Aggregate suitability and Geo-chemical investigation of limestone for construction industries in Pakistan: An approach for economic development

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Abstract

This study investigated the aggregate suitability and geo-chemical characteristics of limestone (LS) for construction industries. The results of aggregate parameters for different applications revealed that specific gravity (SG = 2.6), water absorption (WA = 0.47%), bulk density (BD = 1.58 g/cm³), flakiness index (FI = 16.8%), elongation index (EI = 16.39%), soundness (S = 1.6%), aggregate impact value (AIV = 14%), Los Angles Abrasion value (LAAV = 23.51%), clay lumps (CL = 0.35%), uniaxial compressive strength (UCS = 86.7 MPa), point load test (PLT = 5.18 MPa), ultrasonic pulse velocity (UPV = 5290 m/s) and Schmidt hammer rebound test (SHRT = 49 N) are in accordance with ASTM, ISRM and BSI. Petrographically, the LS is dominantly composed of ooids, peloids, bioclasts and calcite (CaCO₃) with trace concentration of the dolomite. Geochemical results (n = 18) indicated that the LS is dominantly made up of calcite (95.81%); while on average it is composed of 52.08 wt.% CaO, 1.13 wt. % SiO₂, 0.66 wt. %, MgO, 0.80 wt. % Al₂O₃, 0.76 wt. % FeO₂ and LOI were recorded as 42.13 wt. %. Whereas, P₂O₅, TiO₂, MnO, K₂O and Na₂O are found in trace amount. Regression analysis demonstrates that the empirical correlation equation for estimating uniaxial compressive strength with ultrasonic pulse velocity is more reliable than Schmidt hammer rebound test and point load test. The findings of this study strongly suggest LS of the area has a great potential as a raw material in construction industries.

1 Introduction

Construction industries significantly contribute to the socio-economic development of a country. Ever since the launch of the China-Pakistan Economic Corridor (CPEC) in 2015 coupled with rapid construction activities; the demand for the construction material has amplified manifold in Pakistan. With this growing trend, it is essential to explore new avenues of construction material along the CPEC projects. Limestone (LS) is one of the commonly used construction materials. It is an important sedimentary rock dominantly composed of calcite (CaCO₃) mineral. As a raw material, LS is widely used in many industries especially in construction and cement industries. Cement's compositional chemistry mainly depends on the geochemistry of limestone which is the major raw material used in cement. Lime (CaO) as a raw material constitutes about 75% of the cement's composition (Bensted 1978). Similarly, LS as an aggregate constitutes major raw material of concrete. As an aggregate material via extracted quarrying operations it is used in the construction of the roads, foundations, bridges and tunnel lining, and are essential for the development of modern economy (Galetakis et al. 2012). In order to evaluate aggregate suitability for any construction application it is utmost necessary to perform a series of engineering tests, including specific gravity (SG), water absorption test (WA), bulk density (BD), flakiness index (FI), elongation index (EI), aggregate impact values (AIV), Los angles abrasion value (LAAV), uniaxial compressive strength (UCS), point load test (PLT), ultrasonic pulse velocity (UPV) and Schmidt hammer rebound test (SHRMT) (Khanlari and Naseni 2018).

Previously, researchers like R.S Boynton (1980) and Oats (1998) have worked on the industrial utilization of limestone. A study was conducted by Hussain et al. (1989), describing the petrological and industrial applications of Nizampur limestone, NWFP, Pakistan. The finding of the research proved that the LS of the study area is well qualified for its use in cement industries. Similarly, Bilqees and Shah (2007) have worked on limestone deposits of Kohat area for industrial applications and suggested its usage in cement industry. Jan et al. (2009) have studied limestone of the Nizampur area and have recommended its use in cement, glass and paper industries. Bilqees et al. (2012) have evaluated the Abbottabad limestone and found out that it can be used in various industries including cement. Bilqees et al. (2015) have also worked on the Samana Suk Formation, Kawagarh Formation, Lockhart Limestone and Margalla Hill Limestone of Abbottabad area and qualified it for cement and construction usage. Likewise, Malahat et al. (2018) and Rehman et al. (2018) have worked on the aggregate suitability of limestone in Khyber Pakhtunkhwa. However, there are still huge reserves of limestone which are not evaluated yet. Therefore, the current research work is designed in continuation of the research work done so far in order to assess the unexplored and untested limestone resources of the Southern Khyber Pakhtunkhwa which is rich in limestone deposits. Furthermore, the scope of this study also includes establishing simple correlation equations of UCS with PLT, UPV and SHRT. A large number of correlation equations for estimating the UCS using the PLT, UPV and SHRT have been developed over time. Broch and Franklin (1972) Bieniawski (1975), Cargill and Shakoor (1990), Akram and Bakar (2016); Salah et al. (2014) developed correlation equations for the estimation of UCS from PLT. Similarly, Sharma and Singh (2008), Kurtuluş et al. (2010), Yagiz (2011) and Sarkar et al. (2012) have formulated correlation equations for the calculation of UCS from UPV. For the estimation of UCS from SHR, Singh et al. (1983), Sheorey (1984), Haramy and DeMarco (1985), O'Rourke (1989) and Shalabi et al. (2007) have developed correlation equations. However, most of the researchers have developed single correlation equation based on variety of rocks which underestimate the authenticity of these equations. By using these correlation equations for all types of rocks result in UCS values with large variability.

Therefore, an attempt has been made in the current study to develop empirical correlation models to be used for specific rock types and local geology. For this purpose, the LS of the Samana Suk Formation (SSF) of the Middle Jurassic age was selected for the present investigation. SSF is a commonly distinguishable strata spread over in a wide area of northern, Pakistan. It is regarded as the most dominant lithological strata of carbonates in the Mesozoic strata of Samana Range (SR), Kohat Tribal Range (KTR), Trans Indus Ranges (TIR), Salt Range (SR), Kala Chitta Range (KCR) and Hazara Mountains (HM) (A. Nizami and Sheikh 2009). The data obtained was also subjected to regression analysis in order to establish correlation between different characteristic features.

2 Material And Method

2.1 Study area description
This study was conducted along Sheikh Budin Hills (SBH) Section situated in District Laki Marwat at a distance of 8 km. This area lies in Toposheet No. 38 L/15 of the Survey of Pakistan at Latitude 32º 17′ 43″ N and Longitude 70º 45′ 10″ E (Fig. 1). In SBH section, the SSF is composed of massive and medium to thick bedded limestone. This section is accessible from Peshawar through Laki Marwat in northeast and Dera Ismail Khan in south via Indus Highway. The thickness of the SSF at the studied section is 87.57 m (A. R. Nizami 2009).

2.2 Geological setting

The western extension of the Salt Range constitutes the TIR in lesser Himalayas. The study area is the south-western part of the Marwat Range (MR) in the TIR as shown in Fig. 1. Structurally, the study area possesses many thrust faults: Sheikh Budin Thrust, Pezu Fault and Paniala Fault (Blinski et al. 1998). Stratigraphically, the study area is composed of rocks ranging from Early Permian to Pliocene-Pleistocene with three main unconformities (Ali 2010). Datta Formation and SSF of the Jurassic age are well developed (Fig. 2). The SSF is mainly composed of limestone which is yellowish brown and grey in colour as shown in Fig. 2.

2.3 Samples collection and testing procedure

An 87.5 m thick section of the SSF at SBH was sampled and geological observations were recorded. Two types of rock samples were collected; grab samples for geochemical analysis i.e. major oxides evaluation and for petrographic studies and bulk samples for the determination of mechanical properties. The rock samples were mainly dolomitic limestone and were fresh homogeneous, isotropic, and with no major discontinuity or macroscopic structural phenomenon. To preserve the in-situ conditions, the rock specimens were saturated prior to measuring the rock properties. The collected samples were evaluated for BD ASTM C29 (2009) BS812-112 (1990), SG and WA tests ASTM C127 (2012), FI and EI ASTM D4791 (2010), aggregate soundness test ASTM C88-05 (2005), AIV BS 812–112 (1990), CL and friable particles ASTM C142/C142M-10 (2010), LAAV ASTM C131 (2006) and compressive strength of cubes ASTM C170-16 (2016). PLT ASTM D5731-95 ((1995)), UPV ASTM D2845-00 (2000) and SHRTM ASTM D5873-00 (2000) were performed to determine the physical and mechanical properties of LS. All the engineering tests are performed according to different international standard of ASTM, ISRM and BSI. Major oxides determination including (CaO, MgO, Na₂O, K₂O, MnO, P₂O₅, TiO₂, Fe₂O₃ and Al₂O₃) were conducted using atomic absorption spectrophotometer (Model AA700, PerkinElmer) and UV/VIS spectrophotometer (UV/VIS 400 technique) in the National Centre of Excellence in Geology, University of Peshawar, Pakistan. The ASTM C289 (2007) test was performed in order to find the alkali-silica reactivity of the aggregate of the LS. A chemical reaction takes place under specific humid conditions between the silica exist in aggregate and alkalis present in the cement; thus, forming an alkali-silica gel which leads to swelling/expansion owing to absorption of water and eventually results in cracking of concrete.

2.5 Petrography

The petrographic analysis is used to assess the mineral composition of aggregate parameters and to infuse the reactive constituents. The detailed petrography was performed in accordance with ASTM C295 (2012) to find out the various depositional and diagenetic fabrics to explain the possible effect of these depositional and diagenetic fabrics on the engineering properties of the under investigated rocks.

2.6 Statistical analysis

Statistical analysis like Pearson correlation matrix analysis (PCMA) was performed by XLSTAT version. Graphical representation was carried out by Sigma plot (ver.12.5, 2016 Systat Software, Inc.) For the comparison of the analytical results, descriptive statistics were carried out for standard deviation, mean, minimum, and maximum using Microsoft Excel 2013.

3 Results And Discussion

3.1 Engineering properties

The measured minimum, maximum and mean values of all geo-mechanical parameters of limestones are within BSI (British Standards International) and ASTM (American Standards for Testing Material) standards limits for road and concrete aggregate as given in Table 1. Similarly, Table 2 displays measured minimum, maximum and mean values of UCS, PLT, UPV and SHRT. The SG of the study area ranges from 2.66 to 2.67 (2.66). According to ASTM C127 (2012), the value of SG for the aggregate used in concrete should not be less than 2.6 and WA should not surpass from 2.5%. Thus, the value obtained are within the range of the ASTM. The BD varies from 1.54 to 1.59 g/cm³ (1.58 g/cm³). The calculated values of BD of the aggregate samples are well within the permissible range. The values of FI and EI of the limestone range from 15.20–19.40% (16.84%) and 14.12–18.80% (16.39%), respectively which are within limits of BS 812 105.1 (1989) and BS 812 105.2 (1990), respectively. FI and EI are physical properties which are related to shape of the aggregate fragments. Higher values indicate lower strength and anisotropic properties when used as aggregate for road and cement concrete (Naeem et al. 2014).

The soundness value ranges from 1.3 to 1.9% (1.6%) which shows that all the aggregate samples of the SSF are well within the permissible range (<12%) of ASTM C88-05 (2005). The AIV is an important index test that provides instant measures about the pulverization resistance of an aggregate
against abrupt shock and impact (Smith MR 2001). The AIV of the LS samples ranges from 12.37-16.44 % (14.067 %). Thus, the aggregate impact values are well within the range of permissible limits of BS 812. The LAAV ranges from 21.76% to 26.04% (23.51%), which is less than 40% as quantified by ASTM C131 (2006). Clay lump and friable particles varies from 0.24 to 0.42% (0.35%), lesser than 1% as specified by ASTM C142/C142M-10 (2010). The UCS of the limestone cubes from the Samana Suk Formation ranges from 73.83 to 101.47 Mpa (86.77 MPa) (Table 2), which is in the category of high strength according to International Society for Rock Mechanics (ISRM 2008), while Selby (1980) classified it as moderately strong rocks. Furthermore, PLT values vary from 4.76 to 5.89 Mpa (5.18 MPa) which make these rocks in the category of strong rocks according to strength classification of rocks by Selby (1980). UPV ranges from to 4835.50 to 5729.32 m/s (5290.08 m/s) which falls in excellent category according to study conducted by Malhotra (1976) on crushed limestone in concrete, while SHRT varies from to 43 to 58 N (49 N) (Table 2). The SHRT values put the LS in the category of moderately strong to strong rocks (Selby 1980).

3.2 Geochemical evaluation

The geochemical results of the major oxides are shown in Fig. 3. The LS of the study area is dominantly comprised of calcite mineral (95.69%). It has high concentration of CaO which ranges from 49.96 to 55.20 % (52.08 %). The correlation coefficient results exhibit significant positive correlation of LOI to CaO (r = 0.867) and CaCO$_3$ (r = 0.950) which signifies the purity of limestone (Table 3). However, both LOI and CaO show negative correlations with SiO$_2$ (Table 3) The higher concentration of calcite and CaO enhances the strength and durability of the aggregate and is in accordance with the international standards as required for cement industry (Lea 1970). The value of MgO varies from 0.11 to 1.47% (0.66%) indicating prevalence of less saline nature by which extensive leaching take place. Also, LS of SSF contains low Na$_2$O 0.03-0.84% (0.38%) and K$_2$O 0.03 to 0.40% (0.22 %) contents. Fe$_2$O$_3$ varies 0.34 to 1.09 % (0.76 %). Iron in the form of oxides (Fe$_2$O$_3$) is present as impurity in the LS which if present in higher amount can cause deterioration in the building construction (Robert S Boynton 1980). The percentage of K$_2$O, MnO, P$_2$O$_5$, TiO$_2$, Fe$_2$O$_3$ and Al$_2$O$_3$ is less than 1.00 %, while SiO$_2$ is less than 2 %. The percentage of MnO, SiO$_2$, P$_2$O$_5$, TiO$_2$, and Al$_2$O$_3$ varies from 0.09 to 0.98% (0.34 %), 0.34 to 1.77% (1.13 %), 0.05 to 0.80% (0.38 %), 0.03 to 0.83% (0.36 %), 0.35 to 1.84% (0.80 %), respectively. Further, the concentration of the LOI ranges from 40.11 to 43.27 % (42.08 %).

Furthermore, the $S_e$ (Dissolved silica) ranges from 29.30-73.92 mmol/L, whereas $R_e$ (Reduction in alkalinity) varies from 137-225 mmol/L. These results illustrate that the aggregates of the SSF are innocuous in terms of ASR and thus have no deleterious effect and shown in Fig. 4 (Grattan-Bellew and Chan 2013).

3.3 Petrographic evaluation

Mechanical properties of rocks are highly influenced by the petrographic features. The petrographic analysis of rock gives significant insights about its mechanical behaviour under stress by studying its grain shape, grain size, fabric, grain boundaries, mineralogical composition and weathering (Irfan 1996). Petrographic examination of the SSF was carried out by following ASTM C 295. The study performed under petrographic microscopic explains the nature of aggregate material (French 1991) in terms of ASR potential, which affects the durability of hardened concrete (López-Buendía et al. 2006). A silica gel is formed when silica of aggregates reacts with alkali of cement in the presence of water. The silica gel causes osmotic pressure which results in the breaking of the bond between aggregate and cement, thus leading to cracks in the structures (Ferraris and Ferraris 1995). Similarly, the clay minerals also create cracks in the structure by expansion and contraction (Chen 2012). Therefore, the petrography of the SSF was essential in order to find out deleterious materials in the aggregate. Moreover, it will also help in unravelling the diagenetic features which affects the engineering properties of rocks.

The LS at the SBH section is yellowish grey to grey in colour. It is medium to coarse grained, compact, hard, massive, and medium to thick bedded limestone. According to Dunham (1962) classification, the LS is comprised of three microfacies namely; grainstone, packstone and wackstone. The modal mineralogy of studied rock samples is shown in Table 4. The stylolites are being observed which show that the rock has undergone through chemical compaction (Fig. 5 (c), (e) and (f). Stylolites have affected the strength of rocks. Those rock samples which have stylolites (SSK1-3 and 6) have low values of the UCS as compared to those specimens which have no stylolites (SSK4 and 5). The chemical compaction may have been caused by the overburden pressure and/or tectonic stresses in the past. Furthermore, the microscopic studies reveal that the limestone is dominantly composed of ooids, peloids, bioclasts and calcite. The allochems are tightly packed and compacted; thus, showing mechanical compaction (Fig. 5b, c, d, e). Calcite is fine-grained. Dolomite crystals are also present in trace amount (Fig. 5a, c). No amount of silica is observed. Consequently, it is concluded that the LS of SSF has no deleterious and harmful minerals as specified by the ASTM C295 (2012) to produce alkali carbonate reaction (ACR) and ASR in the concrete. The effect of petrographic features and microstructure on the properties of aggregates has been explained by Ramsay et al. (1974), Hartley (1974), and Lees and Kennedy (1975). Consequently, petrographic study has been performed on LS to determine its suitability as aggregate source. These petrographic findings are also supported by the geochemical analysis and ASR tests. Therefore, it can be assessed from the above discussion that the limestone of the SSF can be termed suitable for both cement and construction industries.

3.4 Aggregate suitability of limestone for construction industries

Mineral composition of LS is reflected by its chemical composition. Limestone that is used in cement must contain a minimum of 70% calcite ASTM C150/C150M-18 (2018). The percentage of MgO in the clinker should not surpass 5% in the process of cement manufacturing (Oates 1998). The
geochemical evaluation of the LS (Fig. 3) shows that it has high calcite content (95.69) while low contents of alkalis, magnesia and silica (< 2%). The higher concentration of calcite and lower amount of alkalis, magnesia and silica makes it suitable for the cement manufacturing as the obtained values are in accordance with the international standards (ASTM C150/C150M-18 2018). Moreover, alkalis rich limestone is not considered suitable for cement industry, because it causes deterioration of concrete due to ASR (Insley 1950). The values of alkalis in LS show that these values are lower than the objectionable limit for the usage in cement industry. Therefore, the LS of the study area at SBH is recommended for its usage as a raw material in cement industry.

Aggregates constitute about 60-80% of the concrete by volume. Their characteristics, thus, influence the strength, workability and durability of the concrete (Smith 1979; Robert S Boynton 1980; Derucher and Heins 1981). Limestone commonly produces good quality concrete aggregates under normal conditions (Hobbs 1988; Mehta 1986; Lea 1970). Therefore, the LS of the SSF as an aggregate was evaluated. The results of various geotechnical tests suggest that the limestone of the SSF qualifies all the tests (ASTM) and is suitable as an aggregate in different construction industries.

3.5 Estimation of UCS from PLT, UPV and SHRT

UCS was calculated from PLT, UPV and SHRT by simple regression analysis (SRA). The SRA describes a relationship between two variables. Linear ($y = ax + b$), logarithmic ($y = a \ln x + b$), power ($y = ax^b$), and exponential ($y = ae^{bx}$) functions may be applied for establishing simple predictive model. Equations are accompanied by coefficient of determination ($R^2$) that is often called the proportion of variation (explained by the variable $x$). It follows $0 < R^2 < 1$. When the value of $R^2$ is close to 1, most of the variability in $y$ is explained by the regression model (Aboutaleb et al. 2017). In the present study the SRA was attained by plotting UCS against $I_s(50)$ (Fig. S1a in Supporting Information (SI), following correlation equation has been obtained:

$$UCS = 24.15 I_s (50) - 38.23 \quad (R^2 = 0.79) \quad (1)$$

Where $I_s (50)$ is the point load index at 50 mm diameter.

The relationship between the UCS and the UPV for LS is shown in Eq. 2 (Fig. S1b in SI).

$$UCS = 0.03 \text{UPV} - 104 \quad (R^2 = 0.90) \quad (2)$$

Similarly, the correlation equation for the UCS and SHRT (Fig. S1c SI) is given below:

$$UCS = 1.92 \text{SHRT} - 7.42 \quad (R^2 = 0.85) \quad (3)$$

A comparison of the results is essential to check the validity of the obtained correlation equations. Fig. S1d in SI displays the actual measured uniaxial compressive strength values plotted against the calculated uniaxial compressive strength values for the LS for Eq.1. Similarly, Fig. S1e shows the actual measured uniaxial compressive strength values plotted against the calculated uniaxial compressive strength values for Eq.2. For Eq.3, the actual measured uniaxial compressive strength values are plotted against the calculated uniaxial compressive strength values in Fig. S1f in SI. The more nearer the data points to the correlation line, the closer the prediction is to the actual value. This comparison analysis illustrates that although all the obtained equations are good enough to predict UCS. However, by using UPV for estimation of UCS is more reliable than PLT and SHRT. The data points are more closed to correlation line for Eq. 2 (Fig. S1e in SI) as compared to the data points for Eq. 3 and Eq. 1 (Fig. S1d, f in SI).

Furthermore, the obtained equation for PLT is in good agreement with the one derived by Read et al. (1980). Similarly, the derived equation for UPV is somehow close to the obtained equation of Aldeeky and Al Hattamleh (2018), however, in their case the rock used was basalt. Finally, the obtained equation for SHRT is in fair agreement with the derived equation of Tandon and Gupta (2015), however they used quartzite rock.

3.6 Relationship between geo-mechanical and petrographic properties

The geo-mechanical properties of rocks are greatly affected by petrographic characteristics. In fact, petrographic and textural features of the rock control its mechanical properties (Sajid et al. 2016). As the petrographic studies reveal that the LS of the SSF is dominantly composed of ooids, peloids and bioclasts; therefore, these constituents have greatly affected the geo-mechanical properties of the LS. Those samples having high percentage of ooids and peloids and low percentage of bioclasts (SSK3, SSK4 and SSK5) reveal high strength as compared to those samples (SSK1, SSK2 and SSK6) which have low percentage of ooids and peloids and high contents of bioclasts (Table 4). Therefore, ooids and peloids have shown moderate positive correlation with the UCS while bioclasts have shown a linear negative correlation with the latter (Fig. S2 a, b and c in SI). Furthermore, the values of UCS are directly proportional to the values of SG and BD (Fig. S2 d, e in SI). On contrary, UCS is inversely proportional to the values of WA, AIV, soundness, LAAV and CL (Fig. S2 f – j in SI).

4 Conclusions
All the geo-mechanical results of the limestone of the Sheikh Budin Hills, North-western Pakistan are well within the range of values permissible for its usage as an engineering material in construction industries. The geochemical evaluation of limestone indicates that it qualifies the international standard being required for cement manufacturing. Moreover, the ASR test also makes it suitable for its usage as aggregate material. The petrographic studies suggest that the limestone is free of any deleterious or harmful materials which can lead to alkali-silica reactivity. These studies also show that the diagenetic fabric of the limestone is well compacted thus resulting in high strength of these rocks.

Regression analysis exhibits that the empirical correlation equation for estimating uniaxial compressive strength with ultrasonic pulse velocity is more reliable than Schmidt hammer rebound test and point load test. There is a positive correlation of UCS with bulk density and specific gravity while negative correlation with water absorption, aggregate impact value, soundness, los angeles abrasion value and clay lump and friable particles. Pearson's correlation analysis has resulted in establishing strong positive correlation among CaCO₃, CaO and LOI.

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**Tables**

**Table 1** Test results performed on the aggregates parameters for construction industries in Pakistan.

| Sample ID | SG  | WA  | BD  | FI  | EI  | S   | AIV | LAAV | CL  |
|-----------|-----|-----|-----|-----|-----|-----|-----|------|-----|
| SSK1      | 2.67| 0.50| 1.57| 19.40| 18.80| 1.7 | 15.13| 25.00| 0.40|
| SSK2      | 2.66| 0.49| 1.58| 16.08| 17.16| 1.7 | 14.18| 23.32| 0.39|
| SSK3      | 2.67| 0.47| 1.59| 15.20| 14.12| 1.6 | 13.46| 22.66| 0.37|
| SSK4      | 2.67| 0.40| 1.59| 16.16| 15.12| 1.3 | 12.37| 21.76| 0.24|
| SSK5      | 2.67| 0.45| 1.59| 16.64| 16.96| 1.5 | 12.79| 22.26| 0.28|
| SSK6      | 2.66| 0.51| 1.54| 17.56| 16.16| 1.9 | 16.44| 26.04| 0.42|
| Minimum   | 2.66| 0.40| 1.54| 15.20| 14.12| 1.3 | 12.37| 21.76| 0.24|
| Maximum   | 2.67| 0.51| 1.59| 19.40| 18.80| 1.9 | 16.44| 26.04| 0.42|
| Mean      | 2.66| 0.47| 1.58| 16.84| 16.39| 1.6 | 14.06| 23.51| 0.35|

**Standards (Limits) for aggregates**

- ASTM 127 (< 2.6) for road and concrete aggregate
- ASTM 127 (< 2.5 %) for concrete aggregate
- ASTM C-29
- BS-882 (< 40 %) Road and cement concrete
- BS-812 105.2 (max. limit 25 %) for cement concrete
- ASTM C88 (L< 12 %) for concrete aggregate
- BS 812:112 (max. 30 %) for cement concrete
- ASTM C-131 (<40 %) for road aggregates
- ASTM C-142-10 (< 1%) for road aggregate

SG = Specific gravity, WA = Water absorption, BD = Bulk density, FI = Flakiness Index, EI = Elongation Index, S = Soundness, AIV = Aggregate Impact value, LAAV = Long angles abrasion value, CL = Clay lumps.

**Table 2** Strength test results performed on the limestone samples for construction industries in Pakistan.
| Sample ID | UCS   | PLT  | UPV      | SHRT |
|-----------|-------|------|----------|------|
| SSK1a     | 78.44 | 4.92 | 5148.65  | 44   |
| SSK1b     | 81.92 | 5.08 | 5219.18  | 46   |
| SSK1c     | 76.46 | 4.81 | 5046.36  | 43   |
| SSK2a     | 83.41 | 5.25 | 5328.67  | 48   |
| SSK2b     | 80.09 | 4.92 | 5219.18  | 47   |
| SSK2c     | 77.39 | 4.81 | 5114.09  | 45   |
| SSK3a     | 85.60 | 4.92 | 5291.67  | 49   |
| SSK3b     | 90.98 | 5.03 | 5366.20  | 51   |
| SSK3c     | 92.07 | 5.30 | 5442.86  | 52   |
| SSK4a     | 98.34 | 5.68 | 5482.01  | 52   |
| SSK4b     | 100.28| 5.79 | 5602.94  | 56   |
| SSK4c     | 101.47| 5.89 | 5729.32  | 58   |
| SSK5a     | 97.51 | 5.46 | 5562.04  | 50   |
| SSK5b     | 95.27 | 5.35 | 5482.01  | 52   |
| SSK5c     | 92.26 | 5.08 | 5404.26  | 53   |

Table 2 continued

| Sample ID | UCS   | PLT  | UPV      | SHRT |
|-----------|-------|------|----------|------|
| SSK6a     | 79.75 | 5.08 | 4980.39  | 43   |
| SSK6b     | 76.86 | 5.03 | 4948.05  | 45   |
| SSK6c     | 73.83 | 4.76 | 4853.50  | 46   |
| Minimum   | 73.83 | 4.76 | 4853.50  | 43   |
| Maximum   | 101.47| 5.89 | 5729.32  | 58   |
| Mean      | 86.77 | 5.18 | 5290.08  | 49   |

Standards (Limits)
- (High strength 60-200 Mpa ISRM (ISRM 2008)
- Strong rock 4-10 Mpa (Selby 1980)
- UPV>4575 m/s (Excellent) (Malhotra 1976)
- Moderate to strong rock 40-60 N (Selby 1980)

UCS = Uniaxial compress strength, PLT = Point load test, UPV = Ultrasonic pulse velocity, SHRT = Schmidt hammer rebound test
Table 3: Pearson correlation analysis among major oxides of limestone samples of the study area.

| Major oxides | CaO   | MgO  | Na₂O | Fe₂O₃ | MnO | SiO₂ | P₂O₅ | TiO₂ | Al₂O₃ | LOI | CaCO₃ |
|-------------|-------|------|------|-------|-----|------|------|------|-------|-----|-------|
| CaO         | 1.00  |      |      |       |     |      |      |      |       |     |       |
| MgO         | -0.857| 1.00 |      |       |     |      |      |      |       |     |       |
| Na₂O        | -0.133| 0.305| 1.00 |       |     |      |      |      |       |     |       |
| Fe₂O₃       | -0.171| 0.200| 0.277| 1.00  |     |      |      |      |       |     |       |
| MnO         | -0.304| 0.055| -0.385| 0.277| 1.00|      |      |      |       |     |       |
| SiO₂        |      |      |      |      |     | -0.794| 0.645|      |      |     |       |
| P₂O₅        | 0.143 | -0.060| 0.239| 0.269| 0.215| -0.027|      | 1.00 |       |     |       |
| TiO₂        | -0.297| 0.025| 0.014| 0.136| 0.085| 0.073| 0.391|      |       |     |       |
| Al₂O₃       |      |      |      |      |     | -0.653|      |      |       |     |       |
| LOI         | 0.867 | -0.781| -0.284| -0.504| -0.632| -0.068| -0.232| -0.061| 1.00 |     |       |
| CaCO₃       | 0.946 | -0.838| -0.112| -0.259| -0.363| -0.769| -0.045| -0.324| -0.070| 0.950| 1.00 |

Bold values determined significant positive and negative correlation.

Table 4: Modal composition of the limestone of Pakistan.

| Sample ID | Micrite % | Sparite % | Allochems | Dolomite % | Silica % | Stylolites/Fractures | Dunham Classification | Silica reactivity |
|-----------|-----------|-----------|-----------|------------|----------|----------------------|----------------------|------------------|
| SSK1      | 11        | 31        | 24        | 21         | 13       | 58                   | 0                    | yes              |
| SSK2      | 3         | 6         | 32        | 39         | 18       | 89                   | 2                    | yes              |
| SSK3      | 1         | 5         | 62        | 21         | 10       | 93                   | 1                    | yes              |
| SSK4      | 2         | 8         | 52        | 30         | 8        | 90                   | 0                    | no               |
| SSK5      | 3         | 6         | 45        | 34         | 12       | 91                   | 0                    | no               |
| SSK6      | 75        | 2         | 3         | 1          | 19       | 23                   | 0                    | yes              |

Figures
Figure 1

Geological map showing location of the study area in Sheikh Buddin Hills, Marwat Range Pakistan (Gee and Gee 1989). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

a) The outcrop view of the Samana Suk Formation overlaying Datta Formation at foot of the hills. b, c) a close up view of the limestone exposure in the study area.
Figure 3

Showing the major oxides determination of the limestone of the Samana Suk Formation.
Figure 4

Calculated data (stars) of the alkali-silica reactivity on the graph (Grattan-Bellew and Chan 2013).

Figure 5

Photomicrographs showing important petrographic features in the investigated samples of the Samana Suk Formation: grainstone microfacies (a, b, c and d), packstone microfacies (e) and wackstone microfacies (f).
Figure 6

Scanning electron microscopy images showing the fabric and morphology of the limestone of the Samana Suk Formation (Sc: Suture contact; M: Matrix; Sty: Stylolite).

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