and kerb lane) and single/dual carriageway (i.e., divided/undivided). The capacity recommended is within the range of 600 pc/hr/lane to 1000 pc/hr/lane. It is mentioned that the capacity may increase from 1200 pc/hr/lane to 1400 pc/hr/lane under specific conditions such as controlled or no roadside parking, signalised and unsignalised intersection flow conditions, and others.

Regarding the methodology in capacity model development, most of these studies are empirical studies where traffic data (i.e., volume, speed, density, traffic composition) is collected and analysed to produce charts/tables. Some other models adopted include Van Aerde model (Modi *et al.,* 2014), product limit method (Shao, 2011), sustained flow index (Shojaat *et al.,* 2016), headway method (Suresh and Umadevi, 2014), and macroscopic fundamental diagram method (Chandra and Kumar, 2003). Li and Laurence (2015) and Modi *et al.* (2014) applied the Van Aerde Model to estimate highway capacity. While Van Aerde Model is the most commonly used method for capacity estimation, the model's downside is that the estimated capacity value is significantly lower than those estimated with other methods. The estimated capacity value is deterministic and does not consider breakdown flow distribution or breakdown events. The product limit method (PLM) depends on lifetime statistics and was initially researched to assess the variation in capacity values. Shao (2011) and Ben-Edigbe *et al.* (2013) adopted the PLM method to estimate the freeway's capacity. The results show that PLM can capture the capacity stochasticity, but it produces inconsistent results due to arbitrary selection of the capacity value from the cumulative distribution function. The sustained flow index (SFI), the breakdown probability method, is adopted to predict the possibility that traffic flow will continue at a specific value. The volume with the highest probability of sustain is defined as the capacity. Shojaat *et al.* (2016) and Uswaththa *et al.* (2021) adopted the SFI approach to estimate the highway capacity. The headway method considers road user behavior as the primary component of the microsystem of traffic analysis in road capacity estimation. Sohrabi *et al.* (2016), Suresh and Umadevi (2014), and Qasim *et al.* (2020) estimated the road capacity using the headway method. Some of the studies adopted the fundamental diagram approach to evaluate the capacity. The macroscopic fundamental diagram describes the relationship of the three parameters, i.e., speed, density, and volume in a traffic flow stream. Chandra and Kumar (2003) and Jain *et al.* (2019) applied the fundamental diagram method to estimate road capacity. Ashish *et al.* (2022) determined the capacity model for six-lane divided urban arterials by developing speed models. The simultaneous equations are used to develop the speed-flow plot to estimate the midblock road capacity.

It could be observed that there is a lack of research work in quantifying the urban road capacity values, which is essential in urban road design and analysis. The MHCM or RTVM could only be used under certain circumstances. A specific and detailed guideline/manual is required to facilitate a more accurate capacity value estimation for urban roads.

3.0 METHODOLOGY

Since this is an empirical study, traffic data collected from the roads are used in model development and analysis. Twenty-two sites that consist of collector/distributor roads and local roads in Cheras-Kajang, Klang Valley, are selected for data collection. The traffic data is collected during the morning peak hour (8 a.m. – 9 a.m.) from January 2023 to March 2023. The traffic data, i.e., traffic flow, density, and speed, are extracted from the video footage playback in the laboratory. Then, the road capacity is estimated based on the speed-density and the flow-density curve fitted with the traffic data. The regression of coefficient is adopted to justify the data fitting quality. Lastly, the urban road capacity model, i.e., the UrbanCap model, is estimated using the multiple linear regression approach by establishing the regression relationship between the dependent variable, capacity, with the independent variables, i.e., number of lanes, type of carriageway, type of road, and speed limit. With the adoption of the multiple linear regression analysis, we assume the underlying data distribution is normally distributed. Figure 1 shows the flowchart of the research framework.

3.1 Site Selection and Data Collection

The type of roads of interest in this study is collector/distributor roads and local roads in urban area. The factors affecting road capacity, such as the type of carriageway and road and speed limit, are considered during site selection. The sites selected are at the mid-block of the roads, away from roadside parking, bus stops, and intersections. After looking into the possible areas to conduct this research, three locations in Klang Valley were selected: Bandar Sungai Long, Bandar Mahkota Cheras, and Maluri in Cheras-Kajang district. Twenty-two sites were selected. Table 1 lists the sites chosen for this study, the locations, the type of carriageway and road, and their speed limit.

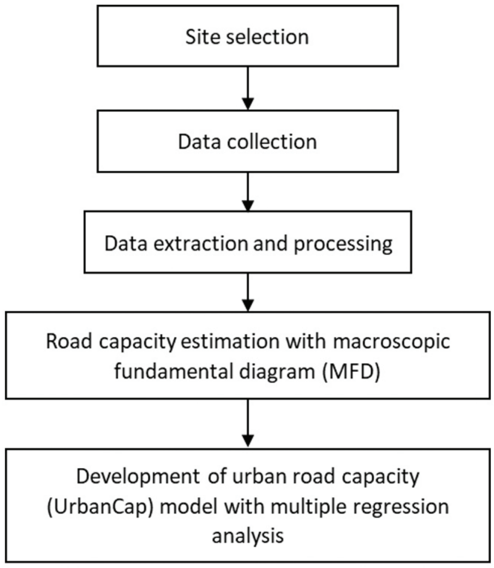

Figure 1: Research framework

Table 1: Sites selected for data collection

Site	Area	Carriageway Type	Road Type	Speed Limit (km/hr)
Persiaran Sungai Long 1	Bandar Sungai Long	2-lane Single	Local	60
Persiaran Sungai Long 2	Bandar Sungai Long	Dual 2	Collector Distributor	60
Jalan Sungai Long (near Green Acre Park)	Bandar Sungai Long	Dual 2	Collector/Distributor	70
Persiaran Bukit Sungai Long 2	Bandar Sungai Long	3-lane Single	Local	60
Jalan Sungai Long (near Forest Green Condominium)	Bandar Sungai Long	Dual 2	Collector/Distributor	70
Jalan Sungai Long (near Sungai Long Residence)	Bandar Sungai Long	Dual 2	Collector/Distributor	70
Persiaran SL 1	Bandar Sungai Long	2-lane Single	Local	30
Jalan Bendahara	Bandar Mahkota Cheras	4-lane Single	Collector/Distributor	70
Jalan Laksamana	Bandar Mahkota Cheras	4-lane Single	Local	60
Persiaran Mahkota Cheras 1	Bandar Mahkota Cheras	Dual 3	Collector/Distributor	60
Jalan Shahbandar	Bandar Mahkota Cheras	4-lane Single	Local	70
Jalan Permaisuri	Bandar Mahkota Cheras	4-lane Single	Local	70
Jalan Dayang	Bandar Mahkota Cheras	2-lane Single	Local	60
Jalan Putera	Bandar Mahkota Cheras	2-lane Single	Local	60
Jalan Inang	Bandar Mahkota Cheras	2-lane Single	Local	60
Jalan Cochrane	Maluri	Dual 3	Collector/ Distributor	60
Jalan Perkasa	Maluri	Dual 3	Collector/ Distributor	60
Lorong Shahbandar	Maluri	2-lane Single	Local	30
Lorong Peel	Maluri	2-lane Single	Local	30
Jalan Perkasa 1	Maluri	2-lane Single	Local	60
Jalan Shelley	Maluri	3-lane Single	Local	60
Jalan Menteri	Maluri	2-lane Single	Local	30

Each of the dual carriageway roads selected in data collection contributes to two sets of data since both carriageways in dual carriageways do not interfere with one another in terms of traffic flow. From Table 1, seven of the roads selected for data collection are dual carriageways, and the other fifteen are single carriageways. Among the selected sites, eight are collector or distributor roads, while fourteen are local roads. These roads were chosen to ensure that sufficient traffic data could be collected for the model development. All of the roads selected are within the residential and commercial areas. The data was collected from January 2023 to March 2023 on Tuesdays – Thursdays during morning peak hours, 8 a.m. – 9 a.m., taking a turn for each site by one surveyor only.

The traffic data is collected through video recording. The camera is set up at the mid-block section of the road selected. It is positioned at a vantage location around the site to ensure the equipment can collect the traffic data over the full stretch of the studied road. The markings are done on the road to indicate the length of a road section. It is to facilitate the speed and density computation later.

3.2 Data Extraction and Processing

The video footage is played back in the laboratory to extract the traffic data, i.e., traffic volume, density, and travel speed for the traffic stream recorded for 1 hour. The number of vehicles for each direction and lane for the dual carriageway and the total volume for the single carriageway (both directions) are counted for each 15-minute interval and sum to 1-hour volume. The traffic volume is converted from the unit of vehicle per hour to passenger-car unit (pcu) per hour using the conversion factor stated in Arahan Teknik (Jalan) 8/86 - A Guide on Geometric Design of Roads (Traffic Signal Design) conversion factor (Public Work Department Malaysia, 2015). The mean travel speed is a weighted mean speed considering the vehicle classification, which is computed by the following equation:

$$V_m = \frac{\sum_{i=1}^{N} n_i v_i}{\sum_{i=1}^{N} n_i} \tag{1}$$

where
V_m = mean stream speed, km/h
N = total number of vehicle categories
v_i = average speed of vehicle of category i, km/h
n_i = number of vehicles of category i (veh)

The parameter required to compute the traffic density is the distance headway or spacing, which is the distance between successive vehicles. Since the distance of a specific stretch of road at the site, which is displayed on the screen of the video recorder, was being measured and marked with visible objects, the distance between the successive vehicles could be captured, and by reviewing the full length of the video recorded, the average distance headway was obtained. Eqn. (2) shows the computation of traffic density with the average distance headway.

$$k = \frac{1000}{\bar{s}} \tag{2}$$

where
k = traffic density, pcu/km
$\bar{s}$ = average distance headway, meter/pcu

3.3 Road Capacity Estimation Using Macroscopic Fundamental Diagram (MFD)

The development of the macroscopic fundamental diagram is essential in determining the relationship between traffic speed, flow, and density of the road. The flow-density and speed-density relationship is developed in this study to assess the capacity of urban roads. The flow-density relationship is characterized by a parabolic curve with a maximum vertex shown by eqn. (3) as follows.

$$q = \beta_1 k^2 + \beta_2 k + c \tag{3}$$

where
q = traffic flow, pcu/h
k = traffic density, pcu/km
β = coefficient
c = y-intercept

The maximum vertex represents the maximum flow, which is the capacity of a roadway. Hence, the road capacity value is determined from the curve by differentiating eqn. (3) and equating it to zero as shown below:

$$\frac{dq}{dk} = 0 \tag{4}$$

where
q = traffic flow, pcu/h
k = traffic density, pcu/km

3.4 Development of Road Capacity Model Using Multiple Regression Approach

Six capacity values are computed for each road based on three categories of classification (type of carriageway, type of road, and speed limit) and two curves (speed-density and flow-density curves). The highest value is adopted as the road capacity based on the computed values. This road capacity value is used as the dependent variable in the UrbanCap model. In contrast, the independent variables chosen are the type of road, type of carriageway, and speed limit of the road. Multiple regression analysis is conducted to find the relationship between the capacity values and the independent variables. Analysis of Variance (ANOVA) is used to justify the statistical significance of the model developed. The F-statistic is referred to verify the significance of the UrbanCap model. The significance of the independent variables to the UrbanCap model is studied with the p-value. The R^2 value is referred to justify the overall model fitting. Eqn. (5) shows the general form of a multiple regression model.

$$q_{cap} = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 \ldots + \beta_n x_n \tag{5}$$

where
q_{cap} = road capacity value (pcu/hr)
x = independent variables
β = coefficient

4.0 RESULTS

This section presents the results obtained.

4.1 The Flow-Density Curve Developed

Figure 2 (left) shows an example of the flow-density curve fitted using the data for a dual carriageway. The vertex of the curve is obtained as the capacity value. Table 2 shows the flow-density curve developed for each category. It is observed from the table that the flow-density curve has a good fitting that has R^2 value that is more than 0.70. The vertex of the flow-density curve (as stated in Eqn. (4)) is derived as the capacity value.

Table 2: Flow-density curve estimation

Model Type		Model	R^2
Type of Road	Collector/ Distributor Road	$q = 97.96 + 31.71k – 0.09k^2$	0.955
	Local Road	$q = 67.96k – 0.4k^2 – 306$	0.995
Type of Carriageway	Dual Carriageway	$q = 93.21 + 34.19k – 0.1k^2$	0.988
	Single Carriageway	$q = 56.73k – 0.48k^2 – 181$	0.761
Speed Limit	60 km/h	$q = 50.32k – 0.36k^2 – 109$	0.704
	70 km/h	$q = 35.03k – 0.1k^2 – 64.01$	0.984

4.2 The Speed-Density Curve Developed

The fitting of the speed-density curve is shown in Figure 2 (right). The curve estimated for each category is shown in Table 3. It is observed that most of the models (such as: the collector/ distributor and dual carriageway models) are estimated to be at a satisfactory level. However, the local road model exhibits a low R^2 value. The models for speed limit categories could not be presented as the models developed are insignificant.

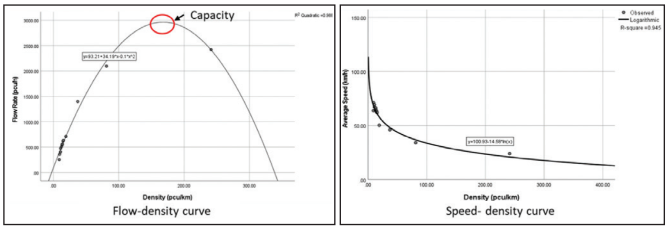

Figure 2: The macroscopic fundamental diagram estimated for dual carriageway

The speed-density curve is fitted into Eqn. (3). Then, Eqn. (4) is adopted to derive the vertex is of the flow-density curve which represents the capacity value.

Table 3: Speed-density curve estimation

Model Type		Model	R^2
Type of Road	Collector/ Distributor Road	$u = 99.83 - 14.49 \ln(k)$	0.919
	Local Road	$u = 80.66 - 6.65 \ln(k)$	0.273
Type of Carriageway	Dual Carriageway	$u = 100.93 - 14.58 \ln(k)$	0.945
	Single Carriageway	$u = 88.66 - 10.3 \ln(k)$	0.462
Speed Limit	60 km/h	Not available	Not available
	70 km/h	Not available	Not available

4.3 The New Capacity Model for Urban Road in Malaysia

The highest value of the capacity estimated from the models shown in Table 2 and Table 3 is adopted as the road capacity value for the specified road. The capacity value (per direction for dual carriageway, both directions for single carriageway) is the dependent variable, while the number of lanes, type of carriageway, type of road, and speed limit are the independent variables. The UrbanCap model is expressed in Eqn. (6) as follows:

$$C = 204.329a + 1358.338b + 6.032S + 1146.334 \tag{6}$$

where
C = capacity, pcu/h (per direction for dual carriageway, both directions for single carriageway)
a = type of road; 0: local road; 1: collector/distributor road
b = type of carriageway; 0: single carriageway; 1: dual carriageway
S = speed limit, km/h
R^2: 0.99

The ANOVA results in Table 4 indicate that the model presented is statistically significant at 95% confidence level, as evidenced by the F statistic and p-value. Table 4 also shows the significance of the variables in the model. It can be

Table 4: The statistical significance test and ANOVA test for UrbanCap model

Statistical Significance						
Variables	Coefficient	Standard error	t-value	Significant level	95% Confidence level	
					Lower bound	Upper bound
Constant	1146.33	76.43	14.99	<0.001	984.30	1308.36
Type of road	204.33	65.07	3.14	0.006	66.39	342.26
Type of carriageway	1358.34	63.12	21.52	<0.001	1224.52	1492.15
Speed limit	6.03	1.47	4.12	<0.001	2.92	9.13
Number of lane	1.89	41.39	0.046	0.964	-85.8	89.62
Anova						
	Sum of squares	df	Mean square	F	Sig.	
Regression	12463214.57	4	311903.64	540.89	<0.001	
Residual	92170.1	16	5760.63			
Total	12555784.67	20				
R^2	0.99					

Note: Dependent variable is road capacity observed that all independent variables tested are significant at 95% confidence level (by referring to the p-value), except the number of lanes variable. The R^2 values estimated for the model is 0.99. Statistically, R^2 describes how the model explains the data variability. Although a higher R^2 value that suggests a better fit is preferred, it doesn't necessarily mean the model is a good predictor in an absolute sense. The R^2 value obtained in this study indicates that the equation/model explains the data variability to a satisfactory level.

The capacity value computed from the UrbanCap model is per carriageway. It considers both direction for single carriageway while it considers one direction only for dual carriageway. Three independent variables define the capacity for urban roads, namely type of carriageway, type of road and speed limit. Unfortunately, the number of lane variable is not included in the UrbanCap model since it is statistically insignificant. It is crucial to mention that the exclusion of the number of lane from the UrbanCap model does not mean that the number of lane variable does not affect the urban road capacity. It only means that the statistical analysis does not support the existence of the relationship. This could be due to insufficient data to support such relationship.

5.0 DISCUSSION

The capacity values computed from the UrbanCap model is compared to the capacity values obtained from the manuals and guidelines locally or globally. These manuals/guidelines include the Malaysian Highway Capacity Manual 2011 (MHCM) (HPU, 2011), Road Traffic Volume Malaysia (RTVM) (Ministry of Works Malaysia, 2020), The UK TA79/99 Guideline (The Highway Agency, 1999), and the Austroads Guideline (Austroads, 2017).

Chapter 4 of MHCM 2011 shows the procedures used to determine the capacity of the multi-lane highways. It is important to note that the types of facilities are focused on highways/expressways in urban/rural areas but not on urban roads (arterial, collector/distributor, and local). The manual used the free flow speed to determine the roadway's capacity (per lane). Figure 4.9 of MHCM 2011 is referred. The flow value for the level of service (LOS) E defines the road capacity. Based on the speed limit (free-flow speed) of 60km/hr and 70km/hr, the road capacity is 1800 pcu/hr/lane and 1900 pcu/hr/lane, respectively. The chart is extrapolated for the 30 km/hr roadway to determine the capacity, i.e., 900 pcu/hr/lane.

The RTVM 2020 gives a capacity model, which is shown in Eqn. (7) as follows:

$$C = I \, x \, R \, x \, T \tag{7}$$

where
C = the maximum one-way hourly capacity (pcu/hr)
I = the ideal hourly capacity (pcu/hr)
R = the roadways reduction factor referring to RTVM 2020 (Ministry of Works Malaysia, 2020)
T = traffic reduction factor referring to RTVM 2020 (Ministry of Works Malaysia, 2020)

The guideline suggested that the ideal capacity for a multi-lane road is 2000 pcu/hr/lane while for a two-lane roadway is 2800 pcu/hr for both ways or 1400 pcu/hr/lane). The roadway reduction factor takes into account the carriageway and shoulder width. A lookup table is used to identify the value of the reduction factor for the carriage width ranges from 5 m to 7.5 m and shoulder width from 1 m to 2 m. The traffic reduction factor considers the terrain type, i.e., flat, rolling, and mountainous, and the percentage of commercial vehicles. In this study, no correction to the roadway reduction factor is carried out for carriage width that is out of the range. In contrast, an extrapolation is carried out for roadways with no shoulder to identify the value.

Referring to the UK TA 79/99 Guideline (The Highway Agency, 1999), the collector/distributor roads in the study area are defined as UAP2 roads, while the local roads are defined as UAP3 roads. The 2-lane dual carriageway has a width of 6.75 m, while the single carriageway has a width of 9 m. It is important to note that the capacity estimated using the guideline is per direction. For a single-carriageway, the busiest direction is considered.

Referring to the Austroads Guideline, the value of 1400 pc/hr/lane is used for dual carriageway while 900 pc/hr/lane is used for single carriageway in this study. Only one direction is considered at one time for dual carriageway while both directions are considered for single carriageway.

Figure 3 shows the capacity estimated by the UrbanCap model and compare with the capacity values obtained from the above manual/guidelines for the seven road sections on a dual carriageway (each road has two directions). It is to be noted that the capacity has the same value for both directions except for those values derived from RTVM, as the traffic reduction factor (T) differs for both directions due to a slightly different percentage of commercial vehicles.

It is observed from Figure 3 that the capacity estimation from the UrbanCap model developed in the study is consistent with the capacity value obtained from the UK and Austroads guidelines. The difference between the capacity value obtained from the UrbanCap model and those shown on the dual-2 carriageway (road section 1- 8) of the UK guideline is less than +6%, the difference with Austroads guideline is less than +10%, and the difference with RTVM method is less than +11%. This difference indicates that the UrbanCap model has a higher capacity value estimation than the values computed from both guidelines. Since the difference is not large (within 10%), it could be said that the UrbanCap model can estimate the dual-2 lane carriageway capacity reasonably. When the capacity values are compared to those obtained from MHCM 2011, it is observed that the differences are lesser than -21%. It shows that the MHCM over-estimates the dual-2 carriageway capacities.

The road sections 9-14 are the capacities estimated for a dual-3 carriageway. It can be seen that the UrbanCap model is insensitive to the number of lanes since the number of lanes is not one of the model's variables. Nevertheless, it is observed that the MHCM constantly overestimates the capacities of these roads when compared to the UK and Austroads guidelines. The capacity estimation by RTVM is sensitive to the roadway reduction factor (R) used in the calculation. As such, it is observed that the capacity estimated differs significantly across different types of roads depending on the carriage width.

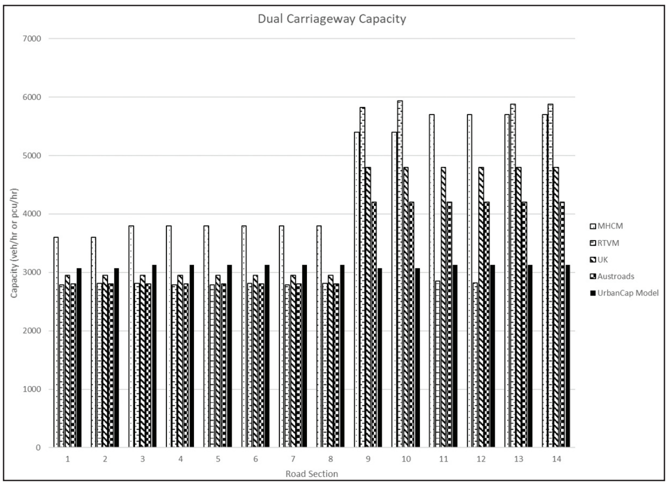

Figure 3: Road capacity estimation with different models for dual carriageway

Note: Legend for road section in Figure 5

Road Section	*Road Name*
1-2	*Persiaran Sungai Long 2 (Northbound, Southbound)*
3-4	*Jalan Sungai Long, Green Acre Park (Northbound, Southbound)*
5-6	*Jalan Sungai Long, Forest Green (Northbound, Southbound)*
7-8	*Jalan Sungai Long, Sungai Long Residence (Northbound, Southbound)*
9-10	*Persiaran Mahkota Cheras 1 (Northbound, Southbound)*
11-12	*Jalan Perkasa (Westbound, Eastbound)*
13-14	*Jalan Cochrane (Eastbound,Westbound)*

For single carriageways, the UrbanCap model considers both directions of the carriageway in the estimation. It is the same approach used in the RTVM method. The UK guideline considers only one direction, i.e., the busiest, while the MHCM and Austroads guideline considers capacity per lane. For consistency and fair comparison, the capacity estimated for the single carriageways account for both directions. The capacity of some road sections is undefined in the UK guideline as quoted in the guideline due to insufficient data. Figure 4 shows the road capacity estimated for single-carriageways. The capacity value estimated using the UrbanCap model is close to the capacity values obtained from the UK guideline, specifically the UAP3 category. The difference in capacity estimation is about less than -1.5% to -15%, except for road section 1, as the UAP2 category is used. The MHCM, RTVM, and Austroads guidelines give a much higher estimation.

It is observed from the above comparison that the UrbanCap model produces a consistent and reasonable estimation of road capacity for urban dual-2 carriageways and single carriageways. The values estimated are close to those estimated by the UK and Austroads guidelines. The capacity values obtained from MHCM are high when compare to the capacity values estimated by UrbanCap model and other guidelines for both single and dual carriageways. The capacity value estimated from RTVM is susceptible to the traffic reduction factor, which is sensitive to the carriage and shoulder width. The capacity value becomes high when the carriageway width is wide. It performs better when the carriageway and shoulder widths are within their ranges. It is important to note that the significant difference between highways/expressways and urban roads is that the capacity of the urban roads is affected by the type of carriageway (dual vs single), the number of lanes, the speed limit, and the roadside development (such as access, bus stop, parking, etc.). Thus, this research study shows that the existing methods adopted in urban road capacity estimation have limitations that warrant further investigation into establishing an urban road capacity model/guideline/manual for Malaysia.

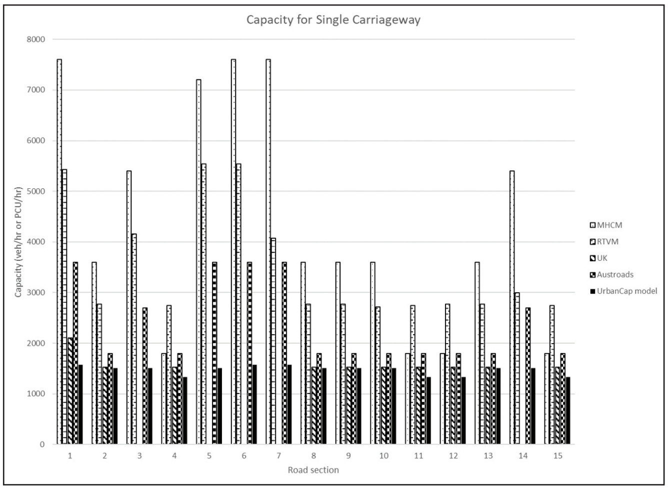

Figure 4: Road capacity estimation with different models for single carriageway

Note: Legend for road section in Figure 5

Road Section	*Road Name*
1	*Jalan Bendahara*
2	*Persiaran Sungai Long 1*
3	*Persiaran Bukit Sungai Long 2*
4	*Persiaran SL 1*
5	*Jalan Laksamana*
6	*Jalan Shahbandar*
7	*Jalan Permaisuri*
8	*Jalan Dayang*
9	*Jalan Putera*
10	*Jalan Inang*
11	*Lorong Shahbandar*
12	*Lorong Peel*
13	*Jalan Perkasa 1*
14	*Jalan Shelley*
15	*Jalan Menteri*

6.0 CONCLUSIONS

This study investigates the capacity for urban roads, i.e., collector/distributor roads and local roads. Twenty-two sites, consisting of seven dual carriageways and fifteen single carriageways in the Cheras-Kajang area in Klang Valley, are visited for data collection. The traffic volume, speed, and density are extracted from the video footage recorded during the site's AM peak hour. The road capacity is determined by fitting the speed-density and flow-density relationship on a chart with the macroscopic fundamental diagram approach. Then, the urban road capacity model is developed using the multiple regression analysis to establish the relationship between the capacity and the independent variables that influenced it, i.e., type of carriageway, type of road, and speed limit. The comparison of the capacity value obtained with the UK and Austroads guidelines shows that the UrbanCap model can produce reasonable estimates. The results also show that MHCM and RTVM have limitations in estimating the urban road capacity.

The limitation of this study is that the number of lanes is not included in the UrbanCap model due to its insignificance. It has reduced the ability of the model to estimate the capacity with three lanes and above. Besides, the model does not consider the side friction factors of the roads (such as parking, side road access, bus stops, and others). These factors could affect the urban road capacity. The speed-density curve estimated for the local road has low R^2 value. It is recommended that more sites and data be collected to improve the model further. It is important to note that the results of the regression analysis is sensitive to the sample size and the sample size selection in the small sample. Last but not least, there is a need for Malaysia to develop an urban road capacity manual or guideline to facilitate the estimation of urban road capacity for road design and analysis.

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STUDY ON THE BENEFITS OF THE IMPLEMENTATION OF GREEN BUILDING RATING IN MALAYSIA

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Abstract

A green building is a sustainable design incorporating environmentally friendly practices in its construction and management. The objective of green building development is to reduce the negative impact of buildings on the environment by mitigating carbon dioxide emissions. Several countries worldwide, including Malaysia have established rating tools under the World Green Building Council to measure sustainability for various types of development. The goal is to encourage all nations to promote green building and replace conventional methods that harm the environment. In Malaysia, two of the most commonly used assessment tools for green building are GBI and GreenRE. The Malaysian government has implemented various policies to manage the construction process of green buildings, such as the National Green Technology Policy, Green Performance Assessment System, and the establishment of Green Technology Master Plan for managing green operations. However, green building projects in Malaysia are still in the formative stage, indicating that the construction industry in Malaysia is still in its infancy with regard to sustainable development. This study aims to investigate the perceived benefits of implementing Green Building Rating Tools in Malaysia. Specific factors that enable company readiness to adopt rating tools include benefits to occupants, facility management, and environmental sustainability. The research methodology used in this study was quantitative, employing a questionnaire survey with 140 respondents. The findings indicate that Facility Management and Environmental Sustainability are significantly related to Company's Readiness to adopt Green Building Rating. It is crucial for policymakers to provide incentives to project teams (developers, consultants, and contractors) to increase awareness about green construction and its implementation.

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Company's Readiness, Green Building, Statistical Analyses

1.0 INTRODUCTION

The construction industry is a vital contributor to the economic growth of most developing countries, as it creates demand for goods and services from related industries. In Malaysia, the construction sector accounted for 3.9% of the Gross Domestic Product (GDP) in 2021 (Department of Statistics Malaysia, 2022). However, the environmental impact of construction activities poses a significant concern, prompting the Malaysian government to establish the National Green Technology Policy (NGTP) in 2009. The NGTP aims to promote the adoption of green buildings, aligning with the broader goals of sustainable development and economic enhancement (Shaikh *et al.,* 2017).

Green building is an important aspect of managing the sustainability approach in a nation. It can achieve the improvements in environmental performance through various techniques and strategies. According to Lee, Gumulya and Bangura (2022), through the construction of the green building, the locality can effectively manage the waste for controlling the environmental pollution. Similarly, with the construction of a green building, the residents become more responsible for the environment.

The World Green Building Council (2022) defines Green Building Rating Tools (GBRTs) as assessment tools that evaluate whether buildings meet specific green requirements. Many developing countries have published and promoted their own rating systems, such as Leadership in Energy and Environmental Design (LEED) in the United States, Green Building Certification Criteria (GBCC) in Korea, Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom, and Green Mark in Singapore. In Malaysia, there are several types of Green Rating Tools available for the construction industry, including Green Real Estate (GreenRE), Green Building Index (GBI), Green Mark, Green Star, Malaysian Carbon Reduction and Environmental Sustainability Tool (MyCREST) and Low Carbon City Framework (LCCF). Implementing green building assessment tools provides an opportunity for the consultants (architects and engineers) and the developers to design an environmentally friendly building that can protect biodiversity and ecosystems, reduce greenhouse gas emissions, and save energy consumption.

Despite global trends toward sustainability, the adoption of green buildings in Malaysia faces challenges, primarily driven by environmental concerns among consumers and project owners (Wong *et al.,* 2021). This study addresses this gap by distributing questionnaires to gather feedback on implementing Green Building Rating Tools in Malaysia. The collected data offer insights into the current adoption levels of green building practices in the country. A collaborative effort from stakeholders, including policymakers, developers, architects, engineers, and contractors, is crucial for overcoming challenges and promoting sustainable building practices. This study contributes to this objective by providing valuable insights into the challenges and opportunities for sustainable development in Malaysia's construction industry.

2.0 LITERATURE REVIEW

The green building supports a more comprehensive agenda for sustainable development. All parties involved in developing the green building, including those offering design, consulting, and construction services, must take responsibility and make efforts towards achieving sustainable construction practices. Both of the party require the willingness for achieving an eco-construction approach to adopt green materials, concepts, and procedures in the construction approach.

The success factor of green building implementation is developed by the project team's awareness of the developer, architect and consultant. Market demand, acceptability, engagement, implementation, education, experience, and awareness are identified as critical factors by Suzila, Asmalia, and Zulkipli (2016). Public awareness is particularly crucial as it is the initial step toward successful green building practices. Interest in green building construction leads to increased understanding of its principles, fostering sustainable construction practices.

2.1 Benefits of Occupant

Building activity has a significant impact on the formation of the social environment. Social sustainability concerns the well-being of individuals who are directly or indirectly affected by construction development, including the incorporation of green imagery, trees, and nature. The purpose of social sustainability is to ensure that the social, cultural, and spiritual needs of people are met by sustainable development in the construction industry (Illankoon, *et al.,* 2016).

The adoption of green building features, such as vegetation and biodiversity, leads to improved indoor air quality, reduced carbon emissions, and enhanced occupant satisfaction. Providing green construction financing at lower interest rates incentivises developers and contractors to invest in sustainable building practices, fostering positive public image and trust. (Li, *et al.,* 2019).

A positive working environment, facilitated by green building features, promotes high levels of well-being and productivity among occupants (Geng *et al.,* 2019). Good indoor air quality positively affects occupant productivity, and lower interest rates for green construction financing contribute to significant reductions in carbon emissions and other environmental impacts. Prioritising occupant benefits leads to increased satisfaction, productivity, and positive impacts on a company's bottom line and reputation.

2.2 Facility Management (FM)

Facility management (FM) is the process of managing and maintaining all the multiple services that enable the facility to become a productive environment for its occupants. It is a wide-reaching field that assists with different activities, including business administration and engineering construction services, as well as managing utilities and ensuring compliance with regulations and safety standards (Sanzana, *et al.,* 2022). Therefore, sustainable facility management together with the use of green technology contribute the building become more energy-efficient and sustainable. It can bring economic benefits because there are energy and water savings from the lifecycle perspective, simultaneously reducing material and natural resource consumption.

A study by Francisco (2019) shows that solar energy technologies building can save up to 30% on the energy use of the building. Properly positioned solar panels optimise energy efficiency by converting solar energy into usable electricity, while the building's orientation maximises natural light, reducing the need for electric lighting during daylight. This is reinforced by Ahmed (2020), emphasising that solar panels enhance energy efficiency by blocking sunlight, preventing excessive heat from entering the building.

Similarly, Ali, Zhang and Yue (2020) point out that green buildings with a rainwater harvesting approach have at least 17% water-saving efficiency. Collecting rainwater during rainfall occasions is a substitute for non-potable purposes such as irrigating gardens, flushing toilets and cleaning cars. The facility manager implements rainwater harvesting system can help conserve water in green buildings by managing water consumption, implementing water-saving measures such as low-flow fixtures, and monitoring water usage to identify leaks and other issues (Cupido, Steinberg and Baetz, 2016). As a result, rainwater harvesting system has a positive economic impact since it reduces the amount of tap water used, which lowers the costs associated with utilising the municipal network and sewage systems. It also benefits from a long-term saving on water bills and an improved environmental profile.

2.3 Environmental Sustainability

Environmental sustainability is a concept of preserving precious natural resources whereas eliminating negative environmental impacts. It is a sustainable approach for the construction industry that provides green public goods to eliminate the environmentally harmful resources generated from economic activities (Oteng, Mensah and Duodu, 2022).

Green building is made of eco-friendly materials with a lower negative environmental impact. Recycling and reusing industrial wastes are effective strategies across various industries for conserving natural resources. In the cement industry, as highlighted by Zhang, Ghouleh, and Shao (2021), green concrete, composed of bottom ash, municipal solid wastes as aggregates, and eco-cement as the binder, exemplifies an eco-friendly construction material. Notably durable, eco-friendly materials contribute to reduced construction waste destined for landfills.

As per Sondh, *et al.* (2022) findings, an efficient Municipal Solid Wastes (MSW) management system can promote sustainable development in accord with good practice under environmental considerations. The management of MSW is integrated by regulating the production, collection, storage, transfer, and disposal of construction wastes to reduce the waste streams. Cudjoe, Wang, and Zhu (2021) endorse environmentally favourable technologies for waste recycling, including the hydrothermal technique, pyrolysis process, and vacuum metallurgy separation, fostering the formation of an organised recycling system. Implementing a circular economy strategy in MSW management for the construction industry can alleviate environmental degradation.

3.0 METHODOLOGY

The quantitative research method is used in this study as the primary tool for establishing empirical relationships. This method emphasises objective measurements by collecting the information, data, and samples to generate a possible solution for the specific problem. Quantitative research involves mostly numerical data on a statistical analysis through the use of large-scale survey research or questionnaire method (Mohajan, 2020). This method generalises the research findings to the population from the selected sample. The reliability and validity of quantitative research are based on the measurement instruments used for the analysis. A questionnaire is distributed to the target respondents in the form of a survey as the instrument for data collection. Afterwards, the respondent data are obtained for analysis by the Statistical Package for Social Sciences (SPSS).

3.1 Conceptual Framework

The conceptual framework refers to a collection of related concepts, ideas, or theories that provide a structure and guidance for research (Imenda, 2014). It is comprised of a group of variable inferences developed from the literature and theory that represent their relationships. By using the conceptual framework, it can easily identify research questions, develop hypotheses, and interpret study results.

Figure 1 describes the relationship between the independent and dependent variables. It is crucial in determining the outcome of the study and understanding the factors that may influence the dependent variable. Independent variable is the variable that is manipulated by the experimenter and is expected to have an effect on the dependent variable. In the other way, dependent variable is being measured for the influent change to the independent variable. The study is carried out to determine the company's readiness to adopt Green Building Rating Tools among the Benefits to Occupants, Facility Management, and Environmental Sustainability.

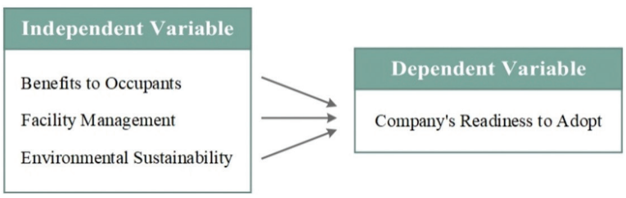

Figure 1: Conceptual framework of study

3.2 Data Collection

Data collection is a systematic process of obtaining and measuring relevant variables to address specific research questions, test hypotheses, and evaluate results (Brondolo, 2021). The target population for this research comprises developers, consultants, and contractors working in the Malaysian construction industry. It is because they are having the working experience in the relevant fields that clearly understand about the current situation in the construction industry.

3.3 Questionnaire Survey

A set of questionnaires were established based on the conceptual framework in this study to investigate the current implementation of Green Building Rating Tools in the Malaysia building industry. The survey forms consist of 4 sections (Section A, B, C, and D) were distributed to developers, architects, engineers, and contractors in Malaysia via Google Forms online. Table 1 shows the summary of the questionnaire.

Table 1: Summary of the questionnaire

Section	Item
A	Section A involves general background questions that collect demographic information of the respondents. These questions aim to obtain information about the respondent's main scope of service, their years of working experience in the building industry, and their employees' size of the company.
B	Section B is focused on assessing respondents' awareness of Green Building Rating Tools. This section aims to determine the extent of familiarity work with green building development, as well as to identify the preferred rating systems for adoption by companies.
C	Section C is related to the dependent variable of this study, which discuss the perceived benefits to occupants, facility management and environmental sustainability of Green Building. Based on these benefits, it can recognise the factors affecting implementation of Green Building Rating Tools in Malaysia.
D	Section D is dedicated to the dependent variable of this study that assesses the readiness of companies in the building industry to adopt Green Building practices. The aim of this section is to determine the factors that influence the implementation of Green Building Ratings and assess the inclination of companies to adopt the principles and practices of Green Building.

3.4 Data Analysis Using SPSS

Statistical Package for the Social Sciences (SPSS) used for analysis of the questionnaires. Descriptive analysis was used to analyse the demographics of respondents in Section A and the awareness of Green Building Rating Tools in Section B. Reliability test was conducted in Section C and D that contain Likert Scale in the questionnaire to ensure the validity and reliability of the results.

Taber (2018) mentioned that the reliability test is commonly approached with the use of Cronbach's Alpha to assess attitudes and other affective constructs. It is used to determine the internal consistency of the quantitative questions, thus strengthening the reliability. The Cronbach's Alpha can be calculated by Equation 1 as shown below.

$$\alpha = \frac{N\bar{c}}{\bar{v} + (N-1)\bar{c}} \qquad (1)$$

where

α = Cronbach's Alpha
N = number of items
$\bar{c}$ = inter-item correlation
$\bar{v}$ = average variance

3.5 Hypothesis Development

During the hypothesis generation stage, it is prudent to convene a diverse group of analysts with varying backgrounds and perspectives for a collaborative brainstorming session. Group brainstorming fosters creativity and often unveils possibilities that individual members may not have considered on their own. In effect, key success factors articulate the important strategic posture for a company to adopt the Green Building Rating Tools in its development project. The proposed hypotheses in this study are as follows:

H_1 : There is a positive significant relationship between Benefits to Occupants and Company's Readiness to adopt Green Building Rating Tools.

H_2 : There is a positive significant relationship between Facility Management and Company's Readiness to adopt Green Building Rating Tools.

H_3 : There is a positive significant relationship between Environmental Sustainability and Company's Readiness to adopt Green Building Rating Tools.

4.0 RESULTS AND DISCUSSIONS

This section presents the results generated from the statistical data analysis conducted using the SPSS statistical software. The questionnaires were completed by a total of 140 respondents.

4.1 Descriptive Analysis

The descriptive analysis summarises the characteristics of the data that has been collected, such as distribution, mean and central tendency. As a results, Table 6 shows the overall respondents' demographic profile is obtained including organisation's main scope of service, role, years of experience and organisation size.

4.1.1 Awareness of Green Building

Figure 2 illustrates the respondent's awareness of green building. The findings reveal that 77.1% of the respondents are familiar with the Malaysia Green Technology Master Plan (GTMP), which is developed by the Malaysian government, while the remaining 22.9% respondents are not aware of it. As a result, the practical application of Green Building Rating Tools is extremely limited in Malaysia. A total of 78.6% respondents reported that they have no practical experience in handling Green Building projects. It is just only 21.4% respondents have participated in the Green Building project, and they have experience in adopting the Green Building Rating Tools for the project and are more familiar with it. Despite the importance of green building, it is not yet common in Malaysia due to unique challenges. Most construction industry stakeholders are not yet familiar with adopting green building assessment tools, which may limit the program's adoption.

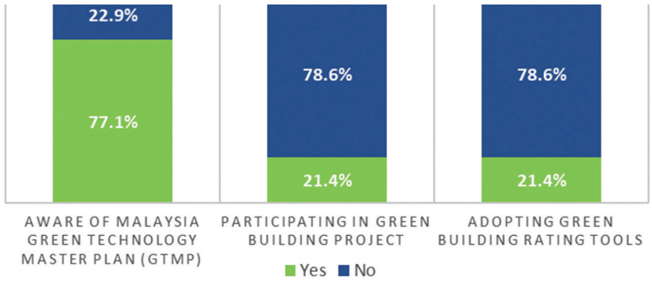

Figure 2: Awareness of green building

4.1.2 Adoption of Green Building Rating

Based on Figure 3, it is evident that the respondents use various green building rating tools in their projects. The majority of the respondents, which is 23 in number, use the Green Building Index (GBI), followed by Green Real Estate (GreenRE), with 12 respondents. As a results, it describes the existing commonly used green building assessment tools in Malaysia were GBI and GreenRE. Generally, GBI and GreenRE are rating systems that aim to promote sustainability in buildings, but they have different scopes and certification processes. GBI is a more comprehensive system that evaluates the sustainability of the entire building, including its design, construction, operation, maintenance, and management. Conversely, GreenRE focuses more on the building's operational performance, such as energy and water efficiency and waste management.

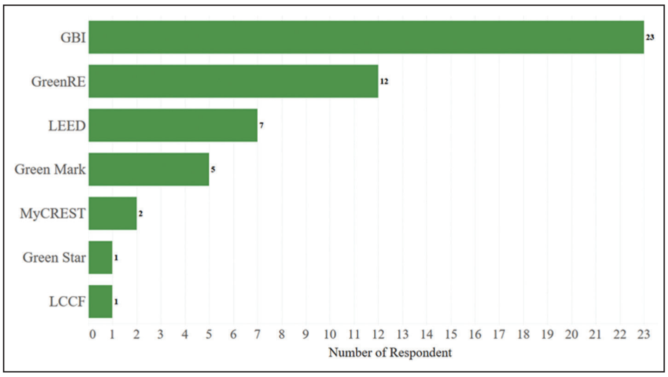

Figure 3: Types of green building rating tool used

In others, seven respondents use Leadership in Energy and Environmental Design (LEED), while five and two respondents use Green Mark and Malaysian Carbon Reduction and Environmental Sustainability Tool (MyCREST), respectively. Lastly, only one respondent each uses Green Star and the Low Carbon Cities Framework (LCCF) in their green building projects.

4.2 Measurements of the Data

The reliability test is used to measure the consistency of variables based on the value of Cronbach's Alpha (Taber, 2018). The higher the accuracy and stability, the more precise the instrument becomes. Multicollinearity test is also conducted to identify potential multicollinearity in the model. Two standard measures, namely tolerance value and Variance Inflation Factor (VIF), are used for this purpose. The tolerance value and VIF are inverse measures of each other. Besides, normality test is conducted to evaluate the normality of the variables.

4.2.1 Reliability Test

Pilot test is used to measure the consistency of the variables based on the Cronbach's Alpha value in the early stage of the study (Taber, 2018). Table 2 shows the number of first 25 respondents in the questionnaire survey. The overall Cronbach Alpha values is accepted with the range of 0.807 to 0.956 through the analysis. According to Uma and Roger (2019), the results show a good reliability among the variables with the Cronbach's Alpha value that is more than 0.8.

Table 2: Cronbach's alpha on reliability test

Variables	Cronbach's Alpha
Independent Variables (IV)	
Benefits to Occupants (IV1)	0.885
Facility Management (IV2)	0.878
Environmental Sustainability (IV3)	0.931
Dependent Variable (DV)	
Company's Readiness to Adopt	0.918

4.2.2 Multicollinearity Test

Table 3 shows the independent variable with the highest VIF value is Facility Management, which obtained a value of 3.401, followed by Benefits to Occupants with a VIF of 3.115, and Environmental Sustainability with the lowest VIF of 2.809. Since all the independent variables have VIF values in the range of 1 to 10, there is no issue of multicollinearity (Saunders, *et al.,* 2019. This means that the three independent variables do not overlap with each other. Therefore, the results of this study are reliable.

Table 3: Multicollinearity statistic

Model	Tolerance	VIF
Benefits to Occupants	0.321	3.115
Facility Management	0.294	3.401
Environmental Sustainability	0.356	2.809

4.2.3 Normality Test

Normality test is conducted to evaluate whether the data collected from the questionnaire is suitable for a normal distribution model. Mishra *et al.* (2019) recommends using the Kolmogorov-Smirnov test when the sample size exceeds 50, which is the case in this study with a questionnaire sample of 140. Hence, Kolmogorov-Smirnov Test is more significance for the normality test.

If the significance (Sig.) value is less than 0.05, it indicates a significant test and a non-normal distribution of the model (Ghasemi and Zahediasl, 2012). As a results, Table 4 shows that all of the variables, both independent and dependent, have a Sig. value of 0.000, which is less than 0.05, indicating non-normality.

Table 4: Kolmogorov–Smirnov test

Variables	N	Sig.
Benefits to Occupants	140	0.000
Facility Management	140	0.000
Environmental Sustainability	140	0.000
Company's Readiness to Adopt	140	0.000

4.3 Regression Analysis

Regression analysis is performed to examine the statistical relationship between independent and dependent variables. Multiple linear regression is used for many independent to one dependent variable analysis for further hypothesis testing.

4.3.1 Spearman's Rho Correlation Analysis

Spearman's Rho Correlation Analysis is a non-parametric method used to determine the strength and direction of association between two ranked variables. Figure 4 presents the correlation analyses, and the results indicate that each independent variable has a positive relationship with the dependent variable. This implies that as the values of the independent variables increase, there is a higher likelihood of the dependent variable also increasing. According to Dancey and Reidy (2004), Spearman's Rho coefficients between 0.4 and 0.7 indicate a strong correlation. Table 5 represents Spearman's Rho Correlation of the variables which are strong relationships with the Company's Readiness to adopt Green Building Rating Tools.

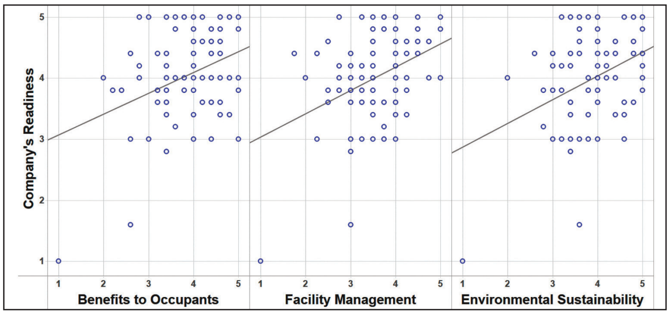

Figure 4: Correlation strength

4.3.2 Multiple Linear Regression

Since there are 3 independent variables (Benefits to Occupants, Facility Management, and Environmental Sustainability) in this study, multiple linear regression is used to determine the statistical relationship between the variables. The result of Beta (β) and p-value for multiple linear regression is shown in Table 5.

Based on Table 5 the independent variables, Facility Management (IV2) and Environmental Sustainability (IV3) have obtained 0.006 and 0.020 of p-value respectively. Hence, there is a significant relationship between these variables and the dependent variable which are less than 0.05 in significant. Moreover, Facility Management (IV2) and Environmental Sustainability (IV3) have higher β values of 0.349 and 0.267 respectively, indicating that they have a stronger impact on the DV.

In contrast, Benefits to Occupants (IV1) yields a β value of 0.038, indicating a relatively modest influence on the Company's Readiness to Adopt Green Building Rating Tools (DV), contributing to a mere 3.8% of the variation. The p-value associated with Benefits to Occupants is 0.754, exceeding the 0.05 threshold, consequently deeming it statistically nonsignificant.

4.3.3 Hypothesis Testing

Hypothesis testing was executed through the analysis of p-values, with a threshold set at 0.05. A p-value below 0.05 signifies support for the hypothesis at a 95% confidence level.

Table 5: Results on hypothesis testing

	Hypothesis	Correlation	Beta (β)	p-value	Decision
H_1	There is a positive significant relationship between Benefits to Occupants and Company's Readiness to adopt Green Building Rating Tools.	0.460**	0.038	0.754	H_1 is rejected.
H_2	There is a positive significant relationship between Facility Management and Company's Readiness to adopt Green Building Rating Tools.	0.588**	0.349	0.006	H_2 is accepted.
H_3	There is a positive significant relationship between Environmental Sustainability and Company's Readiness to adopt Green Building Rating Tools.	0.553**	0.267	0.020	H_3 is accepted.

Based on the H_1 correlation coefficient between Benefits to Occupants and Company's Readiness is 0.460**, which indicates a strong correlation. Among all three independent variables, Benefits to Occupants are the least correlated with Company's Readiness. Table 5 shows that the p-value for Benefits to Occupants is 0.754, which is higher than 0.05 ($p > 0.05$) and therefore not statistically significant. As a result, Hypothesis 1 (H_1) is rejected, indicating that there is no significant relationship between Benefits to Occupants and Company's Readiness to adopt Green Building Rating Tools.

H_2 indicates a strong correlation between Facility Management and Company's Readiness, with a correlation coefficient of 0.588**. Among all three independent variables, Facility Management has the highest correlation with Company's Readiness. Companies with a strong focus on Facility Management are more likely to be prepared to adopt rating tools. Besides, Table 5 further confirms the relationship between Facility Management and Company's Readiness, with a significant p-value of 0.006, which is lower than the significance level of 0.05 ($p < 0.05$). Thus, Hypothesis 2 (H_2) is accepted.

H_3 shows that there is a strong correlation between Environmental Sustainability and Company's Readiness to adopt Green Building Rating Tools, with a correlation coefficient of 0.553**. Among all three independent variables, Environmental Sustainability are the second-highest correlated to Company's Readiness. Companies that prioritise sustainability are more likely to be motivated to adopt Green Building Rating Tools and the adoption of these tools can help companies improve their environmental performance and achieve their sustainability goals. Table 5 further supports this relationship, with a significant p-value of 0.020, which is less than 0.05 ($p < 0.05$). Therefore, Hypothesis 3 (H_3) is accepted.

Table 6: Summary of respondents' background

	Percentage	Respondent (N=140)
Main Scope of Service		
Architectural Consultant	12.86%	18
Construction Contractor	7.14%	10
Developer / Project Owner	41.43%	58
Engineering Consultant	32.86%	46
Quantity Surveying Consultant	5.71%	8
Role		
Architect	14.29%	20
Engineer	34.29%	48
Management	37.14%	52
Quantity Surveyor	9.29%	13
Sales & Marketing	5.00%	7
Working Experience		
6 – 10 years	38.57%	54
11 – 15 years	7.86%	11
16 – 20 years	5.00%	7
Less than 5 years	34.29%	48
Over 20 years	14.29%	20
Organization Size		
5 – 30 employees	45.00%	63
30 – 75 employees	35.71%	50
Less than 5 employees	2.86%	4
Over 75 employees	16.43%	23

5.0 CONCLUSIONS

The study delves into the integration of sustainability practices through green building ratings in the construction processes of firms. Despite achieving a commendable awareness level of 77.1% regarding the Green Technology Master Plan (GTMP) among respondents, the data reveals a considerably low adoption rate of Green Building Rating Tools in Malaysia, standing at only 21.4%. This low adoption is attributed to a lack of knowledge about green technologies and their regulations among project teams involved in green building projects. In order to elevate the adoption rate of GBRTs in the Malaysian construction industry, the government can offer incentives such as tax breaks, subsidies, and grants to encourage adoption. This can make it more financially attractive for building owners and developers to invest in green building practices.

The conceptual framework contributes to understanding the complex interplay between different factors influencing a company's readiness to adopt GBRTs. The correlation analysis supports the significance of Facility Management and Environmental Sustainability in shaping this readiness, emphasizing the importance of these elements in the broader context of sustainable development in the construction industry. The study's findings emphasize a strong relationship between Facility Management and Environmental Sustainability and a company's readiness to adopt GBRTs. Companies that prioritise sustainability and implement robust Facility Management practices demonstrate an elevated readiness to adopt GBRTs, leading to an overall improvement in their environmental performance. However, the study reveals that Benefits to Occupants did not exhibit a significant relationship with a company's readiness to adopt GBRTs. This divergence suggests that decision-makers may prioritise factors other than occupant benefits when considering the adoption of GBRTs. While occupants can influence the demand for green buildings, the decision-making process is often steered by stakeholders driven by economic and social considerations.

In conclusion, the maturity level of GBRTs development emerges as a critical factor influencing green building practices. As Malaysia's construction industry is in its early stages concerning sustainability, there is a need for increased GBRTs development and implementation to promote sustainable building practices. Policymakers hold a crucial role in providing incentives to project teams and promoting GBRTs implementation. Overall, increasing the adoption rate of Green Building Rating Tools in Malaysia will require a combination of government incentives, education, industry collaboration, mandatory regulations, and financial institutions' incentives.

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FEASIBILITY STUDY OF SOLAR-POWERED ELECTRIC VEHICLE CHARGING INFRASTRUCTURE AT SELECTED PETROL STATIONS IN MALAYSIA

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Abstract

The transition from the conventional internal combustion engine (ICE) to electric vehicles (EV) are expected to result in higher total electricity demand in the country. With the introduction of more EVs into the market, the need for charging stations will grow, subsequently increasing power consumption. This research study aims to assess the potential of solar energy production at petrol stations in central region of Peninsular Malaysia and assess the feasibility of solar-powered petrol stations in meeting the energy demands of electric vehicles. Ten samples of existing petrol stations are selected to install a solar-powered DC charging station as a case study. The physical characteristics of the ten sites such as the rooftop area were then analysed by using Google Earth. PVsyst software was then used to design and simulate the solar PV system and the expected solar energy yield can then be found. To study their energy consumption, 90kW DC charger was chosen as the load. As the result, it is found that 90% of the sampled petrol stations are able to generate enough energy to meet the estimated annual energy consumption of the 90kW DC charging system. Naturally, petrol station with larger rooftop area can generate higher amount of solar energy. The results also showed that the cost to install the solar-powered charging system for both power ratings can be recouped in less than 2 years. Overall, this research study offers valuable insights for addressing the rising energy consumption resulting from the increased penetration of electric vehicles in the future. Additionally, the implementation of solar-powered charging infrastructure aligns with the country's renewable energy objectives and efforts to reduce greenhouse gas emissions. However, the assessment of EV penetration and the adoption of charging infrastructure was conducted based on government targets rather than relying on current data regarding the actual numbers and trends of EVs and chargers in Malaysia. The availability of accurate and up-to-date data on the number of EVs, their battery characteristics, chargers, and user charging behaviors in Malaysia would contribute to further enhancing this research work.

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Keywords:
Electric Vehicle, Fast Charger, Solar Energy, Pvsyst

1.0 INTRODUCTION

The transportation sector is one of the major contributors to greenhouse gas emissions globally. To address this issue, the adoption of electric vehicles (EVs) has been considered as an alternative to conventional internal combustion engine (ICE) vehicles. Malaysia, as a developing country, has set a target to have 100,000 EVs on the road by 2030 (MIDA, 2023). However, the widespread adoption of EVs requires a reliable and efficient charging infrastructure (Dimitriadou *et al.,* 2023). According to the Low Carbon Mobility Blueprint 2021-2030, a dedicated council to implement the policy to plan for the EV charging infrastructure is to be established. As more EVs are introduced into the market, the demand for charging stations will increase, leading to an increase in power consumption. Therefore, it is essential to evaluate the impact of EV chargers on power consumption to ensure the stability of the grid.

As more electric vehicles penetrated the Malaysian market, the demand for the EV charging infrastructures will increases. To solve this problem, more EV charging infrastructures has to be built, especially along the existing expressway. However, there are few challenges that must be encountered, where most of the existing EV chargers are powered by unclean electricity from conventional thermal power plants (Shatnawi *et al.,* 2021). These power plants rely on non-renewable resources such as coal and natural gas. As more EV charging stations are to be installed in the future, the electricity demand to power up these stations will be high, therefore requiring more fossil fuels to generate the power. To overcome this problem and avoid future power shortages, a study must be done to support the power consumption of the EV charging stations from the grid to more green and eco-friendly energy resources such as solar energy. A solar-powered EV charging station consists of the typical components of a conventional EV charging station with the addition of solar PV panels and inverter and battery storage system as optional components. This is also in line with the preference of having solar-powered EV charging infrastructure as outlined in the Low Carbon Mobility Blueprint 2021-2030. The huge carbon pollutant reduction potential of solar powered EV compared with traditional gasoline-fueled cars further reinforces the need of this study (Bin Ye *et al.,* 2015). Hence, this paper aims to assess the feasibility of solar-powered petrol stations at selected locations in meeting the energy demands of electric vehicles in Malaysia.

In this research work, it is important to consider the various types of EV chargers available. However, for the purpose of this case study, the focus will be solely on Direct-Current (DC) chargers as the research variable. Additionally, while there are numerous petrol stations across Malaysia, this project research study is specifically limited to 10 petrol stations located along the North-South Expressway in the Central region of Peninsular Malaysia. Furthermore, there are different types of electric vehicles currently available in the market, including battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs). However, this research project will concentrate solely on studying BEVs. Lastly, this research will only focus on the grid connected PV system, without any additional battery energy storage system.

2.0 METHODOLOGY

At the initial stage of the project, the number of petrol stations as well as their locations along the North-South Expressway will be obtained from the official PLUS Expressway website. As of 26 July 2022, there are up to 100 existing petrol stations along the North-South Expressway (PLUS Expressway, 2023). The petrol stations include Shell, Caltex, Petron, BHP, and Petronas. A sample of 10 petrol stations located in the central region will be calculated and analysed noting that the usage of electric vehicles may be more concentrated in the central region due to its higher population density. Figure 1 shows a sample of a rooftop image of a petrol station at the coordinate of 3.2246017,101.57682758 decimal degrees, which was captured by Google Earth to estimate the net area of the rooftop (Google Earth, 2023). The next step is to use the calculated rooftop area as a parameter to design and size the solar PV system for the selected petrol stations.

The selection of PV modules for the system design was done by taking the modules' efficiency into consideration. Figure 2 illustrates a typical solar-powered EV charging station (Samir, 2020). The efficiency of the PV modules determines how effectively they can convert sunlight into electrical energy. The higher the efficiency of the PV modules, the more energy from the sunlight can be converted into electrical energy. In general, a petrol station operator with the intention to install a solar-powered EV charging station has to decide between monocrystalline or polycrystalline modules as well as whether there is a need for battery storage system within the budgetary constraints. In this paper, a model of monocrystalline PV modules was selected for the design as it has higher efficiency than polycrystalline modules. The specification of the selected module is shown in Table 1 (Shanghai JA Solar, 2021). As for the inverter, it was selected by considering the size of the designed PV system and its expected total power output. According to a previous study, the optimal DC-to-AC ratio should be closer to 1.2 to maximise the specific yield (Kathy, 2018). Table 2 shows the specifications of the selected inverter (Huawei, 2022). Figure 3 shows a sample of the specifications in one of the simulations.

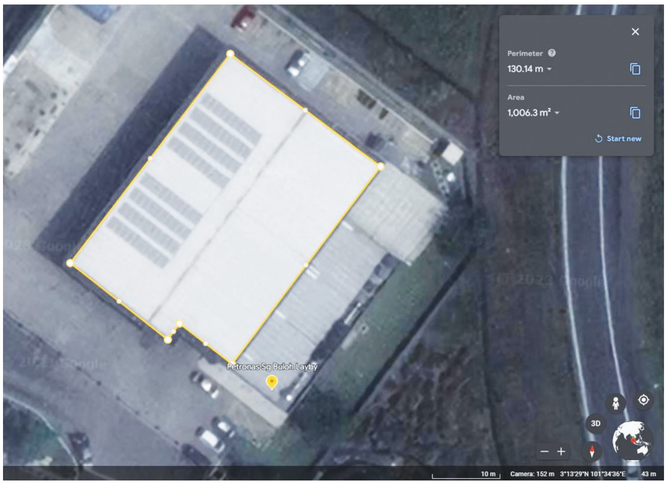

Figure 1: Sample of a rooftop of a petrol station captured by Google Earth (Google Earth, 2023)

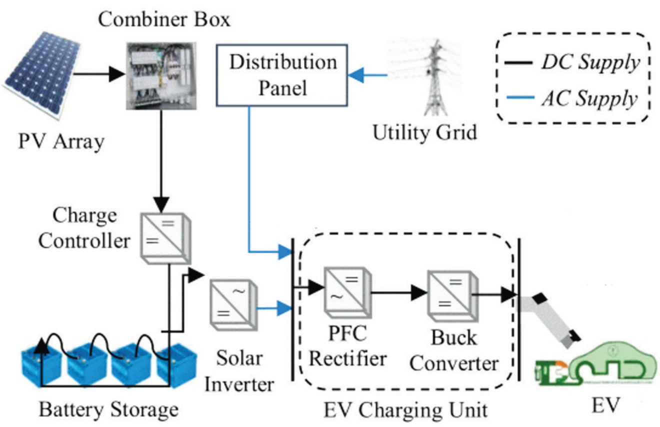

Figure 2: A typical solar-powered EV charging station (Samir, 2020)

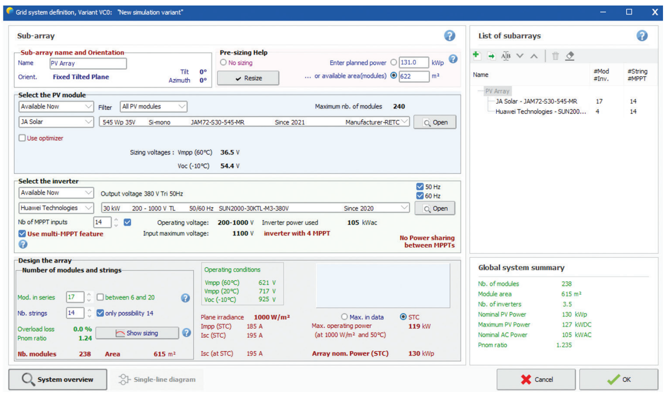

Figure 3: Sizing of PV systems in PVsyst software

Table 1: Electrical parameters of the monocrystalline PV module

Rated Maximum Power (Pmax) [W]	545
Open Circuit Voltage (Voc) [V]	49.75
Maximum Power Voltage (Vmp) [V]	41.8
Short Circuit Current (Isc) [A]	13.93
Maximum Power Current (Imp) [A]	13.04
Module Efficiency [%]	21.1
Power Tolerance	0~+5W
Temperature Coefficient of Isc(α_Isc)	+0.045%/°C
Temperature Coefficient of Voc (β_Voc)	-0.275%/°C
Temperature Coefficient of Pmax (γ_Pmp)	-0.350%/°C

Table 2: Technical specification of the inverter

Max. Input Voltage	1100 V
Max. Current per MPPT	26 A
Max. Short Circuit Current per MPPT	40 A
Start Voltage	200 V
MPPT Operating Voltage Range	200 V - 1000 V
Rated Input Voltage	600 V
Number of Inputs	8
Rated AC Active Power	30000 W
Max. AC Apparent Power	33000 VA
Rated Output Voltage	230 Vac / 400 Vac / 480 Vac, 3W/N+PE
Rated AC Grid Frequency	50 / 60 Hz
Rated Output Current	43.3 A
Max. Output Current	47.9 A
Max. Total Harmonic Distortion	< 3%

Once the rooftops' area has been obtained and the types of solar module and inverter have been selected, the next step is to design and simulate the PV systems based on the design parameters using PVsyst software (PVsyst, 2023). The design parameters that were obtained will be used to size the PV system, which the PVsyst software will prompt the user to enter the rooftop area, types of solar modules, and types of solar inverters. The power ratings of DC chargers for electric vehicles can vary depending on the specifications of the charger model. However, there are several common power ratings for DC chargers that are currently being installed in Malaysia. Based on official websites of TNB Electron, Shell, and Petronas (TNB Electron, 2023), (Shell Recharge, 2023), (PETRONAS, 2023). DC chargers with power ratings of 90kW and 180kW are quite commonly installed in petrol stations along the expressway. It is important to note that the power ratings of the DC chargers can vary further based on the technological advancements and individual charger manufacturer. Nevertheless, the research was focused more on the 90kW power ratings as it is more common along the expressway compared to other power ratings.

The next step in this research work is to calculate the estimated energy consumption of those 90kW DC chargers' power ratings. The equation to calculate the estimated daily energy consumption of the DC chargers is shown in Equation 1 below:

$$Daily\ energy\ consumption = P \times t \times N \tag{1}$$

where:
P = Power rating of DC charger (kW)
t = charging time (hours)
N = Number of EVs charged per day

The parameter N in Equation (1) was obtained by determining the number of EVs and charging points available in Malaysia. The Malaysian government has set a target to have 100,000 EVs on the road by 2030 (MIDA, 2023). As for the charging points, the Ministry of Natural Resources, Environment, and Climate Change (KASA) aims to set up 10,000 EV charging points in Malaysia by 2025 under the Low Carbon Development Plan 2021-2030 (Ministry of Environment and Water, 2021). Since there are no well-established data regarding the number EVs and the charging points that are currently available in Malaysia, this information was used to estimate the number of EVs per charging point. Therefore, based on the government targets, the estimated ratio of EV-to-charging points approximates 10 EVs per charging points.

The total cost of the entire system for each petrol station was calculated based on the number of units of PV modules, solar inverters, and DC chargers installed. The market prices for each component unit are shown in Table 3 (Secondsol Solar Panel, 2023), Secondsol Inverter, 2023), (Tonghe, 2023). Note that the installation costs are excluded from this study as the rate may vary significantly.

Table 3: Market price for each component unit

Item	Price per unit
PV module	RM883.00
Solar inverter	RM9,200.66
90kW DC charger	RM71,495.00

The return on investment (ROI) and payback period for the whole system on each petrol station was calculated using Equation 2 and Equation 3, respectively. The annual profit in Equation 2 refers to the profit generated from the whole investment. The profit for each petrol station was calculated based on the charging rates of the DC chargers. According to TNB Electron, the charging rate for the 90kW DC charger is RM2.20/min (TNB Electron, 2023).

$$ROI = \frac{Annual\ Profit}{Total\ Cost\ of\ the\ System} \times 100\% \tag{2}$$

$$Payback\ Period = \frac{Total\ Cost\ of\ the\ System}{Annual\ Profit} \tag{3}$$

4.0 RESULTS AND DISCUSSIONS

Table 4 shows the simulated solar energy production from each of the 10 selected petrol stations in this study. The average irradiance level received by the Central region is 1778 kWh/m^2. Higher irradiance levels result in a greater amount of energy generation. However, the net area of the rooftops also plays an important role in maximizing the energy harvest from the solar PV system. Based on the obtained results, it can be observed that a larger rooftop area at a petrol station allows for the installation of more PV modules, resulting in higher power generation.

The energy consumption of the 90kWDC chargers' power ratings was calculated using Equation 1. It is important to note that the charging time for an electric vehicle (EV) depends on the EV's specifications and its built-in battery capacity. Based on the assumption of 10 EVs per charging point, as discussed in previous section, if each EV is charged for 30 minutes regardless of the state-of-charge, the estimated daily energy consumption for the charger is 450 kWh. The annual energy consumption of the DC charger was obtained by multiplying the daily energy consumption by 365 days. Thus, the annual energy consumption for the 90kW DC chargers is 164,250 kW.

As observed in Table 4, 9 out of 10 petrol stations can meet the annual energy demand of the 90kW DC charger. The petrol stations with rooftop areas below 510 m^2 could not generate enough energy to support the annual energy demand of the charger. Specifically, Petron Dengkil which has rooftop areas of less than 510 m^2, resulting in insufficient energy generation to meet the energy demand of the 90kW charger.

The number of EVs that can be charged per year for each charger was determined by dividing the annual energy generation by the energy consumption of each EV. Table 5 presents the number of EVs that can be charged per year for each type of charger. Note that the analysis was made based on the assumption of 30 minutes of charging time, regardless of the state-of-charge of the EVs.

Table 4: Designed PV system simulation results in central region

Stations	Area (m²)	Annual Average Irradiation (kWh/m²)	Performance Ratio	Annual Energy Produced (kWh)
Shell Tapah NB	894.84	1757.3	0.848	275808
Petron Behrang Layby SB	936.69	1754.7	0.847	288995
Petronas Ulu Bernam SB	817.63	1758.3	0.846	247892
Petronas Rawang NB	683.51	1772.4	0.846	208150
Petronas Sg Buloh Layby SB	1006.46	1775.2	0.847	311367
Petron NKVE	995.8	1783.1	0.846	307303
Caltex Elite USJ	603.02	1794.1	0.845	185057
Petron Dengkil Elite SB	495.79	1800.8	0.847	155394
Shell Dengkil Elite SB	713.37	1801.1	0.846	225736
Petronas Damansara NKVE	1381.85	1783	0.842	435328
Average	**852.896**	**1778**	**0.846**	**264103**

Table 5: Comparison on the annual charging capacity of the systems

Stations	Annual Energy Produced (kWh)	90kW Power Consumption (kWh)	No. of EVs can be charged by 90kW
Shell Tapah NB	275808	45	6129
Petron Behrang Layby SB	288995	45	6422
Petronas Ulu Bernam SB	247892	45	5509
Petronas Rawang NB	208150	45	4626
Petronas Sg Buloh Layby SB	311367	45	6919
Petron NKVE	307303	45	6829
Caltex Elite USJ	185057	45	4112
Petron Dengkil Elite SB	155394	45	3453
Shell Dengkil Elite SB	225736	45	5016
Petronas Damansara NKVE	435328	45	9674

Table 6: Total cost of the whole system for petrol stations

Stations	Units of PV Module	Units of Inverter	Total Cost of 90kW System (RM)
Shell Tapah NB	340	5	417718.30
Petron Behrang Layby SB	357	6	441929.96
Petronas Ulu Bernam SB	306	5	387696.30
Petronas Rawang NB	255	4	333462.64
Petronas Sg Buloh Layby SB	380	5	453038.30
Petron NKVE	374	6	456940.96
Caltex Elite USJ	224	4	306089.64
Petron Dengkil Elite SB	187	3	264217.98
Shell Dengkil Elite SB	272	4	348473.64
Petronas Damansara NKVE	532	8	614856.28

Table 7: Annual profit for petrol stations

Stations	No. of EVs Charged per Year (90kW)	Charging Duration (min)	Annual Profit for 90kW (RM)
Shell Tapah NB	6129	30	404518.40
Petron Behrang Layby SB	6422	30	423859.33
Petronas Ulu Bernam SB	5509	30	363574.93
Petronas Rawang NB	4626	30	305286.67
Petronas Sg Buloh Layby SB	6919	30	456671.60
Petron NKVE	6829	30	450711.07
Caltex Elite USJ	4112	30	271416.93
Petron Dengkil Elite SB	3453	30	227911.20
Shell Dengkil Elite SB	5016	30	331079.47
Petronas Damansara NKVE	9674	30	638481.07

The total cost for the whole system for each petrol station was calculated by considering the number of units of PV modules, inverter, and chargers used to design the system and is as per Table 6.

The annual profit for each system was obtained by calculating the profit gained from the number of EVs that can be charged with the annual energy generated. With the charging rates for the 90kW chargers being RM2.20/minute and with the assumption of 30 minutes charging time for each EV as discussed previously, the annual profit for all petrol stations can be found in Table 7.

The total cost and annual profit obtained for every designed system previously were used for the calculation of return on investment (ROI) and their payback period. The ROI and payback period for each system were calculated using Equation 2 and Equation 3. The results for all the systems are displayed in Table 8. Again, it is to be noted that the ROI and payback period are estimated without considering the cost of installation.

While this study seems to strongly suggest that solar powered 90 kW EV chargers is highly feasible, do note that there could be practical implementation issues and challenges in ensuring maximization of solar PV being installed at the available space of the petrol stations. Hence, strategies for beneficial charging such as those outlined in (Zachary *et al.*

2023) can be considered. Due to the constraints of low wind speed in general, small wind turbine can be considered for additional renewable energy harvesting to supplement the potential drop in solar energy yield during cloudy or stormy days (Lim *et al.,* 2019).

Table 8: Return on investment and payback period of the systems

Stations	ROI for 90kW System	Payback Period for 90kW System (Year)
Shell Tapah NB	96.84%	1.03
Petron Behrang Layby SB	95.91%	1.04
Petronas Ulu Bernam SB	93.78%	1.07
Petronas Rawang NB	91.55%	1.09
Petronas Sg Buloh Layby SB	100.80%	0.99
Petron NKVE	98.64%	1.01
Caltex Elite USJ	88.67%	1.13
Petron Dengkil Elite SB	86.26%	1.16
Shell Dengkil Elite SB	95.01%	1.05
Petronas Damansara NKVE	103.84%	0.96

5.0 CONCLUSION

In a nutshell, 90% of the petrol stations considered in this study can meet the energy demand of EV charging as per the assumptions made. On the average, the simple payback period for the investment made to install solar PV system to power the charging of EVs is slightly more than one year for most of the petrol stations considered in this study. However, it must be acknowledged that the actual yield of solar energy is dependent on environmental factors such as partial shading due to buildings or trees, accumulation of dusts and dirt on the solar modules just to name a few. Moving forward, more petrol stations from the Northern and Southern regions will be studied to provide a more comprehensive overview of the feasibility of solar powered EV charging stations in Malaysia. ■

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PROFILES

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UNVEILING THE GEOLOGICAL SIGNIFICANCE AND INDUSTRIAL APPLICATION OF LIMESTONE: A COMPREHENSIVE REVIEW

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Abstract

Limestone emerges as a fundamental component within sedimentary rock formations, which provides important information about previous geological eras and environmental circumstances. It retains fossils and remnants of extinct living forms because it mostly contains calcium carbonate. These deposits are used as traces of freshwater, marine, and terrestrial habitats from the past. Furthermore, variations in the creation of limestone provide hints about past geological events like tectonic activity and sea level shifts. Scientists can reconstruct previous ecosystems, temperatures, and evolutionary patterns by analysing limestone, which helps us better comprehend Earth's environmental dynamics and history over millions of years. Its versatility extends beyond its geological significance, and its primary uses are in the manufacturing of steel and cement, as well as in the purification of wastewater and the processes involved in the production of bread and sugar. Limestone is also essential for supporting the carbon cycle and improving soil health in agricultural settings. In the review paper, we endeavoured to conduct additional research to comprehend the intricacies of geology and the industrial application of limestone, as well as the need for interdisciplinary collaboration, sustainable practices, and cutting-edge technologies to leverage mineral resources for industrial growth. To be effective, it is essential. This study concludes with a strong call to action, imploring stakeholders to emphasize sustainable practices and encourage interdisciplinary collaboration while using limestone. By adhering to these guidelines, we can maximise the benefits of this priceless natural resource for both industrial use and environmental sustainability while also protecting it for future generations.

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1.0 INTRODUCTION

Limestone, a common sedimentary rock primarily made of calcium carbonate ($CaCO_3$), plays a significant role in geological stories and industrial environments. Its industrial value, combined with its geological significance, highlights its importance as a key component influencing the history of our planet and current attempts (Tanijaya, Tappi and Jabair, 2021). From a geological perspective, limestone is a living reminder of the Earth's turbulent past, having withstood aeons of environmental shifts and geological processes (Lisci, Pires and Sitzia, 2022). Its development provides essential insights into previous habitats, temperatures, and biological evolution (Lawan Muhammad, 2018). It is anchored in the build-up and lithification of marine sediments rich in calcium carbonate. Limestone becomes a tangible repository that preserves fossilised remains and geochemical traces that shed light on the complexities of Earth's history when seen through the lens of paleoenvironmental reconstruction (IUGS, 2022). At the same time, limestone is used in a wide range of industries and uses far beyond its geological roots (Ridha *et al.,* 2013). Limestone is essential to many human undertakings, ranging from building and cement production to agriculture and environmental restoration. Its adaptability as a raw material for soil amendment, road construction, concrete, and lime manufacturing highlights its vital significance in contemporary society (Hwidi, Tengku Izhar and Mohd Saad, 2018). The sustainable management of limestone resources and the reduction of related impacts are shaped by the intersection of environmental considerations, economic issues, and technical developments (Bliss, Hayes and Greta Orris, 2012). This paper aims to clarify the complex interactions between limestone's geological significance and its numerous industrial uses, highlighting the material's role in furthering scientific knowledge, stimulating economic progress, and fostering environmental sustainability.

1.1 Geological Formation of Limestone

Limestones are rocks that contain more than 50% carbonate minerals, at least 50% of which are aragonite or calcite. The colours of limestone range from white to grey to dark grey to yellow, green, blue, and occasionally even black (Silva *et al.,* 2022). A mixture of clayey material, glauconite, or finely dispersed ferrous compounds causes a greenish tint, while the presence of ferric iron causes a reddish or brownish coloration (Müller, 2021). Compared to fine-grained limestones, which are typically indicative of deeper, potentially decreasing circumstances during early diagenesis, coarse-grained limestones typically exhibit lighter colours, which are linked with well-oxidised environments. Magnesium carbonates, dolomite, silica, glauconite, gypsum, fluorite, siderite, sulphides, iron and manganese oxides, phosphates, clays, and organic materials are among the several impurities found in limestone (Rajendran and Nasir, 2014).

A calcareous sandstone, shale, etc. is defined as having a $CaCO_3$ content of slightly less than 50%. Differential weathering frequently occurs in its carbonate portion, giving it the appearance of limestone (Bakhshipouri *et al.,* 2009). Insoluble quartz grains and other materials are typically inconspicuous and readily released during weathering processes. Certain calcareous eolianites that contain less than 30% $CaCO_3$ go on to form karst landforms and other limestone characteristics. The majority of sedimentary carbonate rocks are the result of deposition in marine environments, with paralia and autogeosynclines serving as the main repository in neritic settings. Although it is not as common as that of banks, platforms, and shelves, calcium carbonate can also build up in deep water and in coral atoll structures encircled by an abyssal zone (Fairbridge *et al.,* 1961). Modern seas contain large amounts of calcium carbonate in its dissolved state, but certain requirements must be satisfied for the mineral to precipitate as a solid (Silva *et al.,* 2022). The primary biological process used to precipitate calcite from seawater is shown in Figure 1.

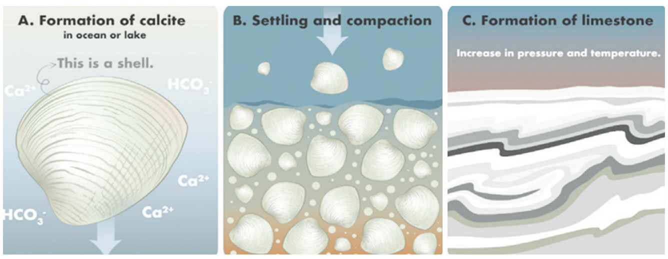

Figure 1: The process by which limestone (a rock) and calcite (a mineral with the formula $CaCO_3$) are formed Image credit: Rock Archive (Kärt and Ichiko, 2021)

Calcite is used by a variety of marine creatures to form their shells and skeletons, which, when they die, fall to the seafloor, where they are buried and compacted into sedimentary rock (Hwidi, Tengku Izhar and Mohd Saad, 2018). The bone pieces and grains may never make it to the seafloor, though, as calcite dissolves readily (Ziveri *et al.,* 2023). Furthermore, the environments in which those marine species live regulate the deposition of limestone in particular geographical areas. Because limestone formation is restricted, its presence or absence in the geologic record provides information about the climate and geographic circumstances of the era.

2.0 IMPORTANCE OF STUDYING LIMESTONE'S GEOLOGICAL SIGNIFICANCE

It is crucial to comprehend the geological significance of limestone because of its complex relationships to Earth's past, present, and future. First of all, the geological profile of limestone offers priceless insights into the evolution of Earth over time by providing pictures of previous habitats, temperatures, and ecological systems (Peters *et al.,* 2022). Through the analysis of limestone formations' composition, texture, and fossil content, scientists are able to piece together the history of past ecosystems and landscapes, revealing the complex interactions between biological evolution and geological processes (Bykova *et al.,* 2017). Furthermore, the development of industrial minerals depends heavily on the geological features of limestone. Limestone is a widely available and abundant commodity that is used as a basic raw material in many different industries, such as manufacturing, agriculture, and building (Lyubomirskiy *et al.,* 2020). Basically, limestone has had geological importance since the past, and studying the geological origins of limestone provides insights into its role in the earth's systems as well as its effects on industrial processes and human communities. Here, we express its relevance in numerous aspects.

2.1 Paleoenvironmental Reconstruction

Limestone is an amazing archive that has a plethora of knowledge on historical climates, ecosystems, and habitats. The fossilised remnants found in limestone can reveal significant facts on biodiversity patterns, evolutionary processes, and extinct living forms (Ayyat *et al.,* 2021). Through the examination of the sedimentary features and geochemical indicators of limestone formations, researchers are able to piece together historical topographies, monitor variations in sea level, and interpret climate patterns spanning millions of years (Rohling *et al.,* 2022).

2.2 Global Carbon Cycle

Over geological time scales, limestone has a significant impact on atmospheric carbon dioxide concentrations and climate dynamics (Oelkers and Cole, 2023). Limestone functions as a carbon sink by absorbing carbon from the atmosphere and storing it in the lithosphere of the earth through the process of carbonate sedimentation (DePaolo, 2015). Knowledge of the weathering, diagenesis, and carbonate deposition processes in limestone formations helps with climate modelling and sheds light on the flows of carbon between Earth's surface (Rohling *et al.,* 2022). To form their calcium carbonate skeletons, calcareous creatures in marine habitats, including corals, molluscs, and foraminifera, draw dissolved carbon dioxide from the water. These species die, leaving behind carbonate-rich remnants that build up on the seafloor and lithify to produce limestone deposits. Through geological time spans, this mechanism deposits carbon in the Earth's lithosphere, sequestering it from the atmosphere. Figure 2 shows the role of limestone in the carbon cycle (Wallmann and Aloisi, 2012).

Limestone contributes to the global carbon cycle in two ways: first, through carbonate sedimentation, it acts as a sink for carbon dioxide, and second, through weathering and dissolution processes, it produces carbon dioxide.

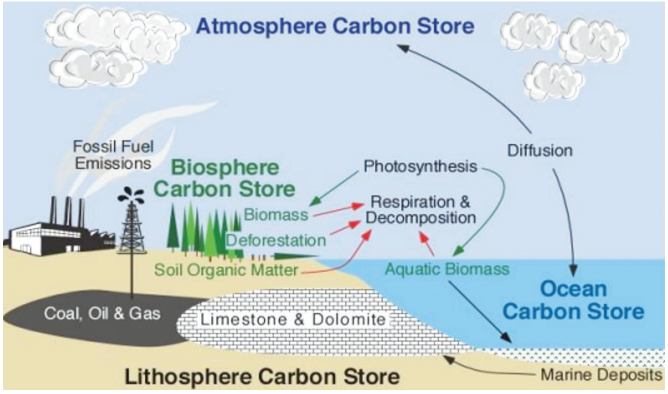

Figure 2: Illustrates the importance of limestone in the carbon cycle

2.3 Topography of Limestone

The physical characteristics of the earth's surface, such as its relief, slope, and height, are referred to as topography. Topography is important in shaping the general characteristics of landforms and influencing different geological and environmental processes in limestone settings. The special morphology of limestone that separates it from other rocks is karst landscapes; because limestone dissolves in water, karst landscapes are created (Zabidi and Freitas, 2006). Surface elements like sinkholes, caverns, and underground drainage networks distinguish these types of landscapes. Because carbon dioxide makes rainwater slightly acidic, it dissolves limestone rock over time, forming subsurface channels and caverns (Veress, 2023). Sinkholes may emerge on the surface due to the collapse of these expanding cavities because of the breakdown of limestone along joints and cracks; caves are also frequently found in limestone locations. The distinctive topography of karst environments is further enhanced by the complex web of underground drainage networks (Stokes, Griffiths and Ramsey, 2010). The limestone formation is affected by erosion, and with time, it forms diverse landscapes, as shown in Figure 2 (Baker, 2015).

3.0 PROCEDURES INVOLVED IN LIMESTONE DEPOSIT FORMATION

The creation of limestone deposits includes an intricate combination of physical, chemical, and biological processes occurring over huge geological time frames (Adenan, Ali and Mohamed, 2017). These activities led to the collection and crystallisation of calcium carbonate-rich minerals, which eventually gave rise to the varied limestone formations visible today (Ehrenberg and Baek, 2019).

3.1 Chemical Precipitation

The action of chemical precipitation is one of the main processes causing limestone deposition (Akinnawo, 2021). When bicarbonate ions (HCO_3^-) from the dissolution of carbonate minerals and the carbon dioxide (CO_2) equilibrium interact with dissolved calcium ions (Ca_2^+), calcium carbonate precipitates from seawater in marine environments. These residues build up on the seafloor over time, creating layers of calcium carbonate sediment that lithify into limestone rocks (Li *et al.,* 2023).

$$Ca_2^{+} + 2HCO_3^{-} \rightleftharpoons CaCO_3 + H_2O + CO_2 \qquad \text{Equation (1)}$$

Calcium ions + Bicarbonate ions⇌ Calcium carbonate (limestone) + Water + Carbon dioxide

This formula depicts the chemical precipitation process that takes place in marine environments when bicarbonate ions (HCO_3^-) and calcium ions (Ca_2^+) react to form calcium carbonate ($CaCO_3$), water (H_2O), and carbon dioxide (CO_2). Over time, the calcium carbonate that precipitates from saltwater builds up on the seafloor and helps to form limestone rocks.

3.2 Biological Accumulation

Biological activity is very important for developing limestone in areas where reefs are formed. Calcium carbonate is extracted from seawater by marine creatures, including corals, microorganisms, and shell-forming mollusks, to build their skeletal systems (Neumann, 1997). Following death, the buildup of these calcium carbonate-rich remnants aids in the creation of biogenic limestone, or limestone reefs and sedimentary strata (Rogers, 2004).

3.3 Lithification

This process turns loose sedimentary particles into cohesive rock formations after calcium carbonate deposits are deposited (Zalzal, 2016). The calcium carbonate sediments undergo compaction and cementation under the pressure of the overlaying sediments and the slow ejection of pore fluids, which consolidates the limestone rocks (Norman, 2015). To give limestone rocks their strength, durability, and resistance to corrosion and weathering (Moftah *et al.,* 2022). The lithification process is an essential part of their production and maintenance. The process of lithification is the final stage of geological processes that turn loose calcium carbonate deposits into cohesive limestone rocks (Al-ramadan, 2006). Coastal processes, such as compaction, cementation, and diagenetic modification, turn sedimentary deposits into durable geological features that shape the terrain and preserve the chronicles of Earth's past (Léonide *et al.,* 2014).

3.4 Diagenetic Alteration

The composition and texture of limestone deposits can be further altered by diagenetic processes such as recrystallisation, cementation, and dolomitisation (Ganai, Rashid and Romshoo, 2018). Larger crystals are formed, and the original sedimentary textures are destroyed through the process of recrystallisation, which is the dissolution and reprecipitation of calcium carbonate minerals (Haywick, 2004). Secondary minerals like silica or calcite precipitate to fill pore spaces and bind sedimentary particles together, causing cementation. Dolomitisation is the process by which dolomite minerals, which are rich in magnesium, replace calcium carbonate to form dolomitic limestone (Memon *et al.,* 2023).

4.0 FACTORS INFLUENCING LIMESTONE DEPOSITION AND LITHIFICATION

The conditions under which limestone deposits aggregate and solidify into rock formations are shaped by a confluence of geological, environmental, and biological processes that impact limestone deposition and lithification (Fenton and Scott, 1932). The following are some of the major variables affecting the lithification and deposition of limestone:

4.1 Geological Environment and Its Impact on Limestone Formation

The conditions under which limestone deposits aggregate and solidify into rock formations are shaped by a confluence of geological, environmental, and biological processes that impact limestone deposition and lithification (Fenton and Scott 1932). The accessibility and geographical distribution of calcium carbonate sediments, which provide the groundwork for limestone deposition in a variety of habitats, are significantly influenced by the geological background (Zhang *et al.,* 2022). First, for limestone production, marine environments, especially coral reefs, and shallow tropical seas, are ideal because shallow tropical seas are ideal for the growth and preservation of creatures that produce calcium carbonate because they have high temperatures, plenty of sunshine, and relatively little input of terrestrial silt (Rohmann, Oceanic and Oceanic, 2014). Calcareous algae, corals, and other creatures that form reefs flourish in these conditions, actively participating in the bio-mineralisation processes that produce calcium carbonate deposits (Bergman *et al.,* 2020). The seabed is exposed to sunlight due to its shallow, clear waters, which allows photosynthetic organisms to grow and use dissolved carbon dioxide for photosynthesis, precipitating calcium carbonate (Paxton *et al.,* 2023).

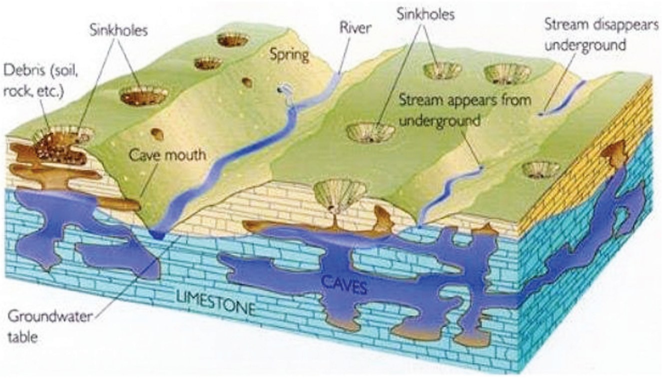

Figure 3: The topography of the karst formed by the formation of limestone

These sediments eventually undergo lithification, which is the process that creates limestone rocks. The second environment is coral reefs. Due to the rapid growth of reef-building corals and related calcareous species, coral reefs, one of the planet's most biodiverse ecosystems, represent hotspots of limestone deposition (Lucey, Haskett and Collin, 2021). Coral reefs are made up of aragonite or calcite calcium carbonate skeletons secreted by corals, which are members of the species Cnidaria (Blakeway, 2018). A wide variety of marine species, such as algae, sponges, and molluscs, find a home and substrate in the complex three-dimensional structure of coral reefs (Hallock, 1997). These organisms' skeletal growth and calcification processes aid in the formation of calcium carbonate sediments (Pastore *et al.,* 2022). Coral reef ecosystems' geological record is preserved through the gradual build-up of coral debris, skeletal components, and biogenic sediments into limestone formations. The stratigraphic distribution is shown in Figure 3 (Wu *et al.,* 2023).

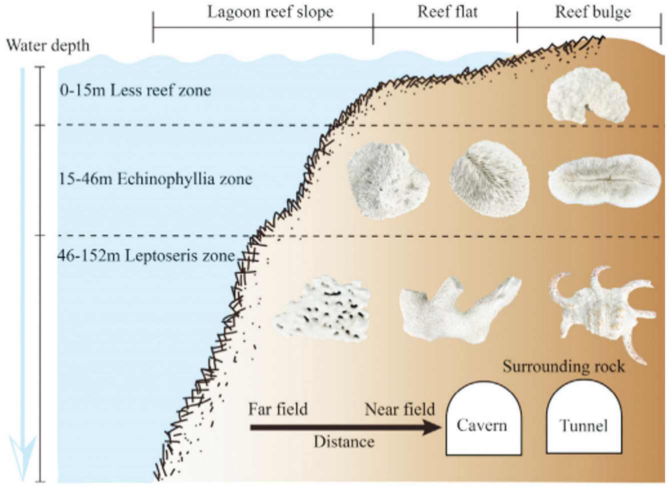

Figure 4: Coral reef of limestone strata schematic diagram

4.2 Weathering and Climate and Its Impact on Limestone Deposition

Limestone alters shape due to weathering and Climate effects and gets damaged over time (Kambakhsh *et al.,* 2024). Pollutants from the atmosphere are gathered by atmospheric water, and surface moisture permits them to enter the stone's pores and accelerate natural processes (Emmanuel and Levenson, 2014). Acidification by contaminating bacteria can be very damaging, especially for limestone. Some human-made substances, such as acids, can have destructive effects on natural stones, and they undergo physical, chemical and biological wear and weathering (Matsubara, 2021). Temperature, precipitation, and humidity all have a significant impact on the chemical weathering and erosion processes that lead to limestone deposition (Hajna, Hajna and Gabrovsek, 2002). The availability and movement of calcium carbonate sediments are shaped by the interaction of weathering dynamics and climate, which eventually affects the formation of limestone (Caserini, Storni and Grosso, 2022).

Warm and humid climates speed up the processes of chemical weathering, which encourages the disintegration of the calcium carbonate minerals found in carbonate rocks (Storage, 2014). The breakdown of carbonate minerals into soluble ions, such as calcium ions (Ca_2^+) and bicarbonate ions (HCO_3^-), shown in equation 2, is accelerated by high temperatures and copious amounts of rainfall (NOAA, 2016). These dissolved ions are carried to downstream ecosystems, such as lakes, rivers, and coastal seas, via surface runoff, groundwater flow, and river discharge. There, they participate in chemical precipitation that leads to limestone deposition. Furthermore, humidity promotes the availability of moisture for chemical reactions, which improves the release of carbonate ions into the aqueous environment and the dissolution of carbonate minerals (Change, 2022).

$$\mathrm{CaCO_3 + H_2O + CO_2 \rightarrow Ca_2{}^{+} + 2HCO_3{}^{-}} \qquad \text{(Equation 2)}$$

Calcium carbonate + Water+ Carbon dioxide →
Calcium ions + Bicarbonate ions

The above formula (Equation 2) represents the chemical reaction that occurs when calcium carbonate ($CaCO_3$) dissolves in water (H_2O) and carbon dioxide (CO_2), forming soluble bicarbonate ions (HCO_3^-) and calcium ions (Ca_2^+) in an aqueous solution.

4.3 Biological Function and Its Impact on Limestone Deposition

In particular, in marine habitats where carbonate-producing creatures are plentiful, biological factors such as the diversity and quantity of organisms that secrete calcium carbonate play a crucial role in the deposition of limestone (Change, 2022). Reef-forming microbes' carbonate-rich sediments are created by the abundant production of calcium carbonate skeletons and shells by marine creatures like corals, foraminifera, and shell-forming molluscs. Colony corals, in particular, build coral reefs by secreting skeletons of calcite or aragonite, which act as a framework for depositing carbonate deposits. Foraminiferal ooze is a fine-grained mud primarily made of calcium carbonate produced by single-celled creatures called foraminifera with shells made of calcium carbonate. In a similar vein, molluscs that make shells, such as gastropods, cephalopods, and bivalves, secrete calcium carbonate shells that build up on the bottom and aid in the creation of biogenic limestone deposits (Ashley *et al.,* 2014). Because of the number of organisms that produce calcium carbonate and their optimal conditions for chemical precipitation, marine environments, typified by shallow tropical seas, coral reefs, and high biological productivity, serve as the principal locations for limestone formation. Climate dynamics, encompassing temperature, precipitation, and humidity, are essential for fostering chemical weathering processes that facilitate limestone deposition in terrestrial and aquatic habitats by releasing and transporting carbonate ions (Antonelli *et al.,* 2018). Calcareous species produce calcium carbonate skeletons and shells, which eventually accumulate as carbonate-rich sediments. Biological factors, including calcareous organisms' diversity and quantity, also enhance limestone deposition (East, 2020). Earth's history and the dynamic interactions between geology, climate, and biology by considering the interplay between these factors and the complex processes that govern limestone formation and evolution across diverse geological settings.

5.0 CLASSIFICATION OF LIMESTONE BASED ON ORIGIN AND COMPOSITION

Limestone is a type of sedimentary rock classified under carbonate rocks. In a broader sense, it refers to rocks where the carbonate content exceeds the non-carbonate content. A carbonate rock is classified as limestone when the predominant minerals in the carbonate fraction are calcium carbonates ($CaCO_3$) such as calcite or aragonite (Moosavi, 2022). On the other hand, it is termed dolomite when the primary mineral is magnesium carbon ($MgCO_3$) (Brief, 2014). Limestone formations are prevalent in geological records from the Archaean era, approximately 2500 million years ago, to the present day. They exhibit a diverse range of origins, which can be broadly categorised into biological and detrital sources.

i. **Biological Origins:** Limestones of natural origin are largely formed of calcium carbonate generated from the skeletal remains of marine organisms such as corals, microorganisms, and shell-forming molluscs (Geologic Time and Earth's Biological History Table of Contents, 2005). Over geological periods, these species amass calcium carbonate through bio mineralisation processes, creating carbonate-rich strata. These collected sediments change into limestone rock formations through compaction and lithification, conserving the biological traces of former marine ecosystems. Limestone generated in situ by chemical precipitation is categorised as endogenetic. The direct precipitation of calcium carbonate minerals from the solution is the source of this limestone, which frequently occurs in coastal environments with high concentrations of dissolved calcium and carbonate ions (Hashim, 2022). Large-scale limestone deposits are created over time by the build-up of precipitated calcium carbonate, which reflects the chemical reactions that take place inside the Earth's crust (Kaczmarek and Fullmer, 2015).

ii. **Detrital Origin:** Detrital limestone is formed from sedimentary particles that have been mechanically moved and deposited, frequently due to wind, water, or ice erosion, transportation, and deposition processes. Detrital limestone sometimes referred to as exogenetic limestone, is usually composed of carbonate-bearing minerals or pieces of previously existent limestone rocks (Lucia, 1995). Limestone rocks are formed by the compaction and cementation of these fragments in depositional environments like river deltas, beaches, or shallow marine basins.

5.1 Classification of Limestone Based on Texture

Different textures found in limestone are a reflection of its geological past. Well-developed crystal structures found in crystalline limestone result from recrystallisation at high temperatures and pressures. Whereas fossiliferous limestone contains an abundance of fossil remains, clinker limestone is made up of fragments held together by secondary minerals, as shown in Figure 5a (Karim and Ismael, 2017). Round ooids are found in oolitic limestone, while fine-grained calcite crystals are seen in micritic limestone Figure 5b (Young and Edmundson, 1954). Calcite crystals protrude from the coarse crystalline textures of sparry limestone Figure 5c. Every texture offers insightful information on the environmental factors and processes involved in the formation of limestone (Pii and Casey, 1998).

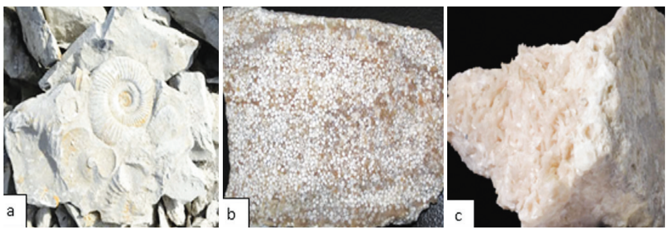

Figure 5 (a): fossiliferous limestone texture,
(b): micritic limestone, (c): crystalline limestone texture
Access online via https://geology.com

6.0 ROLE OF LIMESTONE IN INTERPRETING EARTH'S GEOLOGICAL HISTORY

To understand Earth's geological past through the lens of limestone, one must investigate the variety of forms, patterns of distribution, and distinctive features of limestone throughout various geological epochs (Geologic Time and Earth's Biological History Table of Contents, 2005). This thorough analysis covers several Earth scientific fields, such as sedimentology and stratigraphy. Scientists can reconstruct historical settings, interpret geological processes, and understand the intricate interactions between Earth's dynamic systems across millions to billions of years by combining data from several domains (Wallmann and Aloisi, 2012).

Table 1: An overview of limestone significance in understanding Earth's geological past

Aspect	Description	References
Stratigraphic Record	Limestone formations are useful stratigraphic markers that help with the dating and unit correlation of the rock units. Composite, textural, and fossil content analysis aids in the reconstruction of historical habitats and sedimentary processes.	(Adefris *et al.,* 2022)
Fossil Preservation	Limestone is a valuable resource for learning about historical ecosystems, biodiversity, and evolutionary patterns. Tracking the evolution of species and reconstructing past ecosystems are made easier by the fossils found in limestone rocks.	(Dunbar, 1960)
Paleoenvironmental	Climatic regimes and previous environmental conditions can be inferred from limestone deposits. Certain limestone textures are indicative of paleoenvironmental contexts, which help to deduce historical tectonic events and climate changes.	(Nagar and Town, 2018)
Reconstruction	Historical climatic variations, sea level shifts, and tectonic events by analysing sedimentary formations, geochemical traces, and paleontological data found in limestone rocks.	(Crawley, Holen and Chenoweth, 1985)
Diagenetic Processes	Numerous diagenetic processes affect the texture, porosity, and geochemical properties of limestone. Research on these processes aids in deriving historical chemical interactions and reconstructing the diagenetic history of limestone formations.	(Adenan, Ali and Mohamed, 2017)
Tectonic Significance	Structural characteristics such as folds, faults, and transformations serve as indications of previous mountain-building occurrences and the overall tectonic conditions of a region. The examination of structural geology assists in the reconstruction of previous plate borders, areas of collision, and cycles of mountain building.	(Oost and De Boer, 1994)

The table gives a thorough summary of the significance of limestone in diagenesis, stratigraphy, paleontology, paleo-environmental reconstruction, and tectonics for understanding Earth's geological history.

7.0 INDUSTRIAL APPLICATIONS OF LIMESTONE

Limestone is used in building, industry, and agriculture as a raw material, and its industrial relevance extends far beyond its geological significance. Its versatility in generating agricultural lime, cement, concrete, and lime supports several infrastructure projects and economic sectors across the globe (Amira *et al.,* 2020). For infrastructure planning, economic development, and sustainable resource management, it is crucial to comprehend the distribution and geological characteristics of limestone resources (Korneeva *et al.,* 2019). Beyond its geological significance, limestone is widely used in many sectors of the economy and is a fundamental component of industrial operations.

i. **Construction Industry**
Aggregates, asphalt, and concrete are all produced using limestone, a vital raw resource in the sector (Moftah *et al.,* 2022). Because of its strength, resilience, and adaptability, crushed limestone is used in structural applications, building foundations, and road construction (Malaysia Competition Commision, 2017). Limestone-based products are also prized for their aesthetic qualities, which makes them a top option for landscaping and architectural projects (de Abreu, 2018). Limestone in the cement industry consists of calcium carbonate and magnesium carbonate. The optimal composition of cement rock consists of 77-78% $CaCO_3$, 14% SiO_2, 2.5% Al_2CO_3, and 1.75% Fe_2O_3 (Lawan Muhammad, 2018).

ii. **Manufacturing Sector**
Limestone is utilised not just for cement manufacturing but also for its alkaline characteristics and ability to interact with water, rendering it appropriate for a variety of industrial applications as a crucial precursor in the creation of compounds, including calcium hydroxide, calcium carbonate, and calcium chloride (Shimelis *et al.,* 2022). Limestone is essential in environmental clean-up projects, including wastewater treatment and soil stabilisation, due to its capacity to neutralise acidic pollutants (Sabir *et al.,* 2023). Limestone is essential in metallurgical processes as a flux to remove impurities and improve the efficiency of metal purification methods (Andrew, 2018). Lime, which is made from limestone, is used in chemical production, environmental clean-up, and metallurgy (Panagoda *et al.,* 2023). Calcium carbonate is used in the paint industry as a cost-effective substitute for titanium dioxide, improving opacity and lowering production expenses (Sabir *et al.,* 2023). Similarly, in the paper business, calcium carbonate increases paper opacity, brightness, and printability, leading to increased product performance and reduced environmental impact (Ivaniciuc *et al.,* 2021). Additionally, calcium carbonate is a reinforcing material in

plastic manufacture, imparting stiffness, impact resistance, and dimensional stability to polymer composites.

iii. **Industry of Food Production**

Although limestone isn't used directly, its by-products, such as lime and calcium carbonate, are crucial to some parts of the manufacturing of sugar and bread (Shoira, 2006). In processing sugar cane or sugar beet juice, calcium carbonate, which is generated from limestone, is frequently employed as a clarifying agent (Egorova, Puzanova and Nikolaeva, 2021). Proteins, organic debris, and colloidal particles are among the contaminants found in the juice that is collected from sugar cane or sugar beets (Rayburn, Service and Agronomist, 2005). As a flocculant, calcium carbonate is added to the juice to help these contaminants precipitate and be easier to filter or sediment (Qiao *et al.,* 2016). In bread manufacture, Lime (calcium oxide) or calcium hydroxide is used in factory (Garcia-Vaquero *et al.,* 2023). This method adds slaked lime to dough formulations to improve dough handling properties and alter pH levels. Additionally, lime can improve the elasticity and strength of bread dough by promoting the creation of the gluten network (Fernandes *et al.,* 2022). It's crucial to remember that although these goods made from limestone are utilised at certain points in the creation of bread and sugar, they are only used in limited amounts and have auxiliary functions rather than being main elements.

iv. **Applications in Agriculture**

The main purpose of using large amounts of crushed limestone and hydrated lime in agriculture is to improve soil conditions (Rayburn, Service and Agronomist, 2005). Applying agricultural lime, which is made up of finely crushed limestone, to acidic soils lowers their pH, lessens the toxicity of aluminium, and increases the availability of nutrients for plant growth (Lime, 1924). Lime serves various purposes in this context, such as enhancing the texture of clay soils by increasing the granularity of heavy soil through the flocculation of colloidal matter, transforming insoluble potash minerals into a form that is suitable for plant nutrition, creating an environment where soil bacteria can convert vegetable matter into humus, and lowering the acidity of peaty soils (Jones and Mallarino, 2018). Ground limestone is frequently added as a filler in compound fertilisers to increase weight and inhibit caking. However, limestone is only utilised as a carrier when making calcium ammonium nitrate fertiliser. Additionally, grease and silica bricks are made from limestone, which helps raise crop yields and improve soil quality (Santos *et al.,* 2020).

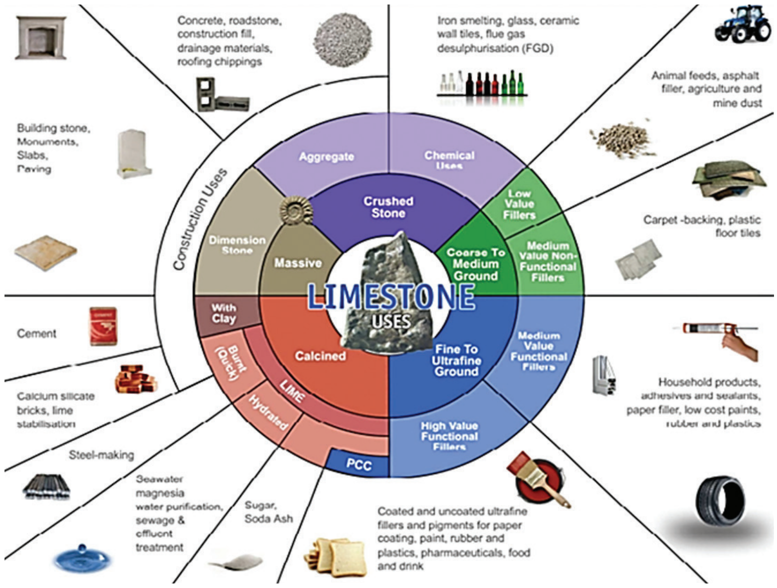

Figure 6: Representation of the various limestone applications in one picture

Limestone resources have economic worth that goes beyond their use in industry; they also support the growth of regional infrastructure and economies (Limestone coast economic diversification, 2012). Initiatives aimed at developing infrastructure, economic planning, and sustainable resource management all depend on an understanding of the distribution and geological characteristics of limestone deposits (Wilson and Amavilah, 2007). To promote industrial growth, construction projects, and economic competitiveness on a local and global level, access to plentiful and high-quality limestone sources is essential (Sindua and Kaihatu, 2022). The above discourse highlights the economic importance of limestone and its diverse industrial uses (Wilson and Amavilah, 2007).

Table 2: Summary of several industrial applications of limestone

Industrial Application	Description	References
Construction Materials	The utilisation of limestone aggregates in the manufacturing of concrete, asphalt, and mortar.	(Přikryl *et al.,* 2016)
Cement Production	One of the widely used cases of limestone is in the manufacture of cement, the importance of cement made from limestone in the construction sector is that it is very durable and resistant to erosion.	(Fauzi, Sidek and Ridzuan, 2020)
Steel Manufacturing	Using limestone as a fluxing agent in the production of steel Limestone's contribution to the purity and quality of steel product.	(Manocha and Ponchon, 2018)
Environmental Remediation	Limestone as a potential low-cost adsorbent for landfill leachate remediation; using limestone in flue gas desulfurization systems for cleaning contaminated water.	(Rosli *et al.,* 2020)
Agriculture	Using limestone in agriculture as a calcium supplement and soil amendment. The advantages of limestone for raising crop yields and soil fertility	(Bay, 2018)
Chemical and Industrial Processes	The use of limestone in the production of chemicals, pulp and paper, and refined sugar. Products made from limestone are used in a variety of industrial areas.	(Micheal and Chukwu, 2023)

The table above provides a concise overview of the wide range of industrial applications in which limestone is essential. Limestone is extremely versatile and can be used in a wide range of chemical and industrial processes, from creating cement and building materials to producing steel, environmental remediation, agriculture, and more. Its extensive use in many industries, which promotes infrastructure growth, environmental sustainability, agricultural production, and manufacturing efficiency, highlights its significance.

8.0 CONCLUSION

The present work has offered a thorough analysis of limestone, encompassing its wide range of industrial uses and geological significance. We highlighted the importance of limestone in Earth's past by talking about its creation processes, fossil content, and paleoenvironmental markers. We also examined its significance in several industrial areas, such as chemical processing, agriculture, environmental clean-up, steel manufacture, cement production, and building.

In geology, industry, and the environment, limestone is extremely important. In terms of geology, it is an essential part of sedimentary rock formations, providing information on historical climatic and environmental circumstances. Limestone is vital to manufacturing cement, steel, building materials, and other products. In terms of the environment, it supports soil health, carbon sequestration, and remediation initiatives, all promoting sustainability and ecosystem health.

Studies should concentrate on expanding our knowledge of the geological processes, fossil content, and environmental effects of limestone. Sustainable development, resource efficiency, and environmentally friendly technologies ought to be the top priorities for industrial operations to reduce environmental damage and encourage the ethical extraction and use of natural resources. We can ensure limestone's long-term sustainability and conservation while optimising its benefits by integrating geological knowledge with cutting-edge industrial practices.

9.0 KEY FINDINGS AND INSIGHTS

Limestone is a sedimentary rock that is a vital repository for Earth's historical records, including fossils and paleoenvironmental markers. Its creation mechanisms, including the deposit of the remnants of marine life and chemical precipitation, provide important climatic and environmental insights. Limestone has a wide range of industrial uses, including the production of cement, steel, building materials, environmental remediation, agriculture, and chemical processes.

Moreover, the geological characteristics of limestone serve as a fundamental basis for numerous industrial industries. Limestone, being a readily accessible and plentiful resource, plays a vital role as a fundamental element in the manufacturing, agriculture, and building sectors. The physical and chemical qualities of this substance are determined by its geological origins, making it crucial for uses such as cement manufacture and soil amendment. Comprehending the geological importance of limestone is crucial for managing resources sustainably and being responsible for the environment. This knowledge helps in making informed choices regarding its extraction, use, and influence on ecosystems. Through the examination of its geological origins, we gain knowledge about its functions within Earth's systems and its impact on industrial processes and human communities, highlighting its ongoing significance in various domains of science and society.

In summary, limestone's diverse economic uses and rich geological history highlight its ongoing importance for Earth sciences and human advancement. We can take advantage of limestone's potential to further scientific understanding, boost economic expansion, and encourage environmental stewardship for future generations by acknowledging and sensibly utilising its significance. ■

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