Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

Carbonate Rock Evaluation: Petrographic Insights and Geotechnical Implications for Construction Industries in the Salt Range Region, Pakistan

Muhammad IBRAHIM[1], Muhammad HAMZA[1], Ihtisham ISLAM[2*], Abdul Rahim ASIF[3], Sajjad AHMAD[1], Babar HASSAN[1], Muhammad SHAN[1], George KONTAKIOTIS[4], Hammad Tariq JANJUHAH[2], Ilias LAZOS[5] and Assimina ANTONARAKOU[4]

Authors' affiliations and addresses:
[1] Department of Geology, University of Peshawar, Peshawar, 25120, Pakistan
e-mail: mhamza0578@gmail.com
e-mail: ibro20522@gmail.com
e-mail: dr.s_ahmed@uop.edu.pk
e-mail: Babarhassan12334@gmail.com
e-mail: Shan19muhammad@gmail.com

[2] Department of Geology, Shaheed Benazir Bhutto University, Upper Dir, KP, Sheringal 18050, Pakistan
e-mail: ihtisham.islam@sbbu.edu.pk
e-mail: hammadtariq013@gmail.com

[3] National Centre of Excellence in Geology, University of Peshawar, Peshawar 25120, Pakistan
e-mail: abdulrahimasif@yahoo.com

[4] Department of Historical Geology-Palaeontology, Faculty of Geology and Geoenvironment, School of Earth Sciences, National and Kapodistrian University of Athens, Panepistimiopolis, Zografou, 15784, Greece
e-mail: gkontak@geol.uoa.gr
e-mail: aantonar@geol.uoa.gr

[5] School of Mineral Resource Engineering, Technical University of Crete, 73100 Chania, Greece
e-mail: ilazos@tuc.gr

***Correspondence:**
Ihtisham Islam, Department of Geology, Shaheed Benazir Bhutto University, Upper Dir, KP, Sheringal 18050, Pakistan
tel.: +923435215277
e-mail: ihtisham.islam@sbbu.edu.pk

Acknowledgement:
The authors would like to acknowledge the National Centre of Excellence in Geology, University of Peshawar (Pakistan) for providing laboratory facilities.

How to cite this article:
Ibrahim, M., Hamza, M., Islam, I., Asif, A.R, Ahmad, S., Hassan, B., Shan, M., Kontakiotis, G., Janjuhah, H.T., Lazos, I and Antonarakou, A. (2024). Carbonate Rock Evaluation: Petrographic Insights and Geotechnical Implications for Construction Industries in the Salt Range Region, Pakistan. *Acta Montanica Slovaca*, Volume 29 (4), 1001-1015

DOI:
https://doi.org/10.46544/AMS.v29i4.18

Abstract

The China-Pakistan Economic Corridor (CPEC) has spurred a massive construction drive in Pakistan, necessitating the exploration of diverse natural aggregate sources to sustain this development. Therefore, this study delves into the petrographic characteristics and mechanical properties of carbonate rocks from the Chichali Gorge (Lockhart and Nammal Formations) and Zaluch Gorge (Amb Formation) in the Western Salt Range, Pakistan. Employing geotechnical analyses adhering to British Standards (BS) and American Society for Testing and Materials (ASTM) standards, various laboratory analyses were conducted. Simple regression analysis unveiled interrelationships among physical parameters. Petrographic scrutiny categorized Lockhart (LF_{Pal}) and Nammal (NF_{Eo}) Formations as wackestone and Amb Formation (AF_{Pm}) as mudstones. Calcite and bioclasts emerged as primary components, shaping the limestones. Petrographic insights elucidated the rocks' engineering traits, establishing correlations between petrography and diverse physical and mechanical properties. Notably, Unconfined Compressive Strength (UCS) and Unconfined Tensile Strength (UTS) exhibited direct associations with calcite content but inverse correlations with porosity and bioclasts. Rocks with higher porosity and water absorption displayed diminished strength, while those with lower porosity exhibited robust strength metrics. Based on these analyses, LF_{Pal} and NF_{Eo} emerged as pivotal sources for small- and large-scale projects, including CPEC. However, due to their elevated silica content, caution is advised concerning AFPm aggregates. This study provides valuable insights for construction endeavors, ensuring informed material selection for optimal project outcomes in the CPEC framework.

Keywords

China-Pakistan Economic Corridor; Carbonate rocks; Petrography; Geotechnical analysis; Construction materials; Geological characteristics; Infrastructure development; CPEC projects

Introduction

Aggregates play a vital role in reinforcing composite materials, reducing shrinkage, and ensuring cost efficiency. Given that aggregates can constitute up to 70% of a concrete mixture's volume, it is essential to scrutinize their chemical, physical, mechanical, and mineralogical properties. These factors significantly impact the concrete's quality and durability (Neville and Brooks, 1999). Consequently, aggregates sourced from natural sites like gravel pits, riverbeds, and rocks must possess the ability to withstand abrasion, disintegration, and crushing (Umar and Wamuziri, 2016; Mamlouk and Zaniewski, 2018; Asif et al., 2022).

Aggregate degradation leads to reduced particle angularity, altered surface texture, and decreased size, thereby lowering shear strength and aggregate grade. Aggregate degradation (AD) is a key factor in the failure mechanism of aggregate materials and can often be predicted from rock strength. Moreover, the suitability of rocks for construction purposes relies heavily on their mineralogical composition. The Uniaxial Compressive Strength (UCS) of rock aggregate shows an inverse relationship with its mineral components, including bioclasts, cement, and texture, as highlighted in the study by Asif et al. (2022) and Kamran et al., 2022. Additionally, the modal mineral composition and grain size significantly impact rocks' physical and mechanical properties, as evidenced by the research conducted on Early Eocene Sakesar Limestone by Akram et al., 2017.

The petrographic characteristics of source rock and subsequent processes, such as hydrothermal activity, faulting, weathering, and folding, have a significant impact on the physicomechanical and durability characteristics of crushed rock aggregate (El-Aal et al., 2021; Zhou et al., 2021). Mineral constituents, hardness, chemical stability, porosity, and composition all impact these qualities. During the petrographic examination of aggregates, constituents such as mineralogy, bioclasts, matrix type, micro-fractures, and texture determine the aggregate quality (Naeem et al., 2014; Hamdi et al., 2015; Petrounias et al., 2018; Sun et al., 2021).

In addition to the influence of mineralogical composition and physicomechanical properties on aggregate quality, it is crucial to consider other factors related to concrete, such as Alkali-Aggregate Reaction (AAR). AAR encompasses both Alkali-Silica Reaction (ASR) and Alkali-Carbonate Reaction (ACR). Failure to take adequate measures against AAR can lead to detrimental effects on the strength, performance, and durability of concretes (Akhnoukh and Buckhalter, 2021). ASR and ACR result from the reaction between alkalis and specific reactive mineral components like strained SiO_2 and $CaMg(CO_3)_2$, respectively (Sanchez et al., 2014). Previously regarded as chemically inert, certain aggregates were later found to be reactive, forming strong bonds at the aggregate and mixture peripheral levels (Shetty and Jain, 2019). In combination with chemical analyses, petrographic investigations play a vital role in distinguishing between reactive and non-reactive minerals. These studies also enable the analysis of reaction rims, silicate gels, micro/macro-structural behaviors, and the carbonation process within structural concrete (Singh et al., 2007; Ransinchung et al., 2008; Andriani, 2021).

Pakistan possesses abundant limestone aggregates, which are crucial for construction (Arshad and Qiu, 2012; Almajed et al., 2021). Various parts of Khyber Pakhtunkhwa have been studied for their physical, mechanical, thermal, and chemical properties, which are vital for construction industries (Bilqees et al., 2012, 2015; Rehman et al., 2020; Hassan et al., 2020; Asif et al., 2021). Identifying new, accessible, and cost-effective aggregate reserves is imperative, especially in regions like the Western Salt Ranges, Pakistan. The CPEC is a huge bilateral initiative to build infrastructure in Pakistan to improve trade with China and further integrate the regional countries. The CPEC-related projects include but are not limited to, the development of roads, bridges, and tunnels (Pakistan Ministry of Planning Report, 2017). Furthermore, the CPEC project's prospects imply major building operations that will necessitate a large number of aggregate deposits, particularly limestone. The limestone-rich Western Salt Range, depicted in Fig. 1, holds the potential to meet this demand. Considering the study area's significance, our research delves into detailed petrographic and geotechnical analyses of limestone from the Western Salt Range. We have specifically explored the carbonate rocks of Chichali Gorge (Lockhart and Nammal Formations) and Zaluch Gorge (Amb Formation) in the Western Salt Range, Pakistan. Beyond assessing its suitability for concrete aggregate, our study also aims to uncover relationships between physico-mechanical properties and petrographic attributes in these limestone sources.

Geology of the Study Area

The Late Permian Amb Formation (AF_{Pm}), Paleocene Lockhart Formation (LF_{Pal}), and Eocene Nammal Formation (NF_{Eo}) were chosen for the important engineering evaluation.

The location of key stratigraphic sections was selected using the Geological Survey of Pakistan toposheet number 36 P/14. The Zaluch Gorge (Longitude 32°47′00″- 32°47′2″ N and Latitude 71°38′50″- 71°38′51″ E). AF_{Pm} has a thickness of 47-88 meters (m) and was distinguished by sandstone, limestone, and shale. The sandy limestone is yellowish to grey and medium to thick-bedded. The sandstone is brownish-grey in color, medium-grained, calcareous, and thick-bedded (Shah, 1977).

The Chichali Gorge is located in Trans Indus Ranges, Mianwali District (Pakistan) and occurs in the survey of Pakistan topographic sheet No 38 P/5 (Lat.32°59'36"N and Long.71°24'14"E). LF_{Pal} contains grey to light grey, medium-bedded, nodular limestone with trace quantities of grey marl and dark bluish grey, calcareous shale that may be found in the Salt Range and Trans-Indus Ranges (Shah, 1977). The NF_{Eo} is comprised of argillaceous limestone, marl, and shale overall. The limestone and marl are light grey-bluish grey, while the shale is grey-olive green in color.

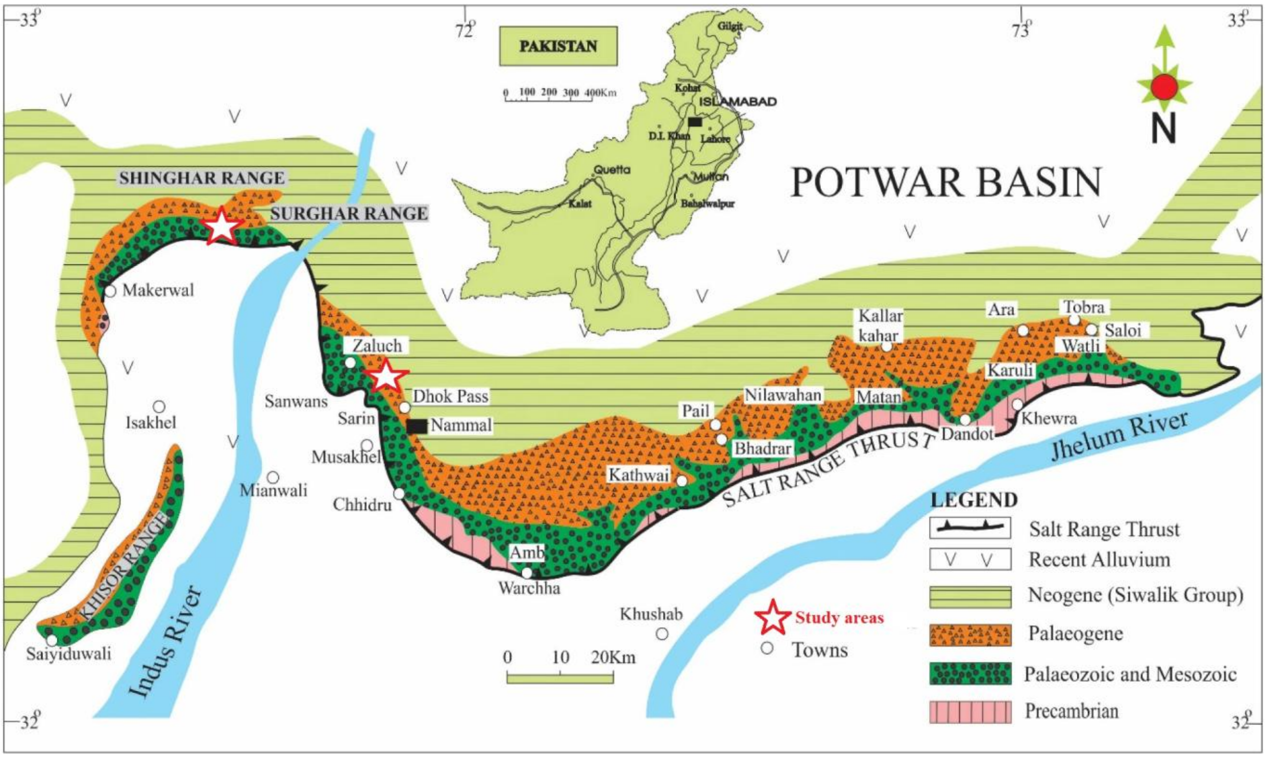

Fig. 1: Geological map showing the location of the study area in Chichali and Zaluch Gorge Western Salt Range Pakistan (modified after Jan et al., 2016).

Materials and Methods

A comprehensive field expedition was organized in the Western Salt Ranges to gather field data, procure appropriate bulk, and grab rock samples for subsequent laboratory analysis. Additionally, detailed observations of outcrops and macroscopic characteristics, including texture, thickness, and color, were meticulously documented during the fieldwork.

For detailed petrographic and physico-mechanical investigations, bulk samples (minimum $1ft^3$ with a weight of about 10–15 kg) were collected from the outcrops of AF_{Pm}, NF_{Eo}, and LF_{Pal} in Zaluch and Chichali Gorge, respectively, in the Potwar Basin. These samples were then carried to the Geotechnical Laboratory at the National Center of Excellence in Geology (NCEG), University of Peshawar, for coring and crushing of the samples. For each sample, a core with a length-to-diameter ratio (L/D) of 2.0-2.5 having a diameter of not less than 50 mm was used (ASTM D-4543-19). Six cores were extracted from each bulk sample, and then the remaining samples were crushed for geotechnical tests performed except for the Alkali carbonate reaction (ACR), which was done at Pakistan Council of Scientific and Industrial Research (PCSIR) Lab Peshawar while petrographic analysis was carried out at Department of Geology, University of Peshawar. The aggregate samples were carefully selected to meet specific size requirements outlined by ASTM standards. These sizes were obtained after processing the crushed aggregate to ensure compliance with the prescribed specifications.

Petrography

For the detailed petrographic analysis, 12 thin sections (4 from each bulk sample) were prepared. Petrographic features such as mineralogy and texture were observed using a polarized light microscope (Model Olympus BX51). Correlations between petrographic and various physical and strength properties were established.

Alkali carbonate reaction (ACR)

ACR is a chemical reaction in either concrete or mortar between hydroxyl ions (OH-) of the alkalis (sodium and potassium) from cement (or other sources) and certain carbonate rocks, particularly calcitic dolostone and dolomitic limestones, present in some aggregates. For the ACR reaction (Gillot and Swenson, 1969), the underlying process Eq. (1) is used.

$$\mathrm{CaMg(CO_3)_2 + 2NaOH \rightarrow CaCO_3 + Na_2CO_3 + Mg(OH)_2}. \tag{1}$$

The reaction is commonly accompanied by dedolomitization and expansion of the affected aggregate particles, resulting in abnormal expansion and cracking of concrete. This procedure can swiftly determine whether or not a certain carbonate rock (limestone, dolostone, or calcitic-argillaceous-dolostone) is suitable to use as concrete aggregate by measuring its alkaline reactivity. A possible ACR could be detrimental to concrete durability if the expansion rate exhibited by a sample is higher than 0.10% (Mansour et al., 2023).

Geotechnical Analysis

All engineering examinations adhered to the established global standards outlined by the American Society for Testing and Materials (ASTM) as well as the British standards (BS). The process involved drilling bulk samples to acquire cores destined for mechanical testing, while the remaining bulk samples were crushed into aggregate size for aggregate testing purposes. The analysis performed, the respective methods, and the testing conditions are described in Tab. 1:

Tab. 1. Geotechnical tests according to ASTM and BS standards

S No.	Number of tests performed	Standards followed	Number of samples tested
1	Soundness Test	ASTM C 88	3 bulk samples (one from each formation)
2	Los Angeles Abrasion Value	ASTM C 131	3 bulk samples (one from each formation)
3	Aggregate Impact Value	BS 812–112	3 bulk samples (one from each formation)
4	Unconfined Compressive Strength	ASTM D 2938-95	6 cores (2 from each bulk sample)
5	Unconfined Tensile Strength	ASTM D 3967	6 cores (2 from each bulk sample)
6	Specific Gravity and Water Absorption	ASTM C 127	3 bulk samples (one from each formation)
7	Bulk Density/Unit Weight Determination	ASTM C 29/C 29	3 bulk samples (one from each formation)
8	Point Load Test (Is50)	ASTM D 5731	6 cores (2 from each bulk sample)
9	Alkali Carbonate Reaction	ASTM C 1260	3 samples (one from each formation)

Results and Discussion

Petrographic evaluation:

Thin sections were prepared for the detailed petrographic examination of limestone from the AF_{Pm}, LF_{Pal}, and NF_{Eo}. It also explains the engineering properties of rocks and the relationship between petrography and different physical and mechanical properties.

The limestone of AF_{Pm} is sandy, brownish grey, medium-bedded, and richly fossiliferous with massive productus (*brachiopod*). According to Dunham's classification scheme (1962) of limestone, AF_{Pm} is classified as mudstone. The calcite content dominates and ranges from 30-40%, with an average of 34%. The bioclasts in the formation are fusulinids and brachiopod spine ranging from 15-25% with an average of 28%. Silica content is high, ranging from 28-30% with an average of 29%, while dolomite ranges from 6-10% with an average of 9% (Tab. 2). The presence of stylolites suggested that the rocks had been chemically compacted, possibly due to prior overburden or tectonic stresses.

Tab. 2. Petrographic analysis of the studied samples from Amb, Nammal, and Lockhart Formations.

Thin sections	Calcite (%)	Silica (%)	Dolomite (%)	Bioclasts (%)	Fractures/veins	Dunham classification
$\mathrm{AF_{Pm}}$ 1	35	30	10	15	Fracture	Mudstone
$\mathrm{AF_{Pm}}$ 2	30	30	10	20	Fracture/stylolites	Mudstone
$\mathrm{AF_{Pm}}$ 3	40	28	6	25	---	Mudstone
$\mathrm{AF_{Pm}}$ 4	30	29	10	25	Fracture	Mudstone
Mean	34	29	9	28		
$\mathrm{LF_{Pal}}$ 1	80	3	7	10	---	Mudstone
$\mathrm{LF_{Pal}}$ 2	70	2	6	20	---	Wacke-Mudstone
$\mathrm{LF_{Pal}}$ 3	70	3	7	20	Fracture/vein	Wackestone
$\mathrm{LF_{Pal}}$ 4	70	4	4	23	---	Wackestone
Mean	73	3	7	18		
$\mathrm{NF_{Eo}}$ 1	55	5	10	25	Fracture	Wackestone
$\mathrm{NF_{Eo}}$ 2	70	2	5	23	---	Wackestone
$\mathrm{NF_{Eo}}$ 3	70	2	5	25	Fracture	Wackestone
$\mathrm{NF_{Eo}}$ 4	70	1	4	27	---	Wackestone
Mean	66	3	6	25		

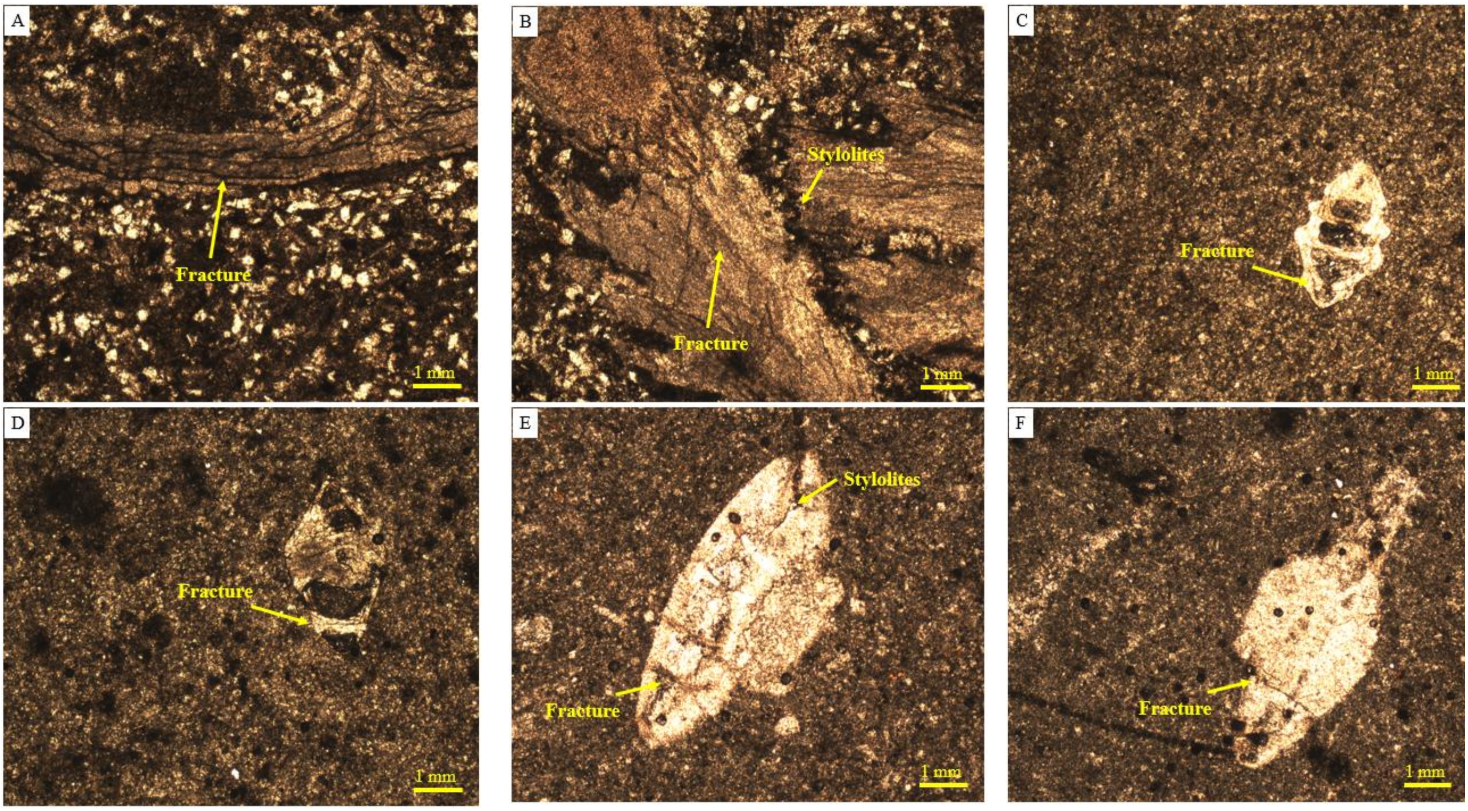

Fig. 2: Photomicrographs of the studied limestones. ***A-B*** *Amb Formation ($\mathrm{AF_{Pm}}$),* ***C-D*** *Lockhart Formation ($\mathrm{LF_{Pal}}$) and E-F Nammal Formation ($\mathrm{NF_{Eo}}$).* ***A*** *fractured brachiopod spine.* ***B*** *Stylolites.* ***C*** *larger benthic Foram (fracture).* ***D*** *Assilina Missila (also having fracture).* ***E & F*** *Assilina Numulite (having stylolites and fractures)*

In the Study area, the $\mathrm{LF_{Pal}}$ is grey to light grey, medium-bedded, nodular limestone. The $\mathrm{LF_{Pal}}$ has abundant foraminifers, corals, mollusks, echinoids, and algae. According to Dunham's scheme (1962), the formation is characterized by wackestone depositional texture. The calcite abundance ranges from 70-80%, averaging 73%. The bioclast content of the formation is from 10-23% with an average of 18%, which are larger benthic foraminifera (*Discocyclina, Miscellanea miscella*) and planktonic foraminifera. Silica and dolomite are present with the mean values of 3 and 7, respectively. Fractures and calcite-filled fractures are seen in thin sections.

In the study area, the NF_{Eo} is composed of shale, marl, and argillaceous limestone. The lower part tends to be shaly and marly, while the upper part is limestone-dominated. The formation contains forams and mollusks. According to Dunham's classification (1962), the studied NF_{Eo} is referred to as wackestone. The calcite ranges from 55-70%, averaging 66%. The bioclasts, ranging from 23-27% with an average of 25%, encompass planktonic foraminifera, larger benthic foraminifera (*Assilina, Ranikothalia, Discocyclina, and nummulites*), echinoderm spine and brachiopod. Silica and dolomite are present with the mean values of 3 and 6, respectively. Further, diagenetically, it is characterized by neomorphic alteration.

Alkali Carbonate Reaction (ASTM C-586)

The studied limestones having expansions <0.1% (Table 3), revealing an innocuous nature, suggest that the studied samples may be free of ACR and are within the allowed range according to the ASTM C-586. The current study is consistent with the findings of Anjum et al., 2018, Naeem et al., 2019, Ullah et al., 2020, and Asif et al., 2022, who found that the deleterious minerals in cement concrete are regarded as harmless with ACR threshold values of 0.10%.

Physicomechanical evaluation

The physical and mechanical properties of the limestone aggregate from the AF_{Pm}, LF_{Pal}, and NF_{Eo} are briefly discussed in this section.

Sulphate Soundness Test (ASTM C 88)

The soundness test aims to assess the extent of disintegration and deterioration experienced by geological materials under various weathering conditions (AASHTO, 2009). It is essential for aggregate materials to demonstrate resistance against degradation caused by factors such as thermal fluctuations, freeze-thaw cycles, and the presence of salt minerals within particle pores. Utilizing geological materials prone to weathering effects as aggregates is discouraged to mitigate the risk of structural failure under field conditions. Soundness values for the analyzed samples of AF_{Pm} is 8.8%, while for LF_{Pal} and NF_{Eo} samples are 2.1% and 2.3% (Tab. 3). The results reveal that the studied rocks have enough resistance to freezing and thawing effects and are well within the range of permissible limits, i.e., 16% (ASTM-C 88–13).

Los Angeles Abrasion Value/Test (ASTM C 131)

LAAV measures the wearing capacity or strength of a rock owing to the rubbing action of steel balls with aggregates, results in powdering, and the resistance to wear and impact is computed. This resistance of aggregate to abrasion is key when used in structures like concrete pavements and roads that constantly remain under heavy load. The abrasion value for AF_{Pm} is 44.7%, which is not within the allowed limit, i.e., 40% (ASTM), while for the samples of LF_{Pal} and $NF_{Eo,}$ 20.5% and 23.3% lie within the permissible limit (Tab. 3).

Tab. 3. Geotechnical analysis of Amb, Lockhart, and Nammal formations with their mean values

Geotechnical tests	Amb Formation (AF_{Pm})	Lockhart Formation (LF_{Pal})	Nammal Formation (NF_{Eo})
	Mean		
Soundness (%)	8.8	2.1	2.3
Loss Angeles Abrasion Value (%)	44.7	20.5	23.3
Aggregate Impact Value (%)	33.4	15.1	16.4
Unconfined Compressive Strength (MPa)	29.2	39	34
Unconfined Tensile Strength (MPa)	5.05	7.95	6.05
Specific Gravity (g/cm^3)	2.61	2.64	2.62
Water absorption (%)	0.33	0.10	0.16
Unit Weight/Bulk Density (g/cm^3)	2.49	2.55	2.54
Point Load (Is50)	5.65	8.07	7.75

Aggregate Porosity (%)	0.85	0.28	0.42
Alkali Carbonate Reaction (%)	Expansion < 0.1% indicating innocuous nature	Expansion < 0.1% indicating innocuous nature	Expansion < 0.1% indicating innocuous nature

Aggregate Impact Value (BS 812–112)

Aggregate impact values assess the ability of aggregates to withstand sudden loads and stress. Aggregates with lower strength may undergo degradation when exposed to abrupt impact loads. The proficiency of the source material serves as a critical indicator of aggregates possessing robust strength and durability. The impact value for the AF_{Pm} is 33.4% (Tab, 3), while for LF_{Pal} and NF_{Eo} are 15.1 and 16.4, respectively. Moreover, the aggregate impact values of LF_{Pal} and NF_{Eo} were well within the permissible range limits, i.e., <30% according to BS 812-112.

Unconfined Compressive (ASTM D 2938) and Tensile Strength (ASTM D 3967)

Unconfined Compressive Strength (UCS) is a crucial mechanical property used to quantify the maximum compressive stress a material can withstand under unconfined conditions. It is determined by subjecting a cylindrical or cubical specimen to axial loading until failure. UCS is a fundamental parameter in geotechnical and civil engineering, providing insights into the rock load-bearing capacity and its response to applied stress without lateral confinement. The measured UCS values for AF_{Pm} are 29; for LF_{Pal}, the UCS value is 39; and for the NF_{Eo} sample, the UCS value is 34 (Tab. 3). All these samples can be categorized as moderately strong according to Anon, 1977, moderately strong according to Anon, 1979, moderate strength according to Anon, 1981 and low to medium-strong rocks according to ISRM, 2007 (Table 4).

Unconfined Tensile Strength (UTS) is a material property that signifies the maximum tensile stress a material can endure before failure. Unlike compressive strength, which measures resistance to compression, UTS assesses a material's ability to withstand stretching or pulling forces. This parameter is crucial in structural and materials engineering, guiding the design and selection of materials for applications where tensile forces are a significant consideration. The UTS value is determined by subjecting a specimen to axial loading until it fractures due to tensile stress. UTS is the measure of the tensile strength by applying a vertical load to develop tension across the diameter of a rock disc being subjected to compression. UTS values for AF_{Pm}, LF_{Pal}, and NF_{Eo} are 5.05, 7.95, and 6.05 respectively.

Tab. 4. Grades of unconfined compressive strength (Geological Society Engineering Group Working Party 1977; Commission of Engineering Geological Mapping of the IAEG; ISRM Commission on the Classification of Rocks and Rock Masses 1981; ISRM 2007)

Geological Society (Anon,1977**)**		**IAEG (**Anon,1979**)**		**ISRM (**Anon, 1981**)**		**ISRM (2007)**	
Term	Strength (MPa)	Term	Strength (MPa)	Term	Strength (MPa)	Term	Strength (MPa)
Very weak	< 1.25	Weak	< 15	Very low	< 6	Very High	>250
Weak	1.25-5	Moderately strong	15-50	Low	10-20	High	100-250
Moderately weak	5-12.50	Strong	50-120	Moderate	20-60	Medium	50-100
Moderately strong	12.50-50	Very strong	120-130	High	60-200	Low	25-50
Strong	50-100	Extremely strong	> 130	Very high	> 200	Weak	5-25
Very strong	100-200					Very weak	1-5
Extremely strong	> 200					Extremely weak	0.25-1

Specific gravity, water absorption, and aggregate porosity (ASTM C 127)

Specific gravity is a fundamental property that quantifies the density of a material relative to the density of water. In the context of aggregates, it provides valuable information about the overall mass and volume relationship. Specific gravity is calculated by dividing the mass of a given aggregate volume by the mass of an equal volume of water. This property is crucial in assessing the quality of aggregates, as it can indicate the presence of lightweight or porous materials that may affect the overall performance of concrete or construction applications. The mean specific gravity of the studied samples from AF_{Pm} is 2.610, for LF_{Pal}, it is 2.64, and for NF_{Eo}, it is 2.62 (Tab. 3). Rocks with a specific gravity of 2.55 or higher are deemed suitable for robust construction projects, according to standards like Blyth and de Freitas, (1974) and ASTM C127-15. Therefore, all the samples analyzed in this study meet the criteria for construction purposes.

Water absorption is a measure of the amount of water that an aggregate can absorb under specific conditions. It is expressed as a percentage of the aggregate's weight and is determined by immersing the aggregate in water and measuring the change in weight over time. Water absorption is a critical parameter in evaluating the durability of aggregates, as excessive water absorption can lead to issues such as freeze-thaw damage, reduced strength, and increased susceptibility to chemical reactions. Low water absorption is generally desirable in high-quality aggregates for construction. Rocks with high absorption values tend to have elevated porosities, making them unsuitable for heavy construction purposes. In the case of the tested samples, AF_{Pm} has a mean absorption value of 0.33, LF_{Pal} has a mean value of 0.10, and NF_{Eo} has a mean absorption value of 0.16 (Tab. 3). However, all these values fall within the permissible range (<2%) for using these rocks as dimension stones and engineering materials.

Aggregate porosity refers to the volume percentage of void spaces or pores within the aggregate structure. These voids can be interconnected or closed, influencing the overall permeability and durability of the material. Porosity is a key factor in understanding the internal structure of aggregates, and it can affect properties such as strength, durability, and resistance to environmental factors. High porosity may indicate a higher susceptibility to moisture-related issues, making it an essential consideration in assessing aggregate quality for various construction applications. Porosity is characterized by the ratio of the volume of voids to the entire bulk volume of the rock. A rock's durability is influenced by its porosity. For instance, fine-grained rocks are more resilient than coarse-grained rocks (Bell, 2007). A rock's shape, size, and mineral arrangement are the key factors of its porosity (Peng and Meng, 2002). The average porosity value for AF_{Pm} is 0.85; for $LF_{Pal,}$ it is 0.28; and for NF_{Eo}, it is 0.42 (Tab. 3).

Bulk Density/Unit Weight (ASTM C 29/C 29)

Bulk density, also known as unit weight, is a fundamental property used to quantify the mass of a material per unit volume. In the context of aggregates or soils, it is a crucial parameter that provides insights into the compactness and overall mass distribution within a given volume. The bulk density is calculated by dividing the mass of the material by its corresponding volume, including both solid and void spaces.

Bulk density is a key consideration for various applications in construction and geotechnical engineering. It influences the design of structures, the stability of slopes, and the performance of materials in construction. High bulk density often indicates a more compact and dense material, while low bulk density may suggest increased porosity or void spaces.

Bulk density is commonly determined by measuring the mass of a known material volume, including solid and void spaces. This property is essential in evaluating the suitability of materials for different engineering purposes and guiding decisions related to compaction, settlement, and overall structural integrity. The unit weight of aggregate used in concrete normally ranges from 1.20 to 1.75 g cm^{-3} (ASTM C29/C29M-17), and the unit weight of the investigated samples exceeds the allowed limit for use as an engineering material (Tab. 3)

Point Load Test (Is50) (ASTM D 5731)

In a point load test, Is50 refers to the Point Load Strength Index at a 50 mm core diameter. It measures the load per unit width required to break a rock sample of specific dimensions. This index is crucial for assessing rock strength and its suitability for various engineering applications, such as construction and mining. In this index test, a rock specimen is subjected to an increasingly concentrated force until failure occurs by splitting the specimen. Coaxial, truncated conical platens are used to apply the concentrated load. The failure load determines the point load strength index and estimates the uniaxial compressive strength. The measured values of PLT for AF_{Pm}, LF_{Pal}, and NF_{Eo} are 5.65, 8.07, and 7.75 MPa, respectively (Tab. 3), which makes those rocks strong, according to the strength classification of rocks by Selby, 1980.

Comparison of AF_{Pm}, LF_{Pal}, and NF_{Eo} with other limestones.

The studied limestone deposits of Pakistan are extensively used as a prime source of lime in various industries like cement, paint, fertilizers, steel, glass, etc., as aggregate and dimension stone in the construction industry, owing to their supreme quality limestone. A comparative account of the various physical properties of the various well-known limestone deposits of Pakistan and the limestone of AF_{Pm}, LF_{Pal}, and NF_{Eo} are summarized in Tab. 5. This comparison shows that the studied limestone units of the Western Salt Range are appropriate for use in various industries and as an aggregate source in the construction sector, except for the AF_{Pm}, as these aggregates should be used with extra caution due to high silica content, LAAV, soundness, and porosity values.

Regression Analysis

Influence of petrographic characteristics on engineering properties

The data about physicomechanical aspects and petrography were plotted into a regression analysis to examine the interconnections between the petrographic and engineering features (Figs. 3, 4). According to Ramsay, 1974, and Lees & Kennedy, 1975, petrographic characteristics and microstructure influence aggregate characteristics, and rock's petrographic and textural features control its mechanical characteristics. Therefore, the effects of the petrographic contents on engineering properties are very important for the suitability of aggregate sources. The objective of the regression analysis is to minimize the squared deviations of measured points from the fitted line, which was calculated via the points. Calculations were also made to determine the fitted lines' equations and coefficients of determination (R^2). Regression models explain most of the variability in y when (R^2) is close to 1. The model is considered significant as long as the p-value is less than 0.05 (Brett, 2004).

Figures 3 and 4 (a-c) present correlations between the studied limestones' petrographic properties, specifically calcite and bioclast concentration, as well as the strength properties (UCS and UTS). Notably, a strong linear relationship was observed between the concentration of calcite and the strength characteristics (UCS, UTS, and PLT) of the analyzed limestones, with R^2 values of 0.86, 0.73, and 0.99, respectively. Conversely, a significant inverse relationship ($p \leq 0.05$) was identified between bioclast content and the strength properties (UCS, UTS, and PLT) of the limestones, with R^2 values of 0.64, 0.48, and 0.65, respectively. These findings align with similar results reported by researchers such as Naeem et al. (2014), Asif et al. (2022), Kamran et al. (2022), and Hussain et al. (2022). Comparative studies by Naeem et al. (2014) on Margalla Hill Limestone (ML) and Lockhart limestone (LL) in the Rumli region of Islamabad, Pakistan, and by Asif et al. (2022) on Eocene carbonates for engineering structures, corroborate the observed correlations. Additionally, research by Kamran et al. (2022) and Zada et al. (2023) exploring similar correlations for aggregates yielded comparable and significant results. It is noteworthy that, in contrast to our current study, previous investigations reported a positive relationship between UCS and calcite as well as PLT and calcite contents. They also noted an inverse relationship between UCS and bioclasts and porosity.

Our analysis has established statistically significant models for the correlations between UCS and petrographic content, as well as PLT and petrographic content, supported by p-values lower than 0.05. These findings contribute valuable insights into the relationship between the mineral composition of limestones and their mechanical properties, enhancing our understanding of their engineering applications.

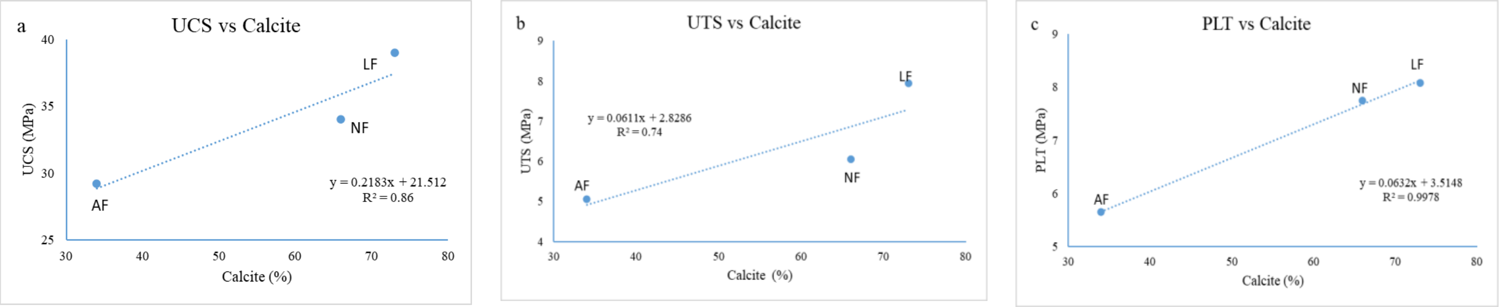

Fig. 3: a-c showing the correlation of calcite with strength properties (UCS, UTS, and PLT)

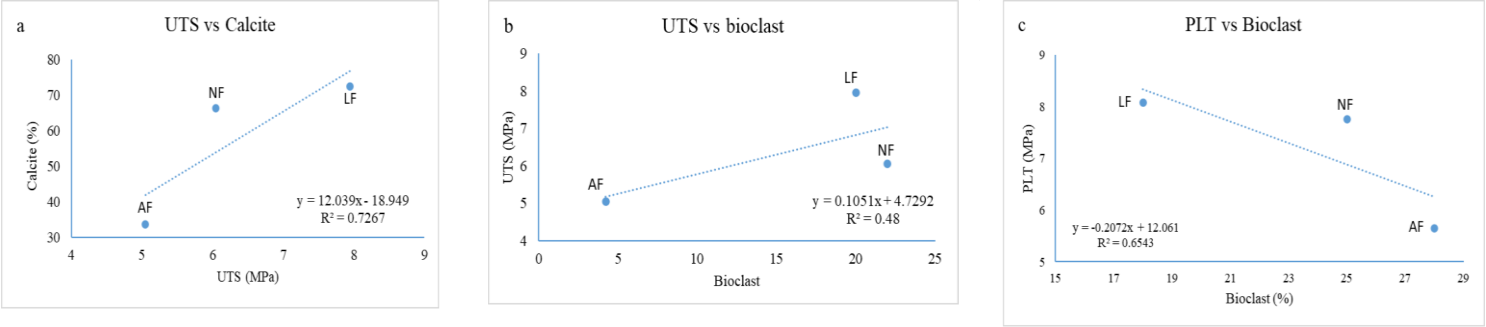

Fig. 4: a-c showing the correlation of bioclast content with strength properties (UCS, UTS, and PLT)

Correlation among engineering properties

Strength properties of rocks, such as uniaxial compressive strength (UCS) and tensile strength, are crucial factors in determining their utility in engineering applications. Generally, a positive correlation exists between UCS and tensile strength in most engineering materials, indicating that higher compressive strength is often associated with higher tensile strength (Farmer, 1983). However, in the case of rock cores, although a positive trend exists, the correlation between UCS and tensile strength is relatively weak due to the inherent strength disparity between compression and tension in rocks. Rocks exhibit significantly higher strength under compression than tension, resulting in lower tensile strength values. Nevertheless, this positive correlation suggests a relationship between these strengths, albeit a weak one, as illustrated in Fig. 5a, which aligns with similar findings by Sadeghi et al. (2022), Asif et al. (2022), and Yasir et al. (2022).

Furthermore, the relationship between UCS and the point load test (PLT) results is generally positive. The PLT assesses a rock sample's ability to withstand applied load without breaking, providing insights into its strength characteristics. While not a direct measure of compressive strength, PLT results often positively correlate with UCS values for various rock types, indicating that rocks with higher UCS tend to have higher point load strength index values, as shown in Fig. 5b, in line with studies conducted by Kamran et al. (2022) and Yusof et al. (2023).

Additionally, the correlation between UCS and water absorption (WA), as well as porosity in rocks, is negative. High water absorption and porosity imply more void spaces and lower mechanical strength, while rocks with lower water absorption and porosity typically exhibit higher UCS. This inverse relationship is highlighted in Fig. 5c and d and is supported by research by Asif et al. (2022), Yasir et al. (2022), and Kamran et al. (2022). Moreover, a positive correlation exists between UCS and bulk density, indicating that denser rocks with higher intermolecular bonds often exhibit higher UCS, as depicted in Fig. 5e, supported by studies like Mishra & Basu (2013) and Aziz and Hussein (2021).

Furthermore, a positive correlation exists between UCS and specific gravity in rocks. Rocks with higher specific gravity typically have denser structures and stronger intermolecular bonds, leading to higher UCS values. This positive relationship is illustrated in Fig. 5f and agrees with the findings by Kamran et al. (2022).

Regarding the Los Angeles Abrasion Value (LAAV), there is a negative correlation with UCS. A lower LAAV, indicating higher abrasion resistance, often corresponds to higher UCS, reflecting better durability. This inverse relationship is depicted in Fig. 5g, supported by studies from Kamani and Ajalloeian (2019), Köken (2022), and Kamran et al. (2022).

Additionally, the correlation between LAAV and Impact Value (IV) is negative, meaning aggregates with high resistance to abrasion tend to have high resistance to impact and vice versa. This relationship, shown in Fig. 5h, is corroborated by research from Kamani and Ajalloeian (2019) and Ismail and Abdulwahid (2021). Furthermore, LAAV negatively correlates with soundness, indicating that aggregates with lower LAAV are more likely to maintain their integrity over time, demonstrating better soundness, as shown in Fig. 5i, supported by Sarfraz et al. (2021).

Lastly, the relationship between soundness and porosity is positive, indicating that materials with lower soundness are often more porous, allowing for moisture intrusion, potentially leading to disintegration over time, as seen in Fig. 5j, in line with findings by Abdelhedi et al. (2020) and Kamani & Ajalloeian (2017). These correlations highlight the complex interplay of various factors in determining the mechanical and durability properties of rocks and construction materials.

Tab. 5. Comparison of different limestones with the studied limestones

Geotechnical properties	**This Study**			Asif *et al.*, 2022		Rehman *et al.* (2020)		Naeem *et al.* (2014)					Ullah *et al.* (2020)	Sarfraz *et al.* (2021)		Anjum *et al.* (2018)
	$\mathrm{AF_{Pm}}$	$\mathrm{LF_{Pal}}$	$\mathrm{NF_{Eo}}$	SF	KF	SSF	KW	MH	KW	LT	SH	SM	WL	MF	ML	KL
Soundness (%)	8.8	2.1	2.3	1.98	1.8	1.88	2.14	–	–	–	–	–	1.007	0.77	0.77	2.54
Los Angeles abrasion value (%)	44.7	205	23.3	22.9	19.96	27.1	20.86	23.93–25.12	14.93–15.85	23.88–24.38	14.08–16.53	14.81–16.92	23.37	25.12	16.93	26.65
Aggregate impact value (%)	33.4	15.1	16.4	14.8	14.48	14.09	14.89	15.36–16.01	11.40–12.71	13.70–15.37	11.80–14.90	11.38–12.08	16.8	20.75	22.03	–
Aggregate crushing value (%)				22.4	19.55	12.84	13.26	–	–	–	–	–	13.1	19.57	19.95	–
Unit weight/Bulk density (g cm^{-3})	2.49	2.55	2.54	1.53	1.51	2.16	2.07	-	–	–	–	–	1.67	-	-	–
Clay lumps and friable particles (%)				0.50	0.37	–	–	-	–	–	–	–	–	–	–	–
Unconfined compressive strength	29.2	39	34	99.35	69.31	–	–	–	–	–	–	–	–	–	–	19.86–39.08
Unconfined tensile strength (MPa)	5.05	7.95	6.05	6	5.8	–	–	–	–	–	–	–	–	–	–	–
Flakiness index				12	15.5	9.97	11.56	13.27–15.78	17.65–19.26	16.15–19.01	12.17–15.23	17.96–19.01	6.5	-	-	16.2–19.0
Elongation index				13	12	12.56	12.07	11.07–13.11	14.23–16.42	10.07–12.20	27.12–28.86	27.01–25.20	7.1	-	-	20.5–25.2
Water absorption (%)	0.33	0.10	0.16	0.72	0.64	0.81	0.89	0.94–1.61	0.60–0.69	0.98–1.36	0.25–0.58	0.38–1.04	0.48	0.65	0.68	0.68
Specific gravity (gcm^{-3})	2.61	2.64	2.62	2.70	2.71	2.68	2.73	2.60–2.63	2.72–2.77	2.70–2.78	2.60–2.64	2.61–2.66	2.7	2.76	2.63	2.72
Aggregate porosity (%)	0.85	0.28	0.42	2.43	2.43	–	–	2.31–2.98	1.76–2.12	2.33–2.69	1.14–1.44	1.04–1.41	–	–	–	–

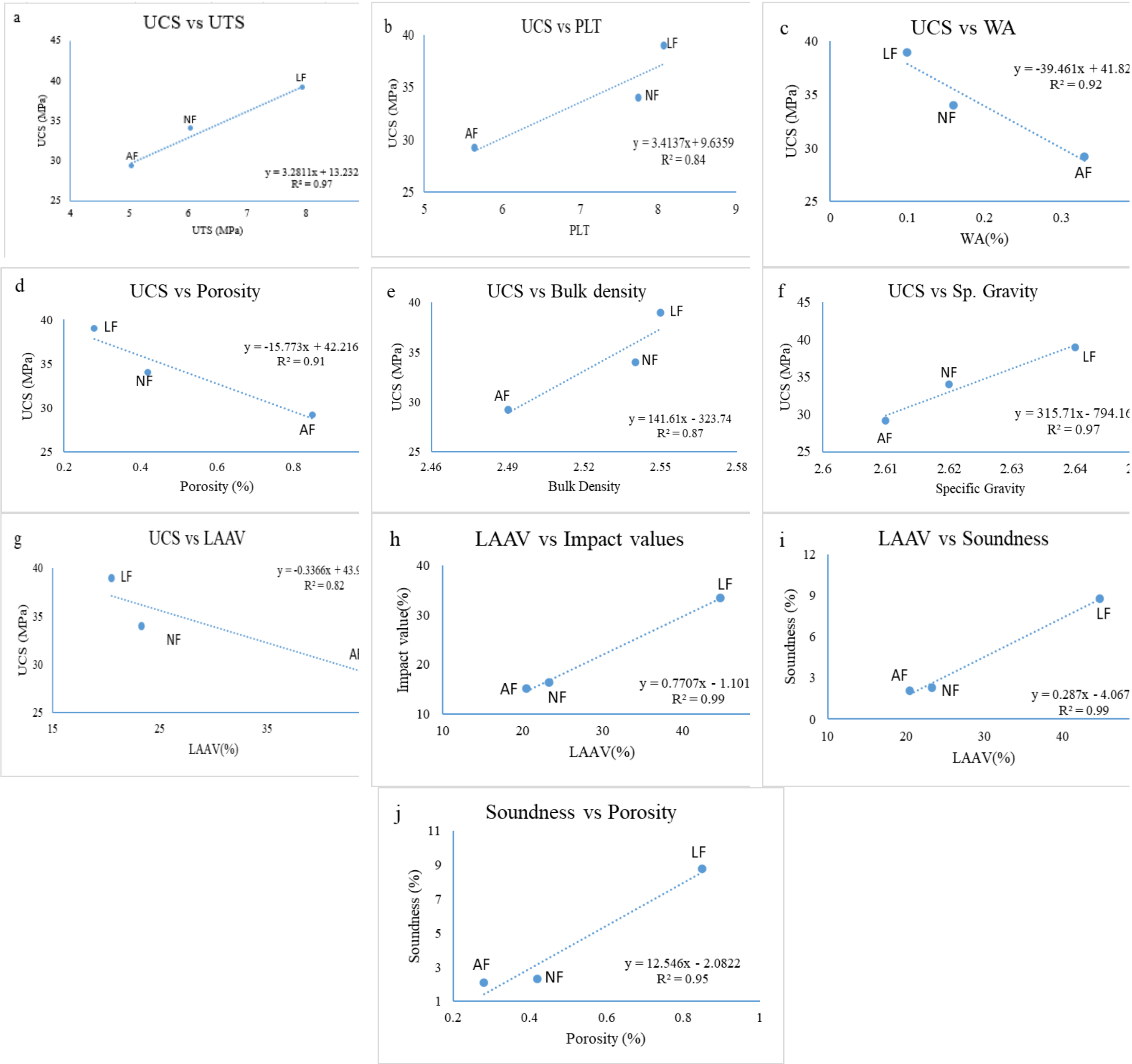

Fig. 5: a-j showing the correlation among the physicomechanical properties

Conclusions

The petrographic and geotechnical investigations of limestone from the Nammal (NF_{Eo}), Lockhart (LF_{Pal}), and Amb (AF_{Pm}) Formations underscore their potential as a valuable construction aggregate source. The rocks, classified primarily as mudstone and wackestone, exhibit favorable engineering properties, with Nammal and Lockhart limestone meeting international standards for various physicomechanical tests. The Amb Formation, while containing a higher percentage of quartz, poses some limitations due to elevated values in parameters like LAAV and Impact values. The correlation between petrographic attributes and strength properties reveals a direct association between calcite content and strength, inversely related to porosity and water absorption. Overall, Nammal and Lockhart limestone emerge as promising materials for road construction, concrete, and engineering applications, offering significant potential for contributing to the country's economic development, particularly in the context of projects under the China-Pakistan Economic Corridor (CPEC).

References

Abdelhedi, M., Jabbar, R., Mnif, T., & Abbes, C. (2020). Ultrasonic velocity as a tool for geotechnical parameters prediction within carbonate rocks aggregates. *Arabian Journal of Geosciences*, 13, 1-11.

Akhnoukh, A. K., & Buckhalter, C. (2021). Ultra-high-performance concrete: Constituents, mechanical properties, applications and current challenges. *Case Studies in Construction Materials*, 15, e00559.

Akram, M. S., Farooq, S., Naeem, M., & Ghazi, S. (2017). Prediction of mechanical behaviour from mineralogical composition of Sakesar limestone, Central Salt Range, Pakistan. *Bulletin of Engineering Geology and the Environment*, 76, 601-615.

Almajed, A., Aldhowian, A., & Abdelrahman, K. (2021). Geological and geotechnical evaluation of limestone rocks along the Riyadh Metro Project (Riyadh City, Saudi Arabia). *Arabian Journal of Geosciences*, 14, 1-15.

Andriani, G. F. (2021). Comment on "Petrographic features influencing basic geotechnical parameters of carbonate soft rocks from Apulia (southern Italy)" [Eng. Geol. 233: 76–97]. *Engineering Geology*, 285, 106053.

Anjum, M. N., Ali, N., Rehman, Z. U., Ghayas, M., & Ahmad, W. (2018). Rock aggregate potential of the limestone units in the Khyber Formation, Khyber Ranges, Pakistan. *International Journal of Economic and Environmental Geology*, 9(4).

Anon, O.H. (1977) The Description of Rock Masses for Engineering Purposes. Engineering Group Working Party Report. *Quaternary Journal of Engineering Geology*, 10, 43-52.

Anon, O.H. (1979) Classification of Rocks and Soils for Engineering Geological Mapping. Part 1: Rock and Soil Materials. *Bulletin of the International Association of Engineering Geology*, 19, 364-437.

Anon, O.H. (1981) "Basic geotechnical description of rock masses. International society of rock mechanics commission on the classification of rocks and rock masses," *International Society of Rock Mechanics and Mining Sciences and Geomechanical Abstracts*, 18, 85-110.

Arshad, H., & Qiu, Y. J. (2012). Evaluation of Dina aggregates for pavement construction in Pakistan. *Advanced Materials Research*, 548, 239-242.

Asif, A. R., Islam, I., Ahmed, W., Sajid, M., Qadir, A., & Ditta, A. (2022). Exploring the potential of Eocene carbonates through petrographic, geochemical, and geotechnical analyses for their utilization as aggregates for engineering structures. *Arabian Journal of Geosciences*, 15(11), 1105.

Asif, A. R., Shah, S. S. A., & Khan, J. (2021). The New Empirical Formulae for predicting the Unconfined Compressive Strength of limestone from Kohat Basin, Pakistan. *Journal of Himalayan Earth Sciences*, 54(1), 33.

Aziz, Q. A. A., & Hussein, H. A. (2021). Mechanical rock properties estimation for carbonate reservoir using laboratory measurement: A case study from Jeribe, Khasib and Mishrif Formations in Fauqi Oil Field. *The Iraqi Geological Journal*, 88-102.

Bell, F. G. (2007). Engineering geology. Elsevier.

Bilqees, R., Sarwar, M. R., Haneef, M., & Khan, T. (2015). Source of cement raw material for the construction of Bhasha Dam in Gilgit Diamir District, Pakistan. *Journal of Himalayan Earth Science*, 48(1).

Bilqees, R., Tahirkheli, T., Pirzada, N., & Abbas, S. M. (2012). Industrial applications of Abbottabad limestone; utilizing its chemical and engineering properties. *Journal of Himalayan Earth Sciences*, 45(1), 91.

Blyth, F. G. H., de Freitas, M. H., 1974. Geology of engineers. ELBS and Edward Arnold, London, 514p.

Brett, M. T. (2004). When is a correlation between non-independent variables "spurious"?. *Oikos*, 105(3), 647-656.

Dunham, R. J. (1962). Classification of carbonate rocks according to depositional textures.

El-Aal, A. A., Zakhera, M., Al Saiari, M., & Tolba, A. (2021). Determination of the geomechanical and chemical properties of carbonate rocks along Najran, Sharourah District, Saudi Arabia: implications for construction and industrial purposes. *Arabian Journal of Geosciences*, 14(17), 1694.

Gillott, J. E., & Swenson, E. G. (1969). Mechanism of the alkali-carbonate rock reaction. *Quarterly Journal of Engineering Geology*, 2(1), 7-23.

Hamdi, P., Stead, D., & Elmo, D. (2015). Characterizing the influence of stress-induced microcracks on the laboratory strength and fracture development in brittle rocks using a finite-discrete element method-micro discrete fracture network FDEM-μDFN approach. *Journal of Rock Mechanics and Geotechnical Engineering*, 7(6), 609-625.

Hassan, E. U., Hannan, A., Rashid, M. U., Ahmed, W., Zeb, M. J., Khan, S., Abbas, S. A., Ahmad, A. (2020). Resource assessment of Sakesar limestone as aggregate from salt range Pakistan based on geotechnical properties. *International Journal of Hydrology*, 4, 24-29.

Hussain, J., Zhang, J., Fitria, F., Shoaib, M., Hussain, H., Asghar, A., & Hussain, S. (2022). Aggregate suitability assessment of Wargal limestone for pavement construction in Pakistan. *Open Journal of Civil Engineering*, 12(1), 56-74.

Ismail, N. R., & Abdulwahid, M. Y. (2021). Engineering Characterization of Local Limestone and Marlstone Aggregates in Koya Area as a Case Study. *Journal of Materials and Engineering Structures*, 8(2), 269-278.

Jan, I. U., Shah, A., Stephenson, M. H., Iqbal, S., Hanif, M., Wagreich, M., & Hussain, H. S. (2016). The sedimentology of the Lower Permian Dandot Formation: A component of the Gondwana deglaciation sequence of the Salt Range, Pakistan. *Rivista Italiana di Paleontologia e stratgrafia*, 122(1), 75-90.

Kamani, M., & Ajalloeian, R. (2017). Evaluation of petrographic number methods efficiency in quality determination of some carbonates rocks. *Geotechnical Geology*, 13(2), 108-115.

Kamani, M., & Ajalloeian, R. (2019). Evaluation of the mechanical degradation of carbonate aggregate by rock strength tests. *Journal of Rock Mechanics and Geotechnical Engineering*, 11(1), 121-134.

Kamran, A., Ali, L., Ahmed, W., Zoreen, S., Jehan, S., Janjuhah, H. T., & Kontakiotis, G. (2022). Aggregate Evaluation and Geochemical Investigation of Limestone for Construction Industries in Pakistan: An Approach for Sustainable Economic Development. *Sustainability* 2022, 14, 10812.

Köken, E. (2022). Assessment of Los Angeles Abrasion Value (LAAV) and Magnesium Sulphate Soundness (M wl) of Rock Aggregates Using Gene Expression Programming and Artificial Neural Networks. *Archives of Mining Sciences*, 401-422.

Lees, G., & Kennedy, C. K. (1975). Quality, shape and degradation of aggregates. *Quarterly Journal of Engineering Geology and Hydrogeology*, 8(3), 193-209.

Mamlouk, M. S., & Zaniewski, J. P. (2014). Materials for civil and construction engineers. London, UK: Pearson.

Mansour, M. A., Ismail, M. H. B., Imran Latif, Q. B. A., Alshalif, A. F., Milad, A., & Bargi, W. A. A. (2023). A systematic review of the concrete durability incorporating recycled glass. *Sustainability*, 15(4), 3568.

Mishra, D. A., & Basu, A. (2013). Estimation of uniaxial compressive strength of rock materials by index tests using regression analysis and fuzzy inference system. *Engineering Geology*, 160, 54-68.

Naeem, M., BinSadiq, R. A., Anwar, M., & Khalid, P. (2014). Mechanical properties and petrographic characteristics of Margala Hill limestone and Lockhart limestone of Rumli area, Islamabad Pakistan. *Acta Geodaetica et Geophysica*, 49, 441-454.

Naeem, M., Zafar, T., Touseef Bilal, M., & Oyebamiji, A. (2019). Physical characterization and alkali carbonate reactivity (ACR) potential of the rocks from Bauhti Pind and Bajar area Hassan Abdal, Pakistan. *SN Applied Sciences*, 1, 1-9.

Neville, A. M., & Brooks, J. J. (1999). Concrete Technology Longman Group UK First ISE reprint 1999 Edinburgh. UK 438p.

Peng, S., & Meng, Z. (2002). Theory and practice of mining engineering geology. *Geological Publ House, Beijing*.

Petrounias, P., Giannakopoulou, P. P., Rogkala, A., Stamatis, P. M., Tsikouras, B., Papoulis, D., Lampropoulou, P., & Hatzipanagiotou, K. (2018). The influence of alteration of aggregates on the quality of the concrete: A case study from serpentinites and andesites from central Macedonia (North Greece). *Geosciences*, 8(4), 115.

Ramsay, D. M., Dhir, R. K., & Spence, I. M. (1974). The role of rock and clast fabric in the physical performance of crushed-rock aggregate. *Engineering Geology*, 8(3), 267-285.

Ransinchung, G. D., Singh, R. N., Kumar, B. N., Kumar, V., (2008) Microstructural behavior of wollastonite and microsilica admixed concrete for rigid pavements. *Journal of Highway Research Bulletin*, 1, 13–20.

Rehman, G., Zhang, G., Rahman, M. U., Rahman, N. U., Usman, T., & Imraz, M. (2020). The engineering assessments and potential aggregate analysis of mesozoic carbonates of Kohat Hills Range, KP, Pakistan. *Acta Geodaetica et Geophysica*, 55, 477-493.

Sadeghi, E., Nikudel, M. R., Khamehchiyan, M., & Kavussi, A. (2022). Estimation of unconfined compressive strength (UCS) of carbonate rocks by index mechanical tests and specimen size properties: central Alborz Zone of Iran. *Rock Mechanics and Rock Engineering*, 1-21.

Sanchez, L. F., Multon, S., Sellier, A., Cyr, M., Fournier, B., & Jolin, M. (2014). Comparative study of a chemo–mechanical modeling for alkali silica reaction (ASR) with experimental evidences. *Construction and Building Materials*, 72, 301-315.

Sarfraz, Y., Basharat, M., Riaz, M. T., Khan, M. A., Shahzad, A., & Ahmed, K. S. (2021). Evaluation of Physico-Mechanical Properties of Crushed Rock Aggregates: A Case Study from the Sub-Himalaya, Pakistan. *Acta Montanistica Slovaca*, 26(3).

Selby, M. J. (1980). A rock mass strength classification for geomorphic purposes: with tests from Antarctica and New Zealand. *Zeitschrift für Geomorphologie*, 31-51.

Shah, S. M. I. (1977). Stratigraphy of Pakistan: *Mem. Geol. Surv*, 12, 138.

Shetty, M. S., & Jain, A. K. (2019). *Concrete Technology (Theory and Practice), 8e. S.* Chand Publishing.

Singh, B. N., Asha, K., & Kumar, V. (2007). Petrographic study of concrete with and without microsilica. *The Researcher*, 1(2), 55-57.

Sun, H., Belhaj, H., & Bera, A. (2021). New insight of correlation between digital rock analysis and petrographic study for rock type classification within carbonate reservoir transition zone. *Arabian Journal of Geosciences*, 14, 1-13.

Ullah, R., Ullah, S., Rehman, N., Ali, F., Asim, M., Tahir, M., Ullah, S., & Muhammad, S. (2020). Aggregate Suitability of the Late Permian Wargal Limestone at Kafar Kot Chashma Area, Khisor Range, Pakistan. *International Journal of Economic and Environmental Geology*, 11(1), 89-94.

Umar, T., & Wamuziri, S. C. (2016). A review of construction safety, challenges and opportunities-Oman perspective.

Yasir, M., Ahmed, W., Islam, I., Sajid, M., Janjuhah, H. T., & Kontakiotis, G. (2022). Composition, Texture, and Weathering Controls on the Physical and Strength Properties of Selected Intrusive Igneous Rocks from Northern Pakistan. *Geosciences*, 12(7), 273.

Yusof, Z. M., Farn, W. S., Leow, C. S., & Lee, J. C. (2023). Rock point load test (PLT index) and its correlation with rock coring rate of bored pile machine. *Physics and Chemistry of the Earth, Parts A/B/C*, 129, 103344.

Zada, W., Hussain, J., Anwar, M., Ullah, W., & Ali, Z. (2023). Physico-mechanical and petrographic insights of Lockhart Limestone, sections of Islamabad, Pakistan. Geotechnical Research, 10(1), 33-45.

Zhou, X., Lü, X., & Liu, C. (2021). Geochemical characteristics of carbonates and indicative significance of the sedimentary environment based on carbon-oxygen isotopes, trace elements and rare earth elements: case study of the Lower Paleozoic carbonates in the Gucheng area, Tarim Basin, China. *Arabian Journal of Geosciences*, 14, 1-18.