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

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Abstract

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

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1.0 INTRODUCTION

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

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

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

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

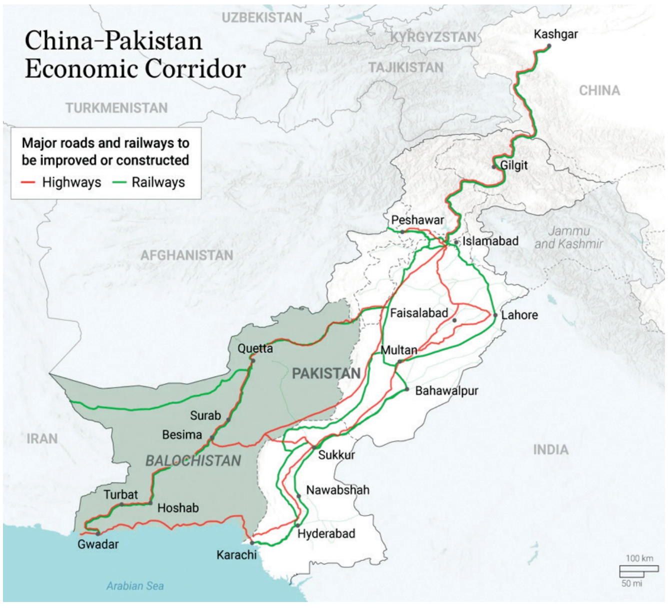

Figure 1: Large-scale project "Pakistan-China Economic Corridor (CPEC)" in Pakistan

performance in alkali–silica and alkali–carbonate reactivity tests, as well as in petrographic and mechanical assessments conducted in accordance with ASTM, AASHTO, and British standards (Gondal *et al.,* 2009; Ahsan *et al.,* 2012; Rehman *et al.,* 2018).

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

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

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

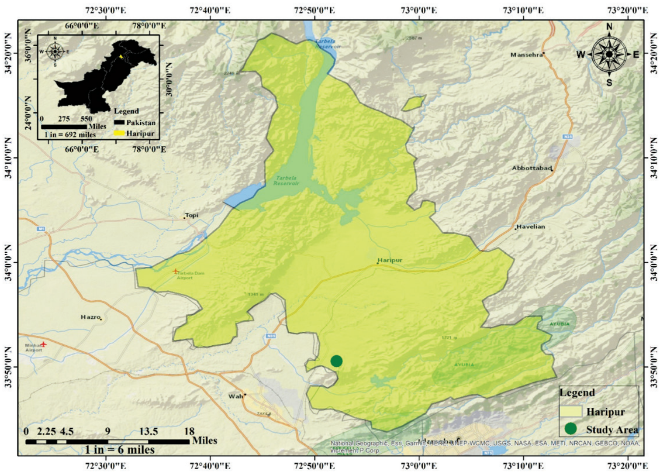

Figure 2: Study area in District Haripur, Khyber Pakhtunkhwa, Pakistan

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

2.0 GEOLOGICAL CONTEXT OF THE SAMANA SUK FORMATION

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

2.1 Location and Tectonic Setting

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

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

2.2 Lithology and Petrography of the Samana Suk Formation

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

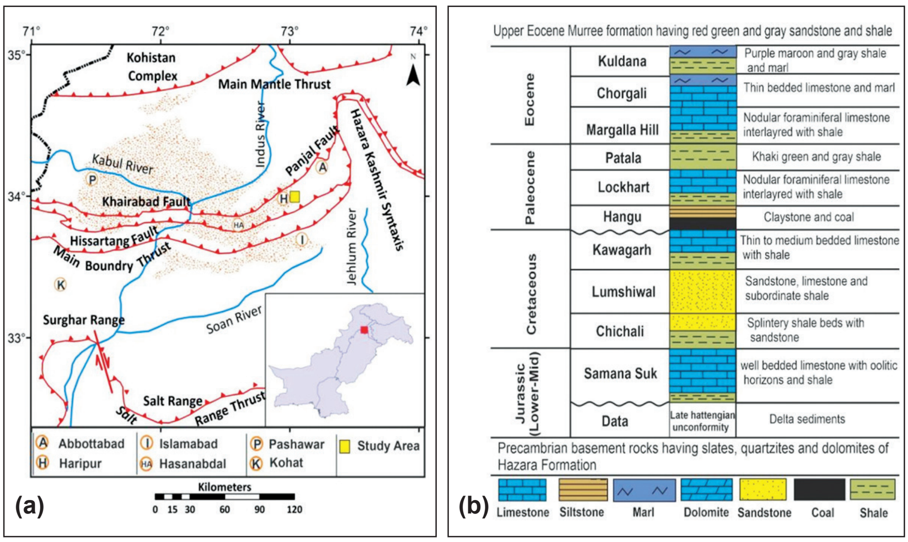

Figure 3: The Geological Setting of the region (a) Showing a Tectonic map of the region (after Hylland and Riaz 1988) indicating the study site's position in the yellow box; (b) Showing Generalised stratigraphy surrounding the examined sections within the research site (Shah, 2009). (Thicknesses are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

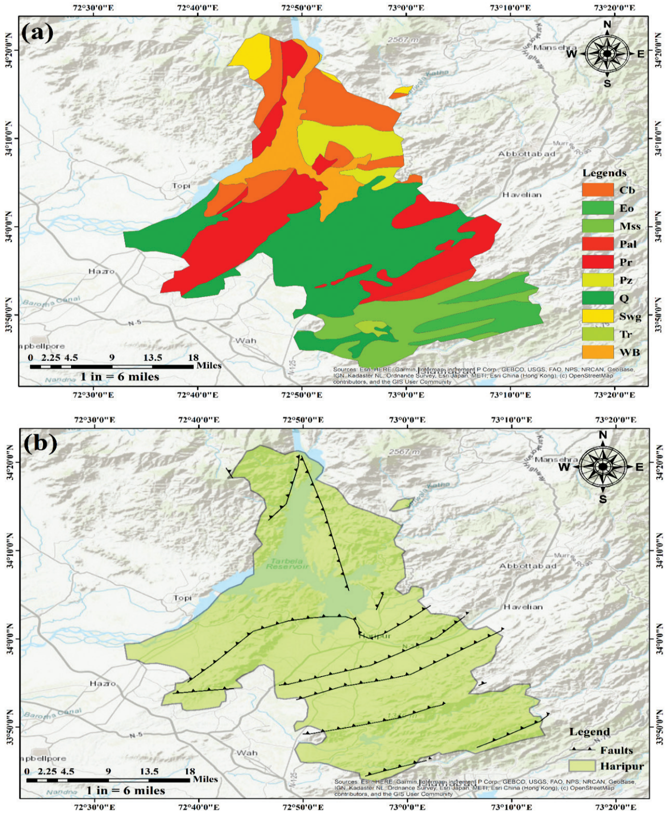

Figure 4: The geological getting of the Haripur District (a) Showing a generalised stratigraphy of District Haripur; (b) Showing a tectonic map of the of District Haripur

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

2.3 Structural Deformation and Tectonic Influence

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

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

2.4 Field Observations and Sedimentary Features

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

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

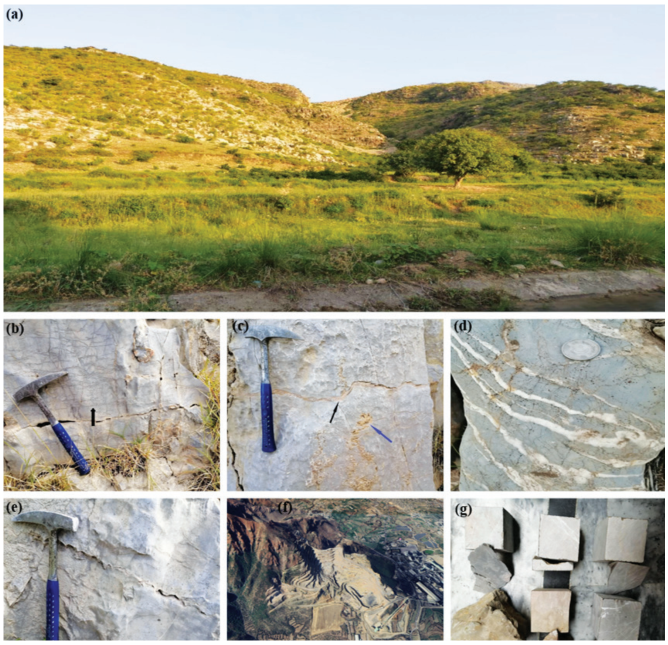

Figure 5: Geological features and strength testing of the Samana Suk Formation at Village Rani Wah, Hattar-Khanpur (a) Panoramic view of the exposed limestone beds; (b) Thick-bedded limestone with fractures (hammer for scale); (c) Medium-bedded limestone exhibiting bioturbation and dolomite-filled veins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

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

3.0 MATERIALS AND METHODS

3.1 Geological Context and Sampling Procedure

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

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

3.2 Laboratory Testing and Analysis

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

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

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

3.3 Petrographic Analysis and Modal Analysis

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

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

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

3.4 Evaluation Standards and Aggregate Suitability

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

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

4.0 RESULT AND DISCUSSION

4.1 Petrographic Analysis

4.1.1 Mineral Composition

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

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

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

4.1.2 Alkali-Silica Reaction (ASR)

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

4.1.3 Alkali-Carbonate Reaction (ACR)

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

4.2 Geotechnical Test Results

4.2.1 Density and Moisture Absorption

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

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

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

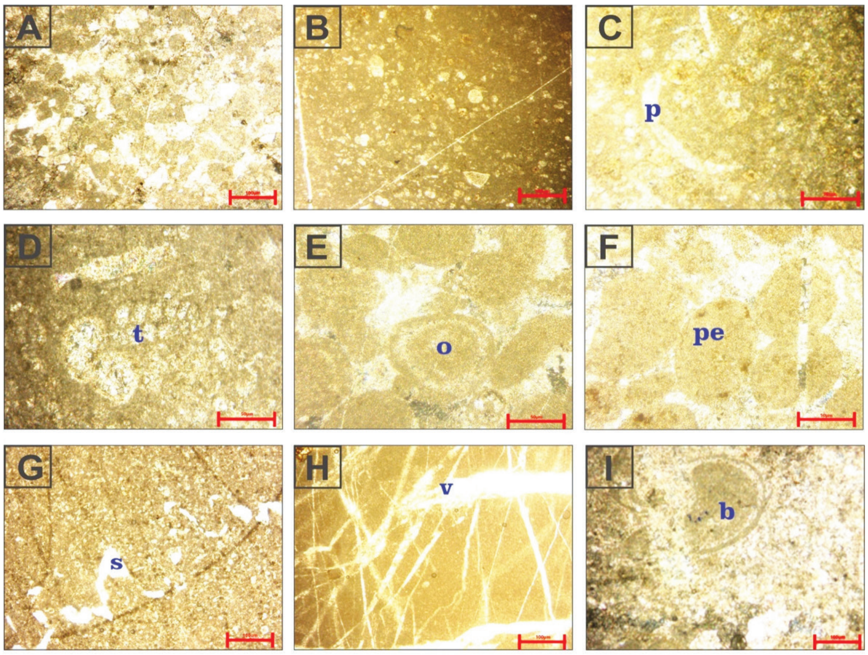

Figure 7: Microphotographs illustrating significant petrographic characteristics observed in the analysed samples of the Samana Suk Formation
A) spar; B) micrite; C) pelecypods (p); D) texularia fossil (t); E) ooids (o); F) peleoids (pe); G) stylolities; H) calcite filled veins; I) bivalvia fossil

4.2.2 Unconfined Compressive Strength Analysis (UCS)

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

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

4.2.3 Split Tensile Strength Analysis

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

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

4.2.4 Soundness Assessment

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

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

4.2.5 Los Angeles Abrasion Test

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

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

4.2.6 Flakiness Index Test

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

Table 1: Geotechnical test results of Sumana Suk Formation Limestone

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

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

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

4.2.7 Elongation Value Test

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

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

4.2.8 Application and Layering of Bitumen

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

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

4.2.9 Density of the Aggregate Compacted/Uncompacted

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

4.2.10 Clay Lump and Friable Particles

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

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

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

5.0 ECONOMIC, SUSTAINABILITY, AND BROADER APPLICATIONS OF LIMESTONE

5.1 Economic Analysis and CPEC Context

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

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

5.2 Sustainability Implications

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

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

5.3 Scalability Barriers and Solutions

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

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

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

5.4 Broader Engineering Applications

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

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

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

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

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

6.0 CONCLUSION

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

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

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

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

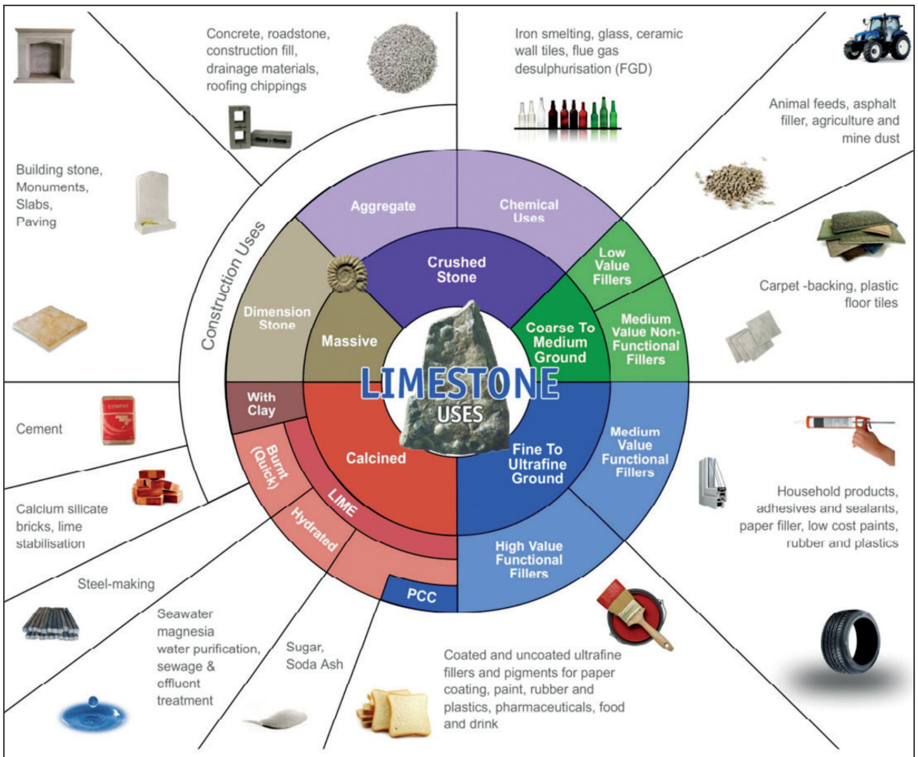

Figure 8: Visual representation of common uses for limestone materials (Kambakhsh et al., 2024)

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

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

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

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

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

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- **Muhammad Ramzan:** Conceptualisation, Methodology, Software, Validation, Formal analysis, investigation, Data curation, Writing original draft, Writing (review and editing), visualisation.
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- **Daniya Ualiyeva:** Software, Writing (review and editing).
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