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# The evaluation of Khyber limestone in Pakistan for using as road aggregate based on geotechnical properties

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## Abstract
Khyber Formation of Paleozoic age, has been studied here to access its physiochemical and mechanical characteristics. There has been several studies on the sedimentology of the Khyber limestone, however, much more detailed study is required to understand it aggregate potential in desired resolution and precision. It is achieved by understanding the rock types, microscopic textures and physical/ mechanical properties. The Khyber Formation is widely exposed in eastern and central parts of district Khyber, Khyber Pakhtunkhwa (KP) Province, Pakistan. It is a thick bedded hard limestone unit. The carbonates in the Khyber Formation are dominated by calcite, with dolomite, and other accessory minerals as minor component. The mechanical and physical properties of aggregates like specific gravity (2.69), water absorption (0.80%), soundness (2.34%), Los Angeles abrasion value (23.60%), aggregate crushing value (12.18%), aggregate impact value (12.76%) flaky index (10.15%), elongation index (13.02%), California bearing ratio (90.35%), coating and stripping values (96.32%), Schmidt rebound attains (34.23) and compressive strength (38.58Mpa) are according to the available standards. The petrographic analyses of samples of Khyber Formation and energy dispersive X-Rays analysis (EDX) illustrate that it dominantly consists of calcite (88-92%) with small to trace assemblage of dolomite (2-8%), ungraded quartz (1-3%) and ores (1-2%). The chemical and petrographic examinations show that the limestone units of the Khyber Formation are inoffensive in terms of Alkali Silica Reaction (ASR) and Alkali Carbonate Reaction (ACR). These characteristics of the limestone units demonstrating that these deposits are potential aggregate for large-scale projects in the KP Province (Pakistan) and region.
***Keywords:*** *Limestone, road aggregates, Schmidt hammer rebound, Khyber Formation*

## 1. Introduction
The economy of the country is reliant on its trade and road pavements which are the backbone of trade that must be built according to the specified standard (Malkani et al. 2017; Bilal & Khan 2019). The land of Pakistan is considered as the central passage way for the future Asian trade as it joins China, Central Asian countries, Russian territories, Afghanistan and Iran to the Arab and Europe countries through China Pakistan Economic Corridor (CPEC) and Gawadar Port in Makran (Anjum et al. 2018; 2021). Throughout the country, a huge amount of aggregate is utilized in engineering work (Abbas et al. 2017). As the life cycle of civil structures depends on the engineering characteristics of aggregate used. Along with other features operating cost of the civil structures also repose on the engineering characteristic of aggregates being utilized (Neville 1996; Hudson 1999).
The quality of aggregates in mortar, concrete, boundless and bound roadway is resolute by these properties (Neville 1981; Smith & Collis 1993; Neville 1996).Therefore, the aim of this article is the examination of the engineering properties, the petrographic analysis (Iqbal et al. 2017), consumption, geotechnical characterization, and economic perspective of the aggregates.

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Griesbach (1892) and Hayden (1898) were the first ones to study the thick Paleozoic limestones in the Khyber Pass area (Shah 1977). Then Stauffer (1968) coined the name Khyber limestone and designated the Ali Masjid village as the type locality. At type locality the limestone is a dominant lithology which grades into marble and dolomite (Shah 1977).The Khyber Formation is broadly exposed in localities of Khyber Pass, Bara Fort, Loe Shilman, Ghund Garh, Tauda Mela and Misri Khel in Khyber Range. The area of interest of the present study is Sur Qamar area, Hamza Baba complex, Ali Masjid fort, Wali Khel and Gurjara areas. These all sections are near to Peshawar-Torkham Road. The study area can be easily accessed from Peshawar Through a network of metallic roads (N5 Motorway, Bara road and Khyber road). Although, the Khyber limestone heterogeneity is a product of a complex history of depositional and post-depositional modifications, yet much more detailed study is required to achieve the desired resolution and precision. Hence, the objectives of this study are the following:
1. To understand Paleozoic limestone mechanical and physical properties.
2. To decipher its rock types and microscopic textures.

## 2. Geological Setting
The investigated area is part of the administrative units of the Peshawar district, Khyber Agency, and is situated at

the southwestern boundary of the Peshawar Basin (Fig 1). The mountains at the Khyber Agency are sedimentary and meta-sedimentary rocks that belong to the Peshawar Basin. The Khyber Ranges are the extension of the Khyber Lower Hazara metasedimentary Fold and Thrust Belt, which lie towards the north of Khairabad-Panjal Thrust and spread eastward from Khyber Pass to Garhi Habibullah (Ahsan et al. 2009; Anjum et al. 2018; Javed et al. 2021).

The strata of Ordovician to Permian is present in the area (Shah 2009). However, tertiary stratigraphic units are not exposed in this region (Shah et al. 2021). The rocks of the Khyber terrain have imprinted the regional structural trend.The low-grade regionally transformed sedimentary (Landikotal Slates) is exposed in the geosyncline. Shagai Limestone is the next older formation as seen in Table 1. This limestone characterizes deposition in a marine environment (Rankey et al. 2019; Abioui et al. 2020). Ali Masjid Formation (sandstone, quartzite, and limestone) may have formed during the Late Silurian-Late Devonian (Khan et al. 1970). The Khyber Limestone of Carboniferous to Permian age is the uppermost formation and capped all the exposed stratigraphic units in the study area (Shah 2009; Table 1).

## 3. Materials and Methods

The study area is situated (Longitude 33° 94' 05" N; Latitude 71° 04' 98"E) in the Khyber Range, Khyber District, Pakistan (Ahsan et al. 2009; Anjum et al. 2018; Fig 1).

In this research, comprehensive field investigation of carbonate rocks of Khyber Limestone were accomplished. To examine the aggregate potential in the Khyber Limestone, sampling was performed with main emphasis on understanding the physical and mechanical properties.

### 3.1. Sampling

The sampling locations (Longitude 33° 94' 05" N; Latitude 71° 04' 98"E) were Sur Qamar quarry, Hamza Baba complex, Ali Masjid Fort, Gurjana and Walikhel Quarries located in study area (Fig 1).

A sampling at a suitable place as shown in Table 2, is the first step of aggregate testing (Kandhal and Parker 1998)

Table 1: Stratigraphy of the Khyber area (Shah et al. 1980)

| Age | Formation | Description |
|---|---|---|
| Carboniferous-Permian | Khyber Limestone | Thick-bedded limestone, marbles locally with small shale intercalations. |
| Devonian | Ali Masjid Formation | Shale, siltstone and limestone beds |
| Silurian to Devonian | Shagai Limestone | Shale, slate, limestone and dolomite |
| Ordovician to Silurian age | Landikotal Slate | Greenish-grey to yellowish grey slate and with abundant basic igneous dykes and sills. |

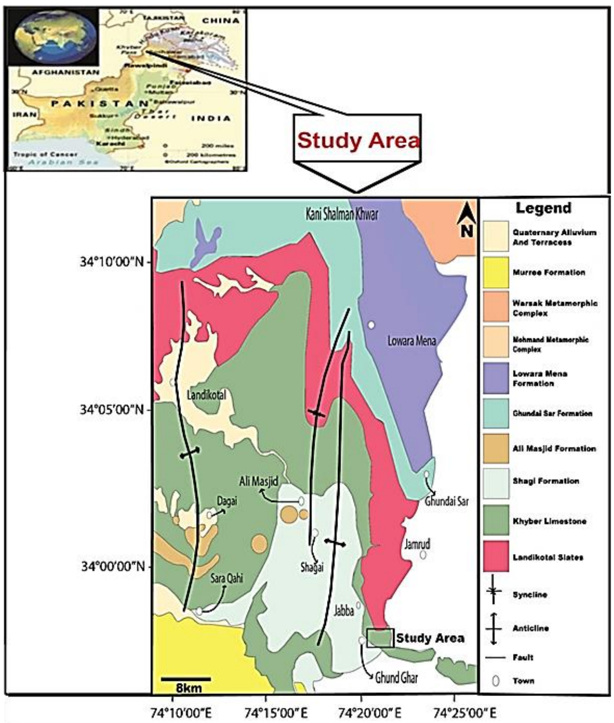

Fig 1. Geological Map of study area in Khyber, Khyber Pakhtunkhwa, Pakistan (Ali et al. 2019).

Samples of Khyber Limestone are collected from stockpiles and outcrops taking care of the uniform distribution of rock beds. The only concern was to collect all possible sizes because the main interest was to study the rock types and their behavior as an aggregate. The sampling method for aggregate was mostly used is stockpile and outcrop sampling. Each sample was labeled, according to its location, quarry naming and source. For aggregate sampling, five quarries are were selected.

Thin sections were prepared and were studied using a petrographic microscope using both cross and plane light. Petrographic analysis (NRMCA 1993) representative samples were chosen for petrographic examination.For EDX the selected samples of Khyber Limestone were crushed to powder form and then analyzed them by using Nicolet X-ray diffractometer in Central Resources Laboratory, University of Peshawar, Pakistan. The Nicolet X-rays diffrectometer give us diffrectogram of the selected samples.

In the field, rock hardness valuation can be attained using the Schmidt hammer as seen in Table 4. The Schmidt hammer tests were conducted on all sites where samples were collected. Schmidt Hammer technique is used to estimate rock strength and it can be performed both in field on rock outcrop and in the laboratory on the rock blocks and cores. There L type is used to generate 0.735 Nm impact energy. In this research work Schmidt hammer is pressed perpendicular against the rock surface in four location (Sur Qamar, Hamza Baba Complex area, Ali Masjid fort, Wali Khil area) in the field. Basically, in the Schmidt hammer technique, the distance of rebound (R) of a controlled impact on a rock surface is measured (Harrison et al. 1998). The strength and toughness of the rock surface are then calculated from the distance of rebound (R) values.

### 3.2. Physical Properties

The endurance and performance of an engineering structure is associated directly to engineering properties of aggregate (Neville 1996) summarized in Table 3. The determined physical properties of Khyber Limestone include specific gravity, water absorption (AASHTO T85-D11 2009), sodium sulfate soundness (AASHTO T-104 2009), coating and stripping with bitumen (AASHTO T-182 2009), flakiness and elongation (B.S 812 section 105.1 and 105.2). To estimate alkali-aggregate reaction potential petrographic examination of these aggregates was conceded out.

### 3.3. Mechanical Properties

The Schmidt hammer method has been used to evaluate the toughness of Khyber Limestone in the field. In demand to meet the required standards unconfined compressive strength (ASTM D-2938 2000), Los Angeles abrasion (AASHTO-T-193 2009), crushing value (ASTM C-131 2003), and Impact value test (BS 1990) were carried out for the determination of mechanical properties of Khyber Limestone.

## 4. Results and Discussion

### 4.1. Lithostratigraphy

Lithologically, the Khyber Limestone about 1000 meters thickness, (Shah et al. 1980; Table 1) is majorly comprised of limestone with shale beds interbedded with it (Fig 2). Several beds of limestone crystalline in the study area. The inferior portion of the formation is interbedded with thick shale with the upper part of the formation is primarily limestone with minor shale. The limestone is frequently changed into marble and dolomite. The dolomite is grey medium-grained and enormous.

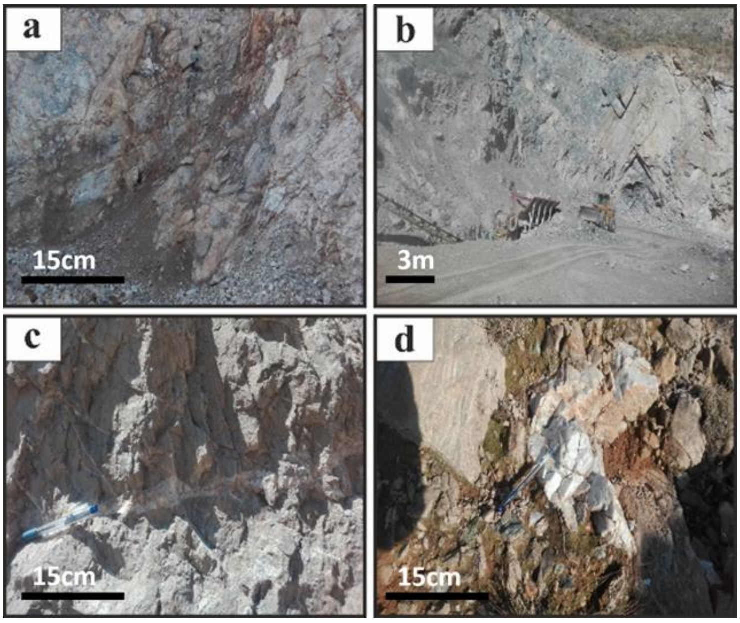


Fig 2. (a) Field photograph of the limestone of Khyber Formation with interbedded shale. (b) Quarry at Sur Qamar. (c) Numerous calcite-filled fractures. (d) Marble in the field area.

### 4.2. Petrographic Analysis
The following are the results of the petrographic analysis as presented in Table 2. The sampling were taken from Sur Qamar quarry, Hamza Baba complex, Ali Masjid Fort, Gurjana and Walikhel Quarries.

Table 2 Percentage composition of the Khyber Limestone of the Peshawar Basin.

| Sample No. | Calcite | Dolomite | Quartz | Ores |
|---|---|---|---|---|
| KHL-1 | 90 | 6 | 2 | 2 |
| KHL-2 | 88 | 8 | 3 | 1 |
| KHL-3 | 94 | 4 | 1 | 1 |
| KHL-4 | 90 | 3 | 4 | 3 |
| KHL-5 | 92 | 2 | 4 | 2 |
| KHL-6 | 90 | 7 | 3 | <1 |

#### 4.2.1. Calcite
The calcite is highly abundant and ranges from 30-90% in thin sections (Table 2). The calcite occurs in the form of sparry calcite (Fig 3c), Micro calcite veins (Fig 3e), well-developed cleavages and microfracture of calcite (Fig 3d, f) are common in the limestone of Khyber (Fig 3).

#### 4.2.2. Neomorphic Calcite
The Khyber Limestone constituents have been variously affected by neomorphism which has caused recrystallization of the lime- mud matrix to sparry calcite (relatively large grains) as presented in Fig 3c staining microphotographs.

#### 4.2.3. Calcite Veins
The calcite veins form 5% of the studied samples (Fig 3e) in staining microphotographs. The samples also reveal more effervescence on putting dilute HCL on its fresh surface, which also attests to the abundance of calcite minerals.

#### 4.2.4. Quartz
Quartz is present as a minor constituent up to 3%, in the Khyber limestone. It is found in the study section in the form of anhedral quartz or from an aggregate of quartz dispersed through the rock. The amount of quartz in the Khyber Limestone is far below their threshold reactivity percentage i.e. >5% distorted quartz for ASR (NRMCA 1993) and 5 to 25% for ACR (Ozol 2006). Thus, the analyzed limestone is not prone to both ASR and ACR.

#### 4.2.5. Dolomite
The dolomite minerals occur as subhedral to anhedral grains in the Khyber Limestone (Ahmad et al. 2021). Dolomite is a well-preserved fabric that is usually related to calcite veins and is considered a secondary phase.

### 4.3. Energy-dispersive X-ray analysis (EDX)
Here, the results of the elemental composition using the EDX analysis of the selected samples of the Khyber Limestone are presented (Fig 4). With the help of this technique, both major and minor oxides of the samples were recorded. This analysis shows that the limestone samples are high in CaO i.e 52.60 to 60.80% and can be regarded as highly pure samples. The amount of $SiO_2$ in the studied limestone is very low and ranges from 1.08 to 1.40%. The amount of MgO is very low and ranges from 1.12 to 1.80% (Table 2). The $Al_2O_3$, $K_2O$, and $Na_2O$ are present in traces in the limestone unit of the Khyber Formation from 0.48 to 0.60%, 0.004 to 0.08%, and 0.14 to 0.48%.

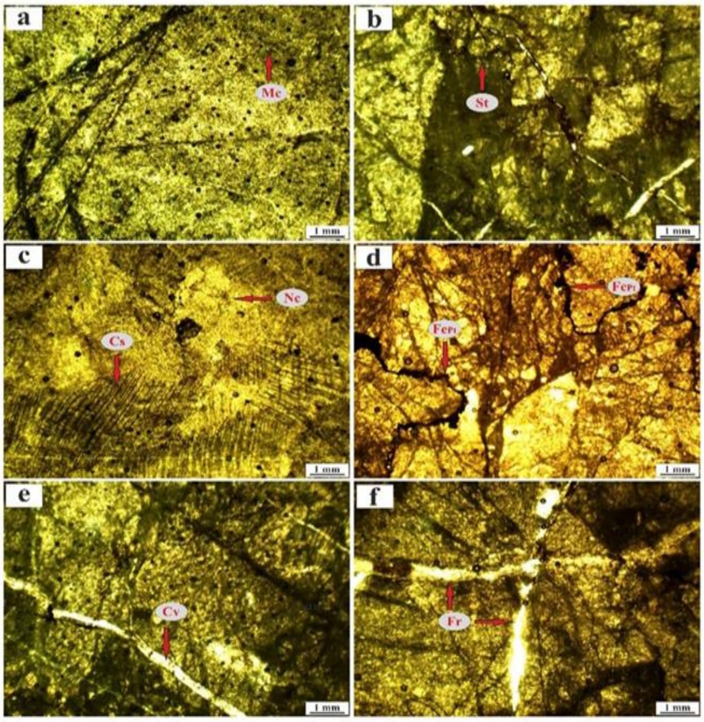


Fig 3. Staining microphotographs of the Khyber Limestone (a) Micritic matrix (Mc). (b) Small amplitude stylolites (St), (c) Neomorphic calcite (Nc) and sparry calcite (Cs), (d) Precipitation of iron solution along a fracture (Fept), (e) Calcite filled veins (Cv), (f) cross-cut calcite filled fracture (Fr).

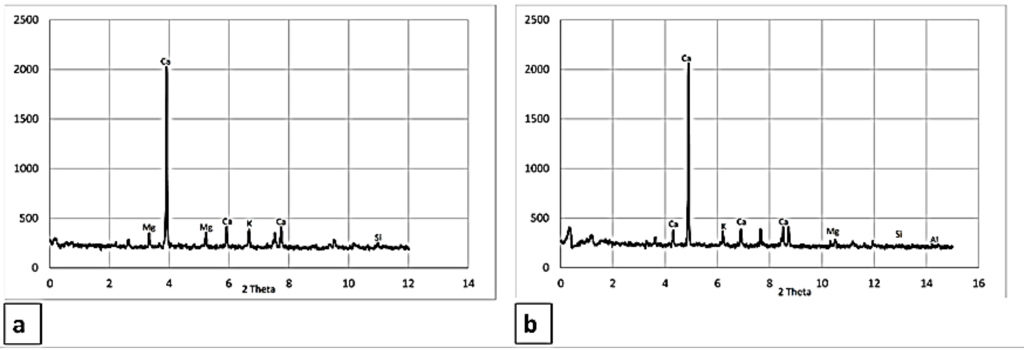


Fig. 4 (a) EDX curve showing the mineralogical composition of the Khyber Limestone at Gurjara area, (b) EDX curve showing the mineralogical composition of the Khyber Limestone at Sur Qamar area. The x-axis represents that the pattern is measured in 2θ and the y-axis is relative intensity of the diffracted beam.

**4.4. Specific Gravity and Water Absorption Test**

The specific gravity of a material is the proportion of the weight of the sample to the given volume of water (AASHTO 2009). It is the substantial property of aggregate that is used to calculate the strength and quality of aggregate (Smith and Collis 1993). Material with high specific gravity enhances the infield performance of the structure (AASHTO 2009). Specific gravity is an indirect tool to conclude the absorption value of aggregate (Yaragal et al. 2020). An aggregate of high absorption value assigns poor quality and low strength aggregate and avoid using in structure experience diverse loads (Yao et al. 2021).

In the recent evaluation, the apparent specific gravity value assorts from 2.65 (minimum) to 2.74 (maximum) with the mean value of 2.69 for Khyber Limestone aggregate. Water absorption value is indirectly obtained from specific gravity that varies between 0.58 (KHL-4) to 1.30% (KHL-3) with a mean value of 0.80% (See Table 3 for other samples). In a recent study, the water absorption value is lower than the maximum 2.5% allowed value.

**4.5. Soundness Test**

A soundness test is deliberated to calculate the degree of breakdown and degradation of geological material exposed to different weathering conditions (AASHTO 2009). The geological material is avoided to use as aggregate that is vulnerable to weathering effect to minimize the failure of a structure during in-field conditions (Gondal et al. 2009). In the studied samples, the percentage values of the soundness test range from 1.90% recorded for KHL-1 to 3.05 recorded for KHL-4 (mean is 2.34% ). The maximum limit of soundness is 10% (maximum) for cement concrete works and 12% for the base course.

**4.6. Los Angeles Abrasion Test**

Los angles abrasion value is used to determine stiffness behavior of aggregate endure to natural and stressed conditions. The toughness of aggregate is resolute from its resistance to breakdown and degradation under physical and chemical conditions (Gondal et al. 2009). When aggregates used in a structure like concrete pavements and roads constantly remain under the heavy load, the resistance of an aggregate to abrasion is the key feature (Smith and Collis 1993). The abrasion value should not exceed 35% and 50% for aggregate use in concrete and road works (AASHTO 2009; Gondal et al. 2009). The value of abrasion varies from 21.18% (KHL-3) to 24.72% (KHL-1) with an average value of 23.60% which are within the safe limit to use as aggregate for road and concrete works.

**4.7. Crushing Value Test**

Crushing value is evaluated to find strength behavior of aggregate under steady applied compressive force by vehicle load (Lu et al. 2019). Low strength aggregate decreases the performance and quality of aggregate (Afroughsabet et al. 2017). The crushing value for aggregate to use in road work and concrete should be less than the maximum value of 30% as specified by international agencies (ASTM D-2938 2000) and 22.5% (Gondal et al. 2009). In the current study, the crushing value range from 9.40% (KHL-2) to 14.26% (KHL-4) with an average of 12.18%, which is well below than maximum allowed value.

**4.8. Aggregate Impact Values Test**

The aggregate impact value test evaluates the performance of aggregate to spontaneous load and stress (Hamedi 2018). The aggregate having lower strength can despoil when subjected to impulsive impact load (Hillel 2003). The competency of the source material is the key pointer of hard and good strength aggregate (Baby 2021). The impact value is an important indicator of good quality aggregate (Ahsan et al. 2009). In the present work, the maximum impact value of 15.69% was recorded in KHL-3. The average value for Khyber Limestone aggregate is 12.76% which is well safe in limits as per the value specified by international societies

**4.9. California bearing ratio**

To measure the resistance of aggregate under controlled density and moisture conditions against standard plunger penetration at the rate of 1.25 mm/min penetration CBR test is used (Esfahani & Goli 2018). The CBR test was performed for all the study samples at 100% compaction level under saturated conditions. The values ranged from 85.70 % for KHL1 to 94.5% for KHL-5 at 100% compaction. The minimum required limit for sub-base is

30% and for base, course is 80% specified by AASHTO (2009).

### 4.10. Flaky and Elongation Test

The test is designed to calculate the portion of a flat and elongated particle in the aggregate mix (Hartley 1974) that causes a serious problem during compaction and infield performance of aggregate base structure (Salih and PSravana 2013). A good quality aggregate is free of flat and elongated particles that enhance the strength and workability of concrete and road works.The flaky and elongation index in the current study is below 15% that is the maximum allowed range (NHA 1998). The flaky index varies from 9.54% for KHL-3 to 10.78% for KHL-1 (mean is 10.15%), whereas elongation index recorded in between 12.37% for KHL-1 to 13.48% for KHL-2 (mean is 13.02%). The average value of flakiness is 10.15% and elongation 12.74%.

Table 3 Engineering properties of limestone unit of Khyber Agency.

| Name of Test | Sample Number | | | | | |
|---|---|---|---|---|---|---|
| | KHL-1 | KHL-2 | KHL-3 | KHL-4 | KHL-5 | Mean |
| Specific Gravity | 2.68 | 2.71 | 2.69 | 2.74 | 2.65 | 2.69 |
| Water Absorption Test | 0.82 | 0.66 | 1.30 | 0.58 | 0.67 | 0.80 |
| Sulphate Soundness Test | 1.90 | 2.01 | 2.05 | 3.05 | 2.69 | 2.34 |
| Los Angles Abrasion Test | 24.72 | 23.34 | 21.18 | 24.26 | 24.54 | 23.60 |
| Aggregate Crushing Value | 10.88 | 9.40 | 12.72 | 14.26 | 13.66 | 12.18 |
| Aggregate Impact Value | 11.16 | 8.81 | 15.69 | 14.16 | 13.97 | 12.76 |
| CBR% | 85.70 | 90.24 | 92.45 | 88.86 | 94.5 | 90.35 |
| Flakiness Index | 10.78 | 9.76 | 9.54 | 10.16 | 10.52 | 10.15 |
| Elongation Index | 12.37 | 13.48 | 12.82 | 13.40 | 13.06 | 13.02 |
| Coating and Striping | 96.78 | 95.14 | 97.36 | 96.54 | 95.8 | 96.32 |
| UCS | 36.05 | 42.65 | 38.84 | 29.25 | 46.15 | 38.58 |

### 4.11. Coating and striping of bitumen

The test is manually performed in laboratory conditions to observe coating and adhesion capacity between aggregate and bitumen (Gondal et al. 2009). The aggregate to bitumen bond should be strong enough to resist striping which is a prerequisite increase the infield performance of asphalt mix road (Jamieson et al. 1995). In the present work, the Aggregate bitumen's coating percentage remains above 95% (NHA 1998) with the highest value of 97.36% recorded for the KHL3 sample.

### 4.12. Unconfined Compressive Strength (UCS) Test

The unconfined compressive test is normally used to measure and examine the workability of aggregate in service under compressive load (Saberian and Li 2021; Fig 5).

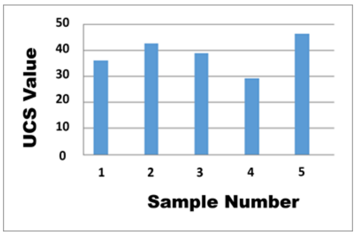


Fig 5. Showing unconfined compressive strength (MPa) of the selected Khyber Limestone samples.

The UCS values for the representative five samples of the studied limestone are 36.05, 42.65, 38.84, 29.25 and 46.15, respectively. The aggregate whose UCS values are between 28 and 110 Mpa are recommended for use as aggregates (Deere and Miller 1966). Hence, the limestone of the Khyber Formation is suitable for asphalt and cement concrete. A comparatively low value of sample 4 as compared to the others as because of large grain size, higher porosity and fractures abundance in sample 4 core. Hence, we can say that rippability of the rocks of Khyber Formation is high as the UCS values except one sample.

### 4.13. Schmidt hammer Rebound Value

In the present study, the Schmidt hammer rebound values (R) were measured at four field locations. Three readings were acquired for each bed in different lateral and vertical positions (R1, R2 and R3) in each section, and then the average value (R mean) was mathematically calculated and deliberated as the demonstrative strength value of the rock bed.

### 4.14. Economic Potential

The thickness of Khyber limestone in the Khyber Pass is about 1000 m (Shah et al. 1977). It also reaches a thickness of 1300 m near the Ali Masjid village (Shah et al. 2021). As Pakistan has great demand of limestone for road aggregate and cement industry for upcoming regional projects (Ullah et al. 2020). At present mining of limestone is a challenge due dykes, sills, intrusive bodies, marble and dolomite bodies. Nevertheless, proper understanding can help and make it important future resource for the country and region.

## 5. Discussion

Field observations reveal that the Khyber Limestone outcrops are existing in the proximity of Khyber Pass highway. The five locations used for sampling are having promising results. The limestone is present along with shale, marble and dolomite. However, the limestone can easily by differentiated because of its light grey colour and more dominated in the upper part of the formation (Shah et al. 2021).

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Table 4 In-situ Schmidt hammer rebound results of limestone unit of Khyber Formation.

| Section No. | Sample No. | $R_1$ | $R_2$ | $R_3$ | $R_{mean}$ | Qualitative rock strength |
|---|---|---|---|---|---|---|
| I | 1 | 36 | 34 | 46 | 38.6 | Moderately strong |
| | 2 | 26 | 24 | 32 | 27.3 | Moderately strong |
| | 3 | 30 | 32 | 38 | 33.3 | Moderately strong |
| II | 1 | 44 | 38 | 48 | 43.3 | Strong |
| | 2 | 26 | 38 | 34 | 32.6 | Moderately strong |
| | 3 | 46 | 38 | 42 | 42 | Strong |
| III | 1 | 40 | 48 | 37 | 41.6 | Strong |
| | 2 | 22 | 26 | 30 | 26 | Moderately strong |
| | 3 | 24 | 30 | 26 | 26.6 | Moderately strong |
| IV | 1 | 24 | 25 | 22 | 24 | Moderately strong |
| | 2 | 42 | 38 | 48 | 42.6 | Strong |
| | 3 | 36 | 42 | 45 | 41 | Strong |

Our petrographic results represent three minerals namely, calcite, quartz, dolomite and clays (Saw et al. 2019; Abioui et al. 2020; Ali et al. 2021). The presence of calcite mud amount in the studied thin section is 88-92% with (1-2%) and clays (0.2-1%). Quartz is present in the Khyber limestone at a minor amount maximum up to 3% and it is far below their threshold reactivity percentage i.e. >5% distorted quartz for ASR (alkali-silica reaction, Ozol 2006) and 5 to 25% for ACR (alkali carbonate reaction, Shah et al. 1980).

The Khyber Formation is low in $SiO_2$ and MgO content so it is non-deleterious/ destructive and not prone to ASR and ACR associated expansions because no reactive component was perceived, so it is useful in cement concrete (Broekmans 2018; Sanchez Roboredo 2020).

Our EDX results show that major CaO, MgO, $SiO_2$, and minor $Al_2O_3$, $K_2O$, $Na_2O$ oxides are identified. Samples ranging with CaO from 52.60-60.80% and are regarded as highly pure samples. The amounts of $SiO_2$ is low and is about 1.08-1.40%. While, the MgO is about 1.12-1.80%. The trace oxides are $Al_2O_3$, K2O, and $Na_2O$ are 0.48 to 0.60%, 0.004 to 0.08%, and 0.14 to 0.48% and are negligible. It represents that Khyber limestone is a pure limestone in terms of impurities (Kadhim et al. 2021). In our analysis, the apparent specific gravity value assorts from 2.65 (minimum) to 2.74 (maximum) with the mean value of 2.69 for Khyber Limestone aggregate. According to Yao et al. (2021), an aggregate of high absorption value assigns poor quality, low strength aggregate and avoid using in structure experience diverse loads.The maximum limit of soundness is 10% (maximum) for cement concrete works and 12% for the base course (Gudissa et al. 2021). According to our results are well below the maximum values, the percentage values of the soundness test range from 1.90% recorded for KHL-1 to 3.05 recorded for KHL-4 (mean is 2.34% ). Our abrasion values ranges from 21.18% (KHL-3) to 24.72% (KHL-1) with an average value of 23.60% which are within the safe limit to use as aggregate for road and concrete works. The safe limits to use in concrete and road works abrasion value are 35%-50% for aggregate (AASHTO 2009; Gondal et al. 2009; Fares et al. 2021).

In the current work, the crushing value range from 9.40% to 14.26% with an average of 12.18%, that is well below than maximum allowed value of 22.5-30%. However, the average value for Khyber Limestone aggregate impact value test is 12.76% which is well below the limits specified by international societies of ASTM, AASHTOO and NHA. For California bearing ratio our results ranges from 85.70-94.5% at 100% compaction, minimum for base course is 80% specified by (AASHTO 2009; Narzary & Ahamad 2018).

The flaky and elongation tests results show that the 9.54% to 10.78% (mean is 10.15%), whereas elongation index recorded in between 12.37% to 13.48% (mean is 13.02%), the values must be below 15% (Guo et al. 2018). In our study, the aggregate bitumen's coating percentage remains above 95% (NHA 1998) with the highest value of 97.36%. The aggregate with UCS values between 28-110 Mpa are recommended for use as aggregates (Deere and Miller 1966; Chen et al. 2019). The UCS values for the representative five samples of the studied limestone are 36.05, 42.65, 38.84, 29.25 and 46.15, respectively. A comparatively low value of sample 4 as compared to the others as because of higher porosity, large grain size and fractures abundance (Liu et al. 2020) in sample 4 core. Hence, the values of various standard aggregate tests for our samples of Khyber limestone for experimental tests like Los Angeles abrasion, soundness, specific gravity, water absorption, flakiness, elongation, impact valve, crushing value and unconfined compressive strength (Gudissa et al. 2021) are within the acceptable ranges of standard specifications of NHA, ASTM and BS standards for normal aggregate used in concrete and asphalt.

Hence, we can conclude that the studied stratigraphic sections and samples fall within the limits of international and national standards for aggregate and its use in concrete (Sims & Poole 2017), base course (Tam et al. 2018), subbase (Fladvad et al. 2017), for construction of roads, pavements, buildings, railroads and other infrastructure and have good economic value (Neumann et al. 2021).

## 6. Conclusions and Recommendations

The limestone units in Khyber Formation, exposed along Khyber Pass in the Khyber Ranges were studied for their geotechnical characteristics and petrographic characters to evaluate their potential as an alternative aggregate source in construction works. Following conclusions are made from this study that the Khyber Limestone presents in the proximity of Khyber Pass highway and cover all the rock sequence existing in the Khyber Pass area and well exposed in a number of localities Bara Fort, Ali Masjid Fort, Loe Shilman, Ghund Garh, Sur Qamar, Tauda Mela, Wali Khel and Misri Khel in Khyber Range. The values of various standard aggregate tests for the studied limestone like Los Angeles abrasion, soundness, specific gravity, water absorption, flakiness, elongation, impact valve, crushing value and unconfined compressive strength are within the acceptable ranges of standard specifications of NHA, ASTM and BS standards for normal aggregate used in concrete and asphalt.

The petrographic study strongly suggested that the limestone unit of the Khyber Formation is composed of dominantly calcite mineral and minor amounts of potassium, sodium, aluminum, silicon and magnesium are also present. The Khyber Formation is low in $SiO_2$ and MgO content so it is non-deleterious/ destructive and not prone to ASR and ACR associated expansions because no reactive component was perceived, so it is useful in cement concrete. From the above test results and petrographic analysis, it is concluded that the Khyber Limestone at the studied section falls under the national and international specifications, so it is concluded that it is a good aggregate for concrete, base course, subbase, construction of pavements and buildings.

However, we can say that rippability of the rocks of Khyber Formation is high as the UCS values except one sample. Henceforth, the limestone of the Khyber Formation is suitable for asphalt and cement concrete. A comparatively low value of sample 4 as compared to the others as because of large grain size, higher porosity and fractures abundance in sample 4 core. Similarly other parameters like fracturing, water amount, Schmidt hammer rebound value and discontinuities can also be taken into understanding rippability of the Khyber Formation.

As Khyber Limestone is highly useful for aggregate and engineering geological projects the following are the recommendations for its better utilization and assessment. As Khyber Limestone is highly recommended for use in any kind of highway and concrete works, new quarries and crushing plants must be set up because there are well-developed exposures of Khyber Limestone in the area of interest. Secondly, the ease of access to outcrop and presence near the Peshawar-Torkham Highway and in the vicinity of Peshawar-Torkham Economic Corridor are plus points for setting new quarries and crushers. Thirdly, care must be taken as Khyber Agency is a mountainous area, so the locality chosen shall not affect the natural habitat and environment. Lastly, keeping economic potential in mind, the cost and profit ratio should be pre-calculated for quarry launching as there is a demand for aggregate in the area.

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