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Resource Assessment of Limestone Based on Engineering and Petrographic Analysis

Javid Hussain [1], Jiaming Zhang [1*], Xiao Lina [1], Khaleel Hussain [1], Syed Yasir Ali Shah [1], Sajid Ali [1], Altaf Hussain [2]

[1] *Faculty of Engineering, China University of Geosciences, Wuhan, China.*

[2] *Faculty of Earth Resources, China University of Geosciences, Wuhan, China.*

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Abstract

The China-Pakistan Economic Corridor (CPEC) is a massive in-progress construction project in Pakistan that connects more than 70 countries via multiple trade channels such as highways, railways, roads, and fiber optics. This project also involves the development of local infrastructure and industrial zones in Pakistan, which demands the discovery of new resources of aggregate to facilitate the construction. Therefore, physical characterization research was carried out on the Kirman hill region (Jurassic limestone), District Kurram, Pakistan, to investigate their suitability for utilization as construction materials using site investigation and laboratory studies. The results outline that all typical engineering parameters are within acceptable limits set by international standards like BS, ASTM, and AASHTO. Bituminous tests revealed that Jurassic limestone is appropriate as an aggregate for asphalt wearing coarse. Likewise, the petrographic study performed shows proper matching with engineering tests. The petrographic analysis of Jurassic limestone showed a minute amount of deleterious content; as a result, it is resistant to Alkali silica reaction (ASR) and Alkali carbonate reaction (ACR) expansions. Based on engineering and petrographic analysis, the Jurassic limestone, Kirman hill region, District Kurram, Pakistan is recommended as a potential aggregate for (i.e., base course, subbase course, cement concrete, and asphalt) and other mega and minor civil construction projects.

Keywords: CPEC; Engineering Properties; Petrographic Analysis; Jurassic Limestone; District Kurram.

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1. Introduction

Limestone is most commonly utilized as a potential aggregate for minor and mega civil projects in Pakistan [1]. It's mostly made of calcite and aragonite, the crystal form of calcium carbonate ($CaCo_3$). Geological materials occur as sedimentary, igneous, and metamorphic rocks [2]. Among these, sedimentary rocks, such as gravels, pebbles, cobbles, and broken rocks, comprise the majority of construction materials [2, 3]. However, igneous and metamorphic rocks can also be used as building materials, depending on their appropriateness and transportation costs. In general, older limestone is more substantial and suitable for use on road surfaces and under pavements. It has been widely used as a crushing aggregate for the construction industry because of its benefits, such as increased concrete strength, reduced risk of ASR, ACR, and reduced drying shrinkage [4]. However, every limestone aggregates are not suitable for construction work because their physical/Mechanical and chemical characteristics vary significantly with various geological sources [5].

* Corresponding author: zjm@cug.edu.cn

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Aggregates must meet strict specifications, and only a few geological formations are capable of meeting this demand. Physical and chemical characteristics affect its suitability as a construction material and these properties are directly related to the quality of the source rock [5]. The geological features of aggregates impact their performance regardless of how they are utilized [6, 7]. Folding, faulting, joints, hydrothermal alteration, and weathering are some of the geological processes that result in aggregate physico-mechanical properties [8]. Therefore, the lithological description and Petrographic analysis of geological parameters are essential for evaluating the physical and chemical characteristics that determine an aggregate's engineering behaviour. Crushed rock aggregates are more suitable in high/heavy transport because it's often more difficult to displace. The foremost purpose is, it is long-lasting and performs well. Because of these reasons, it is frequently utilized to pave industrial zones like railway trails. Over 90 % of asphalt and 80 % of rigid pavements in road construction are composed of crushed aggregates [9, 10].

Pakistan is abundant with limestone aggregates, produced by crushed intact rock. Margala hill Limestone, Kirana hills aggregate, Khyber Limestone, Wargal Limestone, Skaser Limestone, Kohat Carbonates are the major source of aggregate in Pakistan [1, 11-13]. These aggregates were utilized by the National Highway Authority (NHA) for the construction of highways, under China-Pakistan Economic Corridor (CPEC) mega project. CPEC is a billion of dollars' worth project that connects over 70 nations through Pakistan's Gwadar Port. Which involves several long- and short-term projects, including roads, railway lines, and fiber optics. Moreover, this project encompasses both major and small-scale building construction. However, in view of the tremendous increase in the demand for construction materials due to the country's fast population growth and construction minor and mega-projects such as CPEC projects, existing aggregate resources are becoming insufficient. It is essential to conduct prospective exploration for new resource development that fulfills the needs of the construction activities.

The present investigation has been conducted in Northwest Pakistan's (Kurram District) mountainous area (Kirman Hill region) (Figure 1) to determine its suitability as a construction material for minor and mega-projects and other local civil construction projects. To the author's knowledge, no research on the physical/mechanical and petrographic analysis of Jurassic limestone in the Kirman hill region has been conducted. According to Ullah et al. (2020) [14], geochemical, petrographic, and physiochemical investigations can be used to determine the appropriateness of aggregates for construction work. The physical characteristics of Jurassic limestone were compared to the acceptability limits for aggregate sources set by national and international standards (BS, ASTM, and NHA). Physio-chemical characteristics and durability, mineral components, petrographic composition, porosity, specific gravity, hardness, and physio-chemical stability are all intrinsic characteristics of a thin section of rock [8, 15]. When investigating aggregates optically, the presence of bioclasts, the type of matrix, texture, and microfractures are all important factors to analyze. Porosity has a significant impact on the physical properties of rock aggregates [16]. Mineralogy and texture are imperative features that influence a material's physical resistance to crushing, abrasion, volume change, and chemical decomposition. The texture of a rock is a complicated aspect that affects an aggregate's abrasion and crushing properties [17, 18]. The petrographic characteristics of parent rock greatly impact the mechanical properties of crushed rock aggregates. The impact of aggregate qualities on microstructure and other petrographic features has been studied by [3, 19, 20]. The present study focuses on evaluating the resource potential of Jurassic limestone for usage as aggregate based on its geotechnical properties and petrographic analysis to determine its suitability as an aggregate source for roads, cement concrete, and other civil projects. This research will assist in the identification of new prospective resource sites that should be exploited in the near future.

2. Study Area, Physiography, Geological and Stratigraphy Setting of the Area

2.1. Area and Physiography

District Kurram is situated in Northwest Pakistan, Tribal areas, next to the Afghan border (Figure 2), and lies between 33°53'12.30"N, and 70° 9'38.38"E. It is surrounded by Afghanistan in the North and West, the Khyber and Orakzai agencies border on the East, the Hangu district to the Southeast, and the North Waziristan Agency on the South, which covers 3308 km^2 of land. According to the Pakistani census report for 2019, the study area had a population of 619,553.

The District Kurram's most remarkable physiographic characteristics are the wide span of Parachinar Plain in the middle and the towering Spin Ghar that forms its northern border with Afghanistan. The Southernmost plain is delineated by the Mangal and Charmu hills from Pewar Kotal to Kharlachi, and the Mangal hills lie along its western edge [21] as follows, the upper Kurram is divided into five sections:

- Koh-e-Safid (Spin Ghar)
- Tirah Mountains
- The valley of Parachinar
- Southern Mountains
- Western Mountains

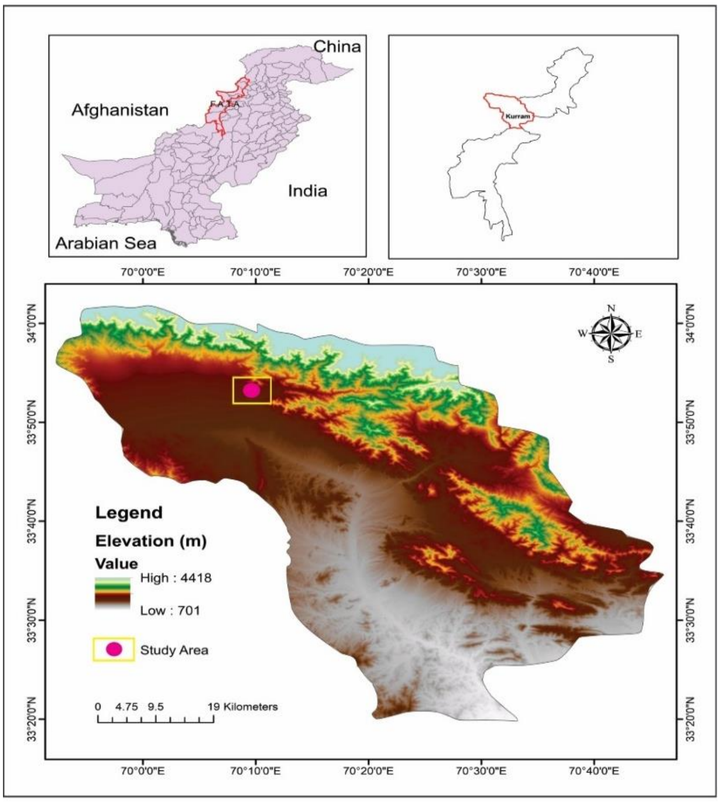

Figure 1. Location map of study area (District Kurram, Kirman hill Region)

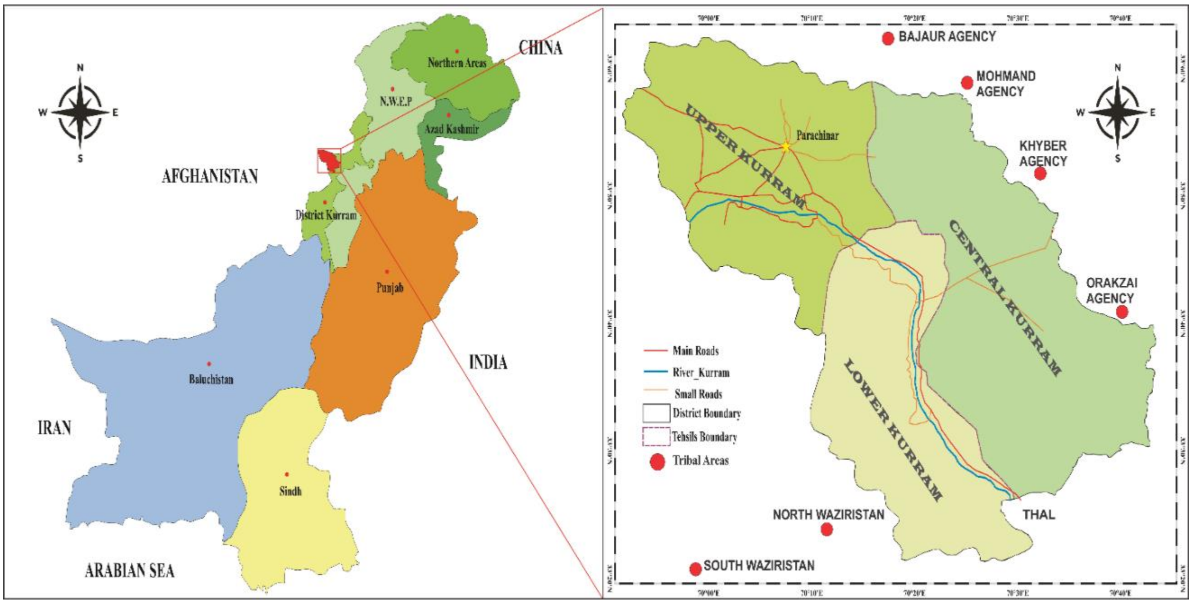

Figure 2. Federally administrated Tribal area, Kurram District

Spin Ghar, 14000 ft. above sea level, is Kurram's most remarkable landmark, and also known as Sufaid-e-Koh, has an East to West orientation between Pakistan and Afghanistan. Several streams that drain the southern slopes of the mountains have formed small valleys across the ridges' slopes. These transverse valleys serve as access points to the range's core, and some notable transverse valleys include Pewar, Shalozan, Shian, Zeran, Kirman, and Dardar; some of these valleys are linked by bypasses that pass through Nangarhar Province in Afghanistan. These peaks have elevations ranging from 3,352 to 3,962 meters. District Kurram temperatures vary from -3°C in the winter to 30-35°C in the summer [21].

2.2. Geological and Stratigraphical Setting of the Area

Pakistan's geological setting is delineated by a collisional plate boundary that extends along with the country's northern and western borders. The collision of the Indian and Eurasian (Karakoram) plates produced the northern plate border. The Kurram Waziristan-Sulaiman-Kirthar Ranges mark the westren boundary, developed as the Indian plate collided with the Afghan Block [21].

The District Kurram is located where two foreland collisional orogens meet. The Tirah Range is an extension of the Samana Range to the West, including the Kala Chitta and Margalla mountains, to build the hill range [22]. The Main Boundary Thrust (MBT) divides the outer Lesser Himalayas from the sub-Himalayas in the South, and this hill range is part of it (Figure 3). The scarcity of sub-Himalaya molasse deposits makes differentiating the MBT in the Kurram Agency from Thal westward. The juxtaposition of the two structural trends at the confluence of two collision boundaries [21].

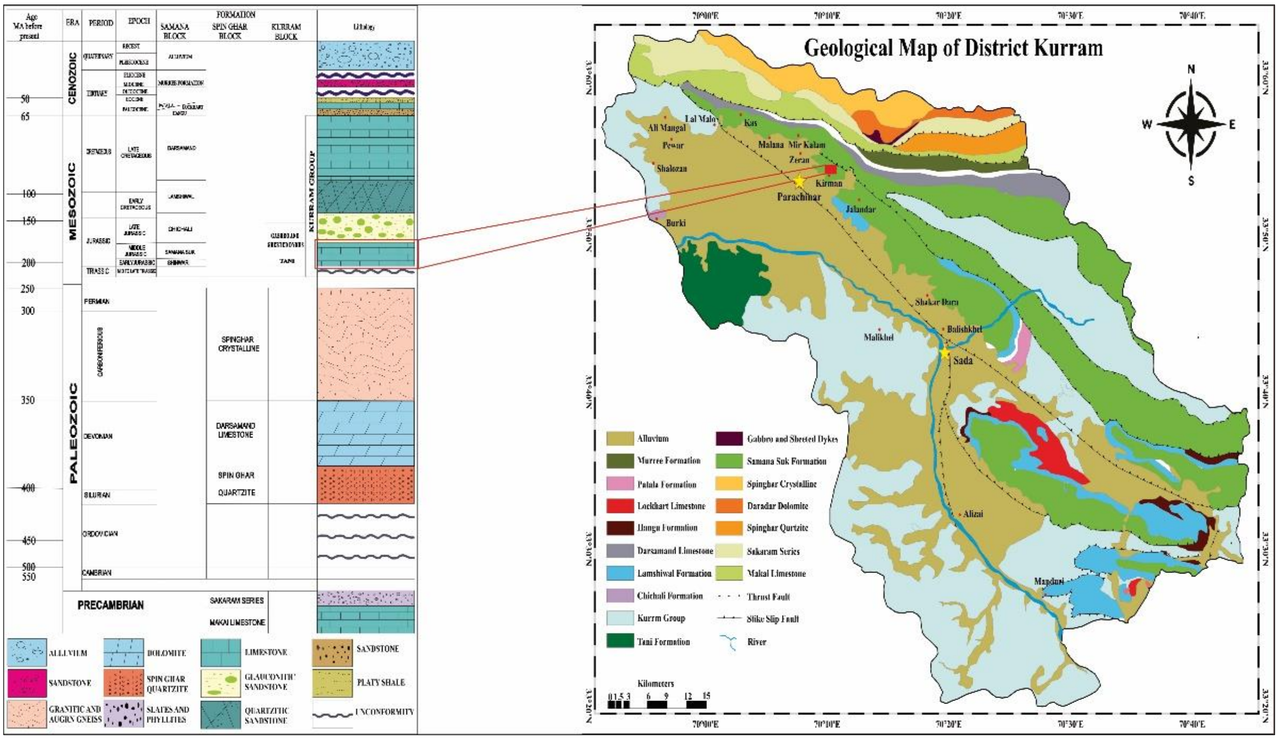

Figure 3. Geological Map of District Kurram, Pakistan

According to Lithology, the District Kurram is divided into two geological zones (Northern and Southern). The northern zone, located north of the Kurram River, comprises crystalline and metamorphosed Precambrian and Paleozoic rocks. Generally, unmetamorphosed Mesozoic rocks and Miocene Indian Shelf sedimentary rocks [23]. The northern domain lithological units dated from the Precambrian to the Miocene eras and are often buried by massive mounds of sediment [21]. The southernmost zone is made up of western thrust sheets that have been imbricated and pushed Eastward across Indian Shelf deposits south of the Kurram River. The thrust sheet series cover the Triassic to Cretaceous eras. The allochthonous series consists of the outer shelf and slope sequences, as well as deep marine sediments and ophiolites [23]. The Kurram Group was named by Meissner et al. (1975) [24] without differentiating any stratigraphy. The southern zone rocks are Cretaceous to Paleocene in age.

2.2.1. Samana Block

The Samana block is a succession of lithostratigraphic units in the Makai Thrust footwall of Spin Ghar block in the South that were studied in this research. Two sets of lithologies separate the block into two thrust sheets. The Indian Plate Shelf Sequence is located in the Outer Lesser Himalayan hill ranges (Samana, Kala Chitta, and Margalla Ranges). This group of rock unit dates from the Triassic and Miocene periods. The Kurram group, which comprises Cretaceous rocks, defines the upper thrust sheet [25]. The Indian-Plate Shelf Sequence contains Mesozoic rocks such as the Jurassic Samana Suk, Darsamand, Kawagarh formations, and the Cretaceous consists of Chichali, Lumshiwal formations (Figure 4).

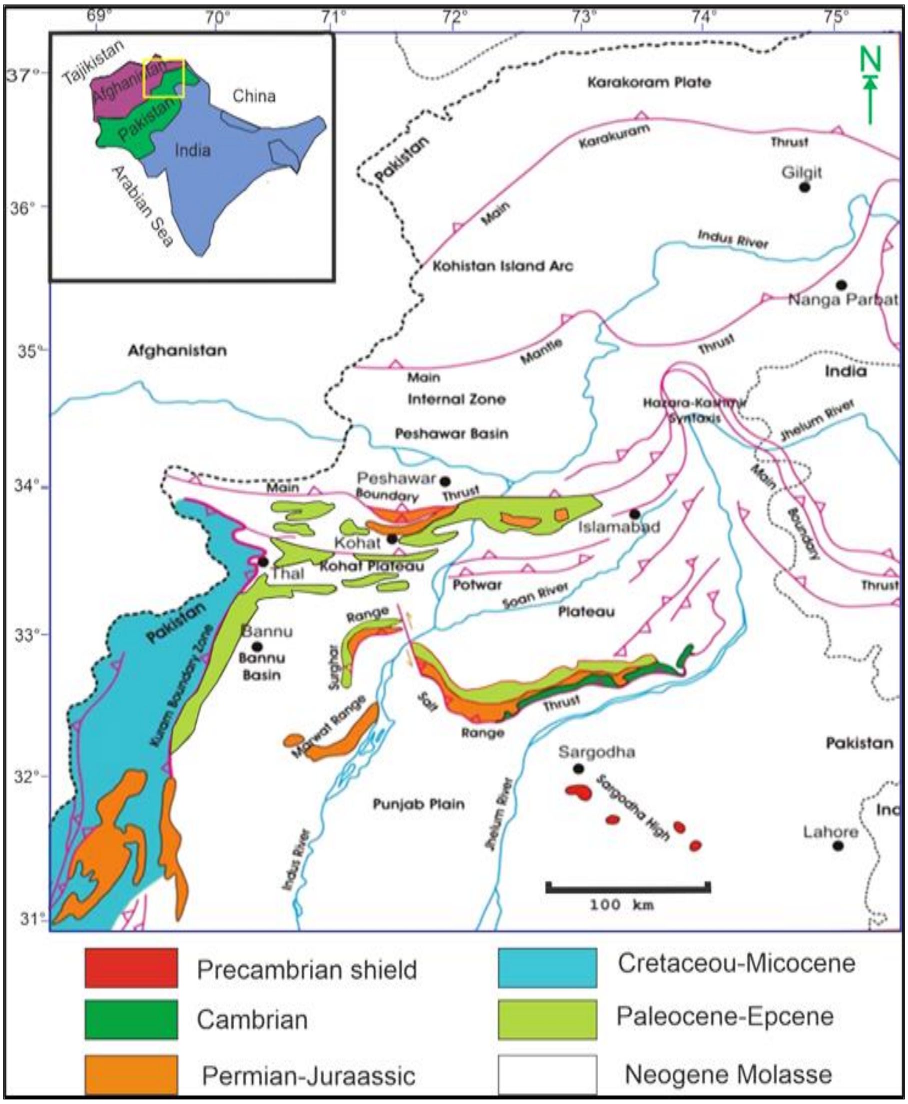

Figure 4. Map of Western Himalayas shows the (MBT), Kohat Plateau (KP), and Kurram Boundary Zone (KBZ) in North Pakistan Modified after [13]

2.2.2. Samana Suk Formation

Davies (1930) [26] named the Kohat District and the Orakzai Agency's Samana Suk limestone, later retitled by Shah (1977) [27] as Samana Suk formation. The formation in the field is made up of light grey to grey and dark grey limestone with traces of reddish-grey sandstone (Figure 4). The limestone revealed at the Samana anticline's core is more than 345 ft. thick, whereas the top few feet are visible at Khadimak. Partly metamorphosed Samana Suk Limestone, colloquially known as marble, is located 5 km north of Parachinar. The limestone is non-oolitic and huge at the base, and it varies in color from light grey to dark grey. Limestone with thin to medium bedded has generated stylolites layers [21]. The Samana Suk limestone has unconformable contact with the Cretaceous Lumshiwal-Chichali formations is characterized by a pitted, grooved, ferruginous, eroded surface. Based on fossil identification (Belemnopsis sp. and perisphinctid ammonites) by Fatmi (1974) [28], the Samana Suk formation was dated as Middle Jurassic.

3. Materials and Methods

Field and laboratory work were employed to investigate the Samana Suk formation and assess their aggregate suitability for construction purposes. Materials for laboratory analysis were acquired from the Jurassic limestone Samana Suk formation of the Kirman hill region. Currently, various high-capacity crushers operate in Samana Suk Kirman limestone, generating crushed aggregates for road and building construction. The current research is carried out for aggregate (Coarse) at the China University of Geosciences, Wuhan, China.

3.1. Field Work

In the study area, fieldwork was conducted to collect representative samples for laboratory analysis. Depending on the feasibility of the adopted [29] standard, samples are usually available in block or crushed form. Outcrop and crushing plant samples were among the samples examined in this study.

The present research focuses on four bulk samples of the crushing plant in the Samana Suk limestone Kirman hill region for Physical/Mechanical and Chemical Properties. Six samples from the outcrop of Kirman hill were used to conduct the petrographic analysis and four samples were collected to conduct engineering analysis.

3.2. Laboratory Work

The samples were subjected to various geotechnical tests using standard techniques advanced by the AASHTO [30]. Under the established standards, physical/mechanical and chemical testing was conducted on all four representative samples to select decent quality and performance-bound aggregate usage in the construction sector.

It is essential to characterize the aggregate. Physical/Mechanical and chemical tests were carried out to ensure that the required standards were met. These aggregates were also petrographically assessed in order to determine their alkali-aggregate reaction potential (ASR & ACR). Each sample was tested four times to reduce the chance of errors and ensure accurate results. The represented samples were prepared and dried in laboratory for the following tests:

3.2.1. Petrographic Analysis

Petrographic studies are frequently employed to determine the reactive components in aggregates [31]. The current petrographic research's main goal is to identify the mineral composition of the rock's aggregate, size, kind, and composition.

To better understand the potential depositional settings and diagenetic material on the engineering properties of the understudied rocks, a comprehensive petrographic analysis was used to identify different depositional environments and diagenetic fabric. In highly alkaline conditions such as Portland cement concrete, aggregates sensitivity to chemical reactions is determined through the analyzed aggregate. Aggregate composition and porosity influence Portland cement concrete's ability to withstand structural collapse in freezing and thawing conditions [32]. Limestone was separated into microfacies for better understanding. Microfacies are classified based on the limestone classification methodology [33].

A model analysis technique was used to determine the mineral percentage. Modal analysis is a rock petrography identification approach that counts the distinct minerals found in each rock type and estimates their mineralogical composition and crystal formation % age. The samples were selected based on their mineralogical composition, which has a strong influence on the quality of aggregate materials [34-36]. According to Jethro et al. (2014) [37], "Equation 1 can be used to compute percentage Mineral Composition".

$$\mathrm{C_m} = \frac{\mathrm{T_m}}{\mathrm{T_{tm}}} \times 100 \tag{1}$$

whereas C_m is the percentage mineral composition (%), T_m is the Total number of count for a mineral and T_{tm} is total number of count for the entire mineral.

3.2.2. Physical Tests

- Specific gravity and water absorption rate according to AASHTO T 85 [38];
- Particles shape (Flakiness and elongation) according to BS-812-105.1 & 2 [39, 40].

3.2.3. Durability Tests

- Los angles test according to ASTM C131-06 [41];
- Soundness test according to AASHTO-T-104-99 [42].

3.2.4. Mechanical Tests

- Aggregate Impact Value [43];
- Aggregate crushing value [44];
- Aggregate bulk density (Unit weight) [45].

3.2.5. Bituminous Tests

- Stripping and Coating test of aggregate [46].

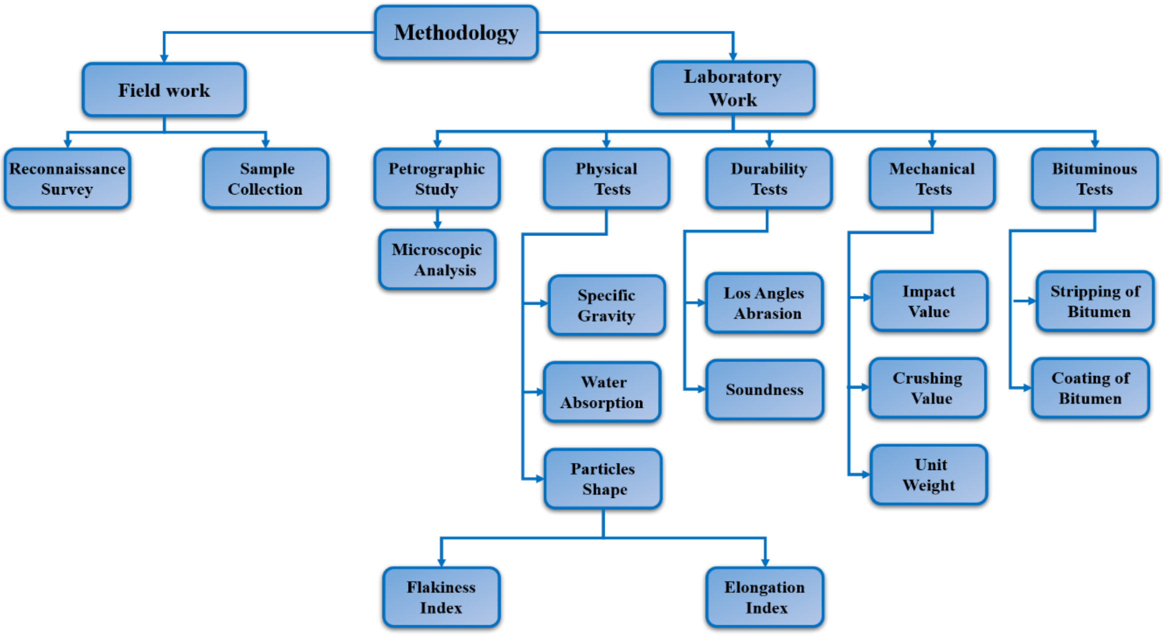

Figure 5. Flowchart of the research methodology

4. Results and Discussions

4.1. Petrographic Analysis

The Jurassic limestone investigated samples of the Samana Suk formation are light grey to dark grey (fresh sample) and yellowish-greyish to yellowish (weathered sample) (Figure 6). It has fine to medium grain, cracked, thin to medium bedded, rigid, compact, and partly recrystallized. Petrographic characteristics have a significant impact on a rock's mechanical properties. The study of rock's grain shape, size, fabric, grain boundaries, mineralogical content, and weathering gives substantial insights into the mechanical behavior under stress [47]. Aggregate reactive components are hazardous since they reduce the material's tensile strength, durability, and ability to adhere. The ASR and ACR occur when the Aggregate interacts with water [48]. From the Petrographic analysis of Jurassic limestone, the stressed conditions stretch microcrystalline veins and nanoplanktons, defining accurate lineation. Nanoplanktons, benthic foraminifera, Ostracodes, and algae are found in fossils (Figure 7 (B, C, E)); veins are multiphase and crosscutting in nature. The stylolites are clear and in line (Figure 7 (C, E, F)). This lends credence to the concept of unidirectional stresses. The dissolution veins and stylolites indicated that the rock is under compression (Figure 7 (A, C, E)). In the veins, calcite is reprecipitated.

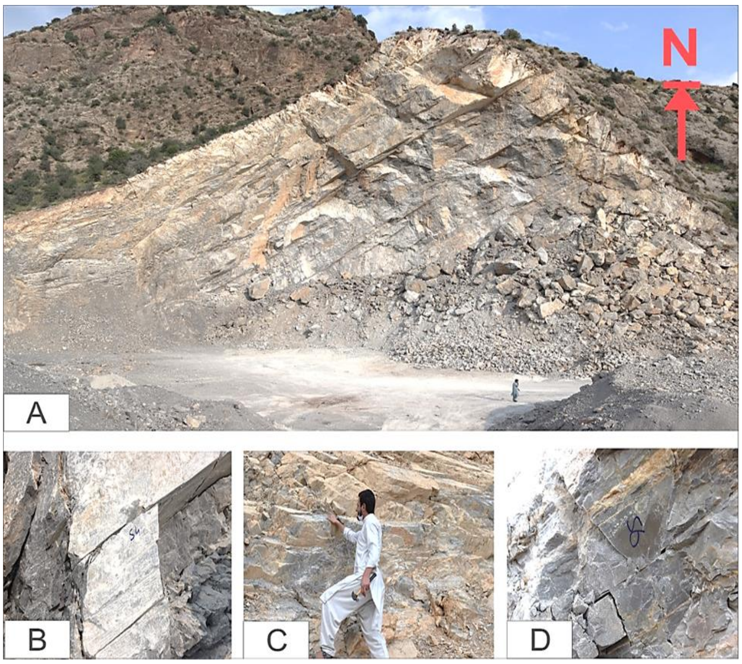

Figure 6. Outcrop view of Jurassic Limestone, District Kurram, Kirman Hill region Parachinar

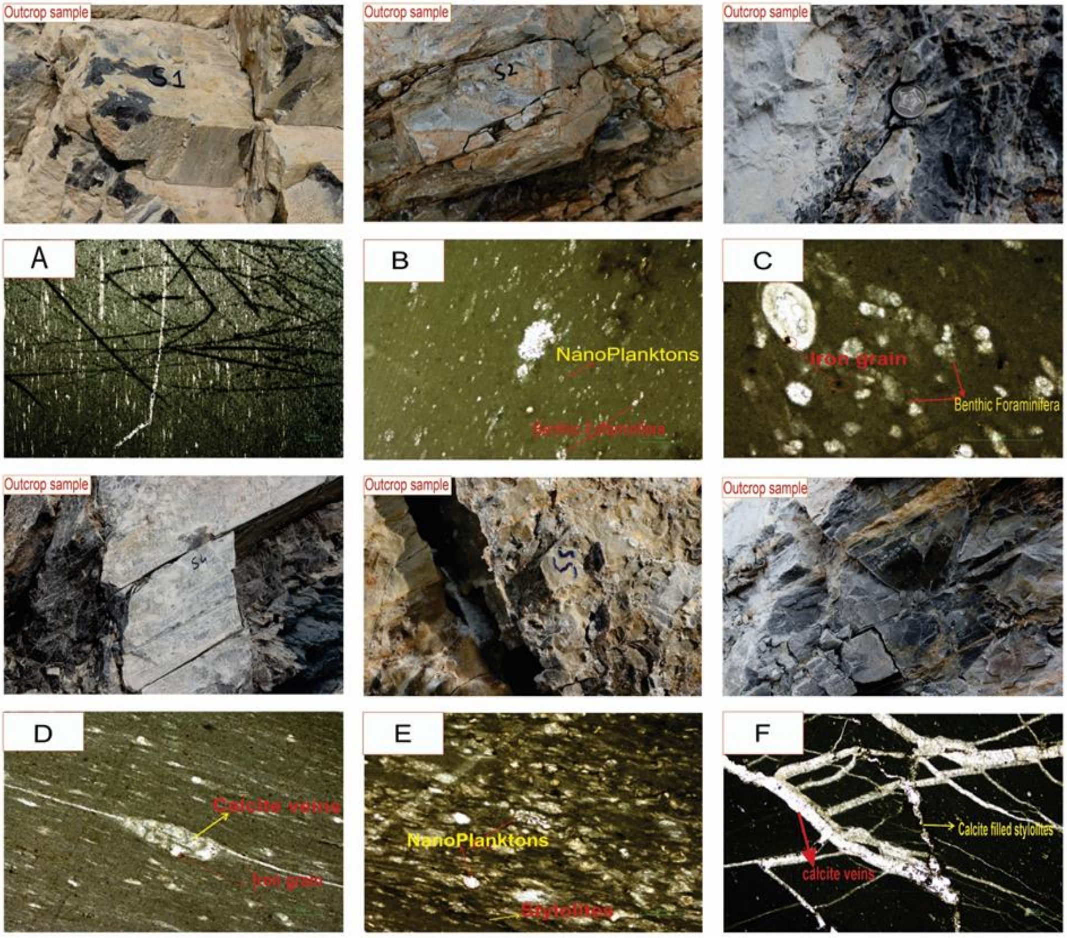

Figure 7. Microphotographs of Jurassic Limestone from different positions, Kirman Hill Region, District Kurram. (A) Rock is tightly stressed, individual fossils are poorly preserved, having Micritic and fine crystalline veins, (B)Very fine-grained and Micritic matrix embedded with Nano planktons and benthic forams, (C)Benthic foraminifera are dominant, microfractures are abundantly present, and stylolite are rare, some bioclasts look Pelecypods and Gastropods, iron grains are available,(D) Stretched and stressed fossil content with no vein content, no stylolites, fractures or vugs are present, the matrix is micritic (E) Very clear stylolite with thinly dark brown ferruginous layer, The rock unit is dominantly packed with Nano planktons and Benthic foraminifera. Algaes and Ostracodes are common. Abundant bioclasts present, some grains look Echinoderm. Some quartz grains are also observable (F) Medium grained calcite-filled veins are dominant, stylolite is refilled with calcite, and the matrix is micritic.

The results revealed that the composition of the matrix is exceptionally finely crystalline, and no grain-to-grain texture was noticed. Furthermore, it is classified as micritic and represents mudflat environment or deeper facies. In shelf carbonate formation, the rock unit marks supratidal/tidal facie or deeper facie (Samana Suk Formation, Jurassic Limestone). Uniserial and biserial foraminifera are common Figure 7 (C). The abundance of calcite (micrite and sparite) indicates the depositional environment is calm and deep. The absence of more biota is an indicator of hypersaline conditions. This is either a deeper marine or supratidal environment and can be mudflats or tidal ponds. The microfacies can be matched to the SMF 23 Microfacies Standard [49]. The Model analysis technique showed that the Jurassic limestone is mostly composed of calcite (in the form of micrite and spar), which is (92-94 %), algal laminations (1-3 %), unusual dolomite (0.5-2 %), rare Quartz (0.5-1 %), ores (0.5-1 %), and clays (1-2 %; around stylolites). According to the Dunham (1962) [33], categorization scheme, the investigated limestone can be classed as "Mudstone". The Jurassic limestone has undergone diagenetic changes such as neomorphic, occasional dolomitization, calcite-filled veins, and stylolites. The neomorphic calcite is made up of a very fine to coarse-grained anhedral spar. The petrographic analysis of selected limestone samples from the Jurassic limestone of Samana Suk formation reveals very minute amounts of deleterious content (dolomite and clay) in the studied samples, indicating that ACR and ASR are not a significant threat. The Samana Suk Formation exposed at Kirman hill region aggregate is recommended as an appropriate source for construction.

4.2. Physical Tests

The parent material is responsible for the aggregate's physical characteristics, such as specific gravity, porosity, and chemical properties [50]. Natural high-grade aggregates should be composed of gravel or broken rocks, and they should be chemically inert, hard, robust, and clean; they should not be particularly water-absorbing, and they must be non-porous. They should have a rough surface and be about cubic in form; no flaky or elongated aggregates should be used, and they should be devoid of other fine materials [51]. Aggregate surface characteristics texture, fines type and quantity, obtained in-place density, and moisture levels in proportion to the required compaction level are some of the most well-known characteristics that determine unbound aggregate layer behavior.

4.2.1. Specific Gravity (SG) & Water Absorption of Aggregate

Aggregate appropriateness in the base, sub-base, and surface layers is shown by the specific gravity and water absorption values [52]. The greater the aggregate strength, the greater its specific gravity [38]. The specific gravity of an aggregate reflects the degree to which it has been compacted, which is directly related to its mineralogy [13]. Rocks with a specific gravity greater than 2.55 are appropriate for massive construction works [53]. Samana Suk formation average specific gravity was recorded 2.74 by using Equation 2. The obtained value of Jurassic limestone is suitable for heavy construction works.

$$S.G = \frac{1}{\frac{P1}{100G1}+\frac{P2}{100G2}+\cdots\frac{Pn}{100Gn}} \tag{2}$$

The pore ratio in an aggregate is measured by water absorption. The higher the pore ratio, the higher the water absorption value in the rock [54]. Weak or poor aggregates have low specific gravity and high water absorption, whereas excellent aggregates have the opposite characteristics [55]. Water absorption in aggregates is reduced when the void ratio is low, which prevents reactions and damages inside the aggregate particles [56]. Although aggregate absorbs some asphalt to form a mechanical bond, water absorption should be within acceptable limits.

$$Absorption\% = \frac{B-A}{A} \times 100 \tag{3}$$

The water absorption rate of Jurassic limestone was recorded at 0.33 % (Table.1) by using Equation 3, which is generally accepted to be well within a stated range of up to 2% [38].

4.2.2. Shape Test (Flakiness Elongation Indexes) for Aggregate

The shape control of aggregate particles is defined by the flakiness and elongation indexes [39, 40]. It is essential to characterize particle shape when aggregates are subjected to high load traffic because the shape might cause particle breakage or deformation [13, 48]. Flattened and elongated coarse aggregate particles are more likely to be fractured than rounded and angular form particles [57]. The workability of roadways is typically affected by particle breakage and deformation. Lower workability is associated with higher flakiness and elongation index values [58]. The average flakiness index for Samana Suk formation is 19.25%, and the elongation index is 11.55%. (Table 1) by using Equations 4 and 5.

$$Flakiness\ Index\% = \frac{W_1}{W_2} \times 100 \tag{4}$$

$$Elongation\ Index\% = \frac{W_3}{W_4} \times 100 \tag{5}$$

Table 1. Average values of Jurassic Limestone from the Samana Suk Formation of different lab testing

Sample No.	Los Angles Abrasion %	Soundness Test%	Specific Gravity	Water Absorption %	Unit weight	Crushing value %	Flakiness Index %	Elongation Index %	Aggregate Impact value	Bitumen Coating
1	26.20	3.54	2.66	0.40	1.70	13.18	19.50	12.00	14.00	>95%
2	25.30	2.74	2.43	0.30	1.80	12.34	17.60	11.60	15.00	>95%
3	24.20	2.42	2.99	0.40	1.65	13.30	20.10	11.70	13.50	>95%
4	25.00	3.16	2.87	0.20	1.75	13.69	21.00	10.90	13.20	>95%
Average	25.18	2.97	2.74	0.33	1.73	13.13	19.55	11.55	13.93	>95%

Flakiness and Elongation Index have maximum allowable limitations of less than 25% and 15% for road aggregate, respectively. Consequently, the Jurassic limestone of the Kirman hill region is well under the specified limits and designated as a road aggregate [39, 40].

The obtained results of specific gravity, water absorption, flakiness, and elongation index values were compared to other widely utilized aggregates in Pakistan (Table 2) and it revealed almost similar findings. The water absorption and specific gravity results indicate that the material under investigation could be safely utilized in asphalt concrete, cement concrete, base, and sub-base. These results for flakiness and elongation are within specification limits, indicating that the aggregate under investigation could be used safely in concrete and asphalt projects.

Table 2. Engineering tests comparison of Jurassic limestone, Samana Suk Formation Kirman hill region with different limestone of Pakistan

Limestone Unit	Los Angles Abrasion %	Soundness %	Specific Gravity	Water Absorption %	Unit weight	Flakiness Index%	Elongation Index %	Bitumen Coating
Margalla Hill Limestone	21.6	1.14	2.72	0.8	2.62	15.78	13.27	100
Kohat Caronates	21.6	1.88	2.6	0.6	2.16	9.97	12.56	100
Lochkart Limestone	2.69	2.33	2.69	0.62	2.78	19.01	12.2	100
Wargal Limestone	23.37	1.007	2.7	0.71	1.67	6.5	7.1	100
Khyber Limestone	26.6	2.85	2.72	0.68	2.01	23.15	15.22	100
SSKL	21.8	2.35	2.57	0.67	1.66	9.36	10.77	100
Kirman Hill Jurassic Limestone (Current study)	25.18	2.97	2.74	0.33	1.73	19.55	11.55	100

4.3. Durability Tests

Aggregate durability is an essential factor in determining the quality of a pavement [59]. Generally, it characterizes the aggregate's ability to withstand environmental, physical, and cyclical loading conditions and is impacted by temperature, moisture, chemical exposure, and freeze-thaw cycles [60]. The use of low-durability aggregates may result in significant gradation changes and a reduction in pavement performance. Aggregate durability is a concept that combines soundness and toughness into a single concept. Aggregate toughness refers to the aggregate's ability to withstand physical stress during manufacturing, production, transportation, and construction. Whereas, aggregate soundness refers to the aggregate's ability to withstand cyclical environmental stress [61].

4.3.1. Los Angeles Abrasion Value (LAV)

The primary purpose of this test is to determine the abrasion and skidding resistance of aggregate [41]. The abrasion value can be used to determine the aggregate loss percentage, which indicates the aggregate strength and toughness or wear and tear properties when subjected to natural impact and stress circumstances [11, 62-64]. The lower abrasion value showed that the aggregate has higher strength [65].

$$Los\ Angeles\ Abrasion\ \% \ = \frac{M_{orignal} - M_{final}}{M_{orignal}} \times 100 \tag{6}$$

Los Angeles Value in studied samples of Samana Suk limestone was recorded 25.18% (using Equation 6) against the maximum tolerable value of 35 % for concrete, 40 % for the base course, and 50 % for sub-base course, respectively, the obtained results are well according to national and international specified standard limits (Table 1).

4.3.2. Soundness Sulphate Test

Aggregate soundness is related to their ability to resist various weather conditions, such as freezing-thawing and wetting-drying cycles, and thermal changes, which generally destroy the aggregate structure and decrease the life of civil structures [11, 48, 66]. Temperature variations cause expansion of volume, and this affects the Concrete's long-term durability. The average soundness values for the Samana Suk formation were recorded at 2.97 % (Table.1) using Equation 7.

$$Soundness\% = \frac{Initial_{mass} - Retained_{mass}}{Initial_{mass}} \times 100 \tag{7}$$

The value compared to the stipulated standards of 10 % (max) for concrete and 12 % (max) for the base course [42]. The obtained values are substantially within the standard stated limitations. The results of the Los Angles abrasion test and soundness test were compared to those of other extensively used aggregates in Pakistan such as Margala hill limestone, Kohat Carbonates, Khyber limestone, etc. (Table 2), they indicated almost identical results. The range of findings is within the specified range, indicating that the aggregate under investigation is suitable for concrete and other construction applications.

4.4. Mechanical Tests

Several mechanical qualities of aggregate are important in the production of concrete, particularly high-strength concrete that is exposed to heavy wear [67]. Aggregate Crushing Value, Aggregate Impact Value, and Unit weight of aggregates are some of the tests addressed here.

4.4.1. Impact Value of Aggregate

The impact value measures an aggregate's toughness and mechanical resistance [65, 68, 69]. Material with a lower aggregate impact value will be more resistant to mechanical damage. Road materials are broken and chipped by high traffic because of the pounding. The material used should be tough enough to resist future impact. In the standard, the following values are permitted:

Heavy-duty concrete flooring = 25%

For all other concrete projects = 45 %

Concrete used in wear-resistant surfaces = 30 %

The average impact value calculated from Samana Suk was 13.93 % (Table 1) using Equation 8.

$$Impact\ value\ \% = \frac{Mass\ of\ fraction\ passing\ no.7\ sieve}{total\ mass\ of\ sample} \times 100 \tag{8}$$

The test findings are well within the established standard limits.

4.4.2. Crushing Value of Aggregate

The crushing value of aggregates is an important factor to consider when choosing high-quality aggregates. Aggregate with a lower crushing value has higher strength because the crushed fraction is less to strengthen its ability to withstand compression [70].

$$C.V\% = \frac{mass\ of\ fraction\ of\ passing\ no\ 8\ sieve}{Total\ mass\ of\ aggregate} \times 100 \tag{9}$$

The aggregate crushing values of the investigated samples of the Samana Suk Formation exposed at Kirman hills were recorded at 13.13 % (Table 1) by using Equation 9, which is comparable to high-quality aggregates as prescribed by BS-812-110 [44].

4.4.3. Unit Weight (Bulk density) of Aggregate

The objective of this test is to determine the unit weight of coarse aggregate, which has a vital role in a concrete mix design and gives a good indication that either aggregate is porous or sound [55]. The test was carried out on loose and compacted (Rodded) aggregates to determine the unit weight in both loose and compacted conditions [45]. The lower void ratio of aggregates with higher unit weight values is considered excellent and efficient aggregates [71]. The average unit weight for the tested sample was recorded 1.73 g/cc (Table 1) by using Equations 10, 11 and 12, which is within the ASTM C29 [45] standard range.

$$Bulk\ density = \frac{Mass\ of\ aggregate\ to\ fill\ cylinder}{Volume\ of\ measuring\ cylinder} \tag{10}$$

$$Bulk\ density\ (SSD) = \frac{Bulk\ density\{1+(Absorption\%)}{100} \tag{11}$$

$$\%Void = \frac{[(S\times W)-M]}{S\times W} \tag{12}$$

When the aggregate impact value, aggregate crushing value, and aggregate unit weight were compared to those of other widely used aggregates in Pakistan, such as Margala hill limestone, Kohat Carbonates, Khyber limestone, and so on (Table 2), the findings were almost equal.

4.5. Bituminous Tests

Bituminous materials, sometimes known as asphalts, are widely utilized in road construction because of their outstanding binding and water-proofing capabilities, as well as their inexpensive cost [72]. Bituminous materials include bitumen, a black or dark-colored solid, and viscous cementitious compounds. These are mostly high molecular weight hydrocarbons generated from petroleum or natural asphalt distillation, with adhesive qualities, and are soluble in carbon disulfide.

4.5.1. Coating and Striping of Bitumen

The main purpose of this test is to assess the petrographic analysis of specific grades of asphalt in terms of adhesive properties at a constant temperature of 25°C [1]. The chemical configuration of the aggregate surface and the degree of roughness significantly impact the nature of the asphalt aggregate bond. SiO2 is a hydrophilic (loves water) mineral with a negative charge usually considered non-adhesive [73]. The aggregate used in the asphalt layer must have high cohesiveness with the bitumen and maintain that cohesion under water and moisture action [54] Aggregate with a higher coating and striping value will have a better blend of binder (bitumen) and aggregate components, improving the durability and strength of any civil structure [46, 74]. The stripping value of Samana Suk formation samples was less than 5% while using 80/100-grade bitumen, and the coating value was greater than 95% (Table 1). The bitumen coating and striping properties are comparable to international standards, and others common aggregates utilized in Pakistan mega and minor civil projects and its strongly suggested that the Jurassic limestone Samana Suk formation, Kirman hill region is an outstanding source of potential aggregates.

Jurassic Limestone of the Samana Suk Formation was derived from the study area and subjected to different standard Geological/Geotechnical tests to determine the engineering properties. The measured mean values of all physical properties, Durability characteristics, Mechanical properties, and bituminous test results of Jurassic limestone aggregate are presented in Figure 8. The Jurassic limestone has a specific gravity mean value of 2.74, while the minimum required for cement concrete is 2.60. This shows that the specific gravities of rock are within acceptable ranges of AASHTO T 85 [38]. Mean water absorption values of the Jurassic limestone were recorded 0.33%. Water absorption value for aggregates used in cement concrete should be less than 2.5 percent, according to AASHTO T 85 [38]. This shows that this limestone satisfies the water absorption requirements for cement concrete. Freeze-thaw damage is prevalent in rocks with absorption rates greater than 3.0% [75]. Furthermore, the rise in hydrostatic pressure inside the cement or aggregate particles as a consequence of ice crystallization and subsequent volume increase is extremely detrimental [17]. Popouts and surface scaling are caused by very porous aggregate. The physical characteristics of flakiness and elongation index are associated with the shape of aggregate particles. When used as aggregate in road and cement concrete, higher values indicate lower strength and anisotropic qualities. The studied sample showed flakiness elongation indexes (Shape test) (19.25 % and 11.55 %, respectively) which are within limits of BS-812-105.1 & 2 [39, 40] and considered suitable for any construction work.

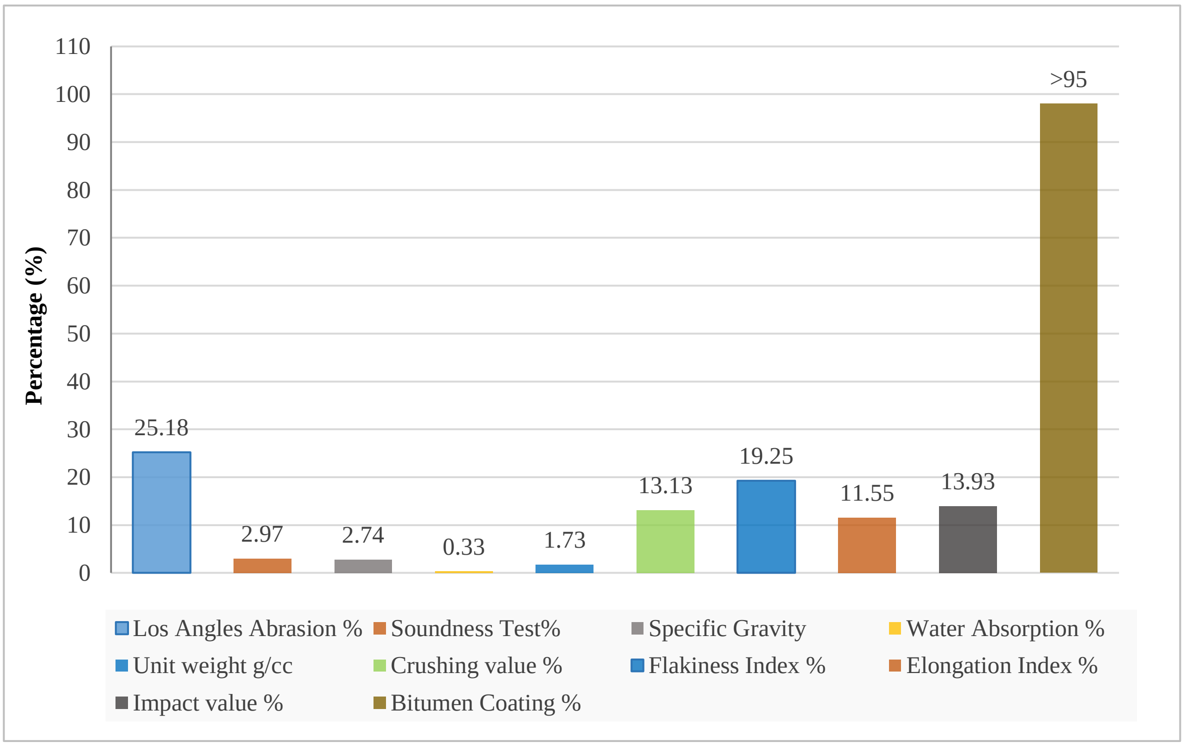

Figure 8. The average results from Jurassic Limestone Samana Suk Formation, Kirman Hill region

The permitted values for the Los Angles Abrasion test for Sub Base are 50%, Base Course is 40%, and Concrete is 35%, the results obtained from the Los Angles Abrasion test were recorded 25.18 %, which is within the allowable limits which imply that these rocks can be used as road aggregate. The result obtained from the Soundness test sample was recorded 2.97 %, according to AASHTO-T-104-99 [42], the average weight loss on each sieve should not exceed 12% in the soundness test; as a result, the Jurassic limestone is resistant to the freeze-thaw weathering cycle and is recommended for aggregate potential.

Durable aggregates have a lower impact value due to their higher resistance to impact, the Samana Suk formation average Impact value recorded for the tested sample was 13.93%, which is strong enough to sustain the applied loads. ACV has a direct impact on pavement stability; if the low-quality aggregate is used, the pavement will easily break [76]. The Samana Suk Formation average crushing value was recorded 13.13 %. ACV varies from around 5% for strong aggregates to 30% for lesser aggregates. Weak rocks create so many fines during testing that have a negative effect on the outcome. The results indicate that these aggregates' toughness and hardness stay stable with increasing stress according to the British Standard method [44]. Based on aggregate bulk density, the percentage voids ratio can be calculated using the unit weight. Aggregate with a higher unit weight has a lower void ratio and a stronger strength due to the highly compacted nature, as outlined in ASTM C29 [45]. The average unit weight in the given samples of Jurassic limestone was recorded 1.73g/cc, which is in the limit specified limit as 2.30–3.10 [45]. The aggregates coating and stripping values are > 95%, demonstrating their strong adhesiveness and its recommended best suitable for the surface layer of pavement according to AASHTO-T-182-84 [46].

The petrographic analysis of the examined limestone comprises different carbonate and skeletal and nonskeletal grains, including bioclast, peloids distributed over micrite and lime, algal laminations, and neomorphic calcite, unusual dolomite, rare quartz (0-1.0%), ores (0.5-1%), and clays (0.5-1.0% around stylolite). According to the Dunham (1962) [33] classification system, the examined limestone is classified as "mudstone". In the petrographic analysis of the Jurassic Limestone Kirman Hill region, no deleterious substances were found, which means it can be used in concrete and roads alongside high alkali cement without any risk of alkali-aggregate reactions.

The recorded values Physical properties, durability characteristics, mechanical properties, and bituminous properties were compared to BS and ASTM standards to determine its suitability as an aggregate source for the construction sector, and it is highly recommended as a prospective aggregate. The Jurassic limestone of the Kirman hill region was also compared to other limestones, including Margalla hill limestone, Kohat limestone, Khyber limestone, Lockhart limestone, and the Shaikh Badin Samana Suk Formation, that are all frequently used in Pakistan for minor and mega projects, and they showed almost the same results (Table 2). Engineering and petrographic findings demonstrate that all physical properties of the Jurassic limestone are within acceptable limits for roads, concrete, and other engineering purposes.

5. Conclusions

- The Jurassic limestone of the Samana Suk Formation, which is well developed and exposed in the Kirman hill region, has been studied for petrographic, physical, chemical, and mechanical properties. It is determined that all test results are within the range according to the international standards, and this Formation is strongly recommended for the construction of any civil mega and minor projects.
- Dunham classifies the Jurassic limestone of the Samana Suk Formation as mudstone. The current findings revealed that calcite is the most abundant component, comprising approximately 92–94% of the total (micrite and spar) with algal lamination (1-3%), rare quartz (0.5-1%), ores (0.5-1%), and clay (0.5-1% around stylolite). The rare amount of deleterious content indicated that Jurassic limestone is not prone to ASR and ACR associated expansions.
- The Samana Suk limestone aggregate showed excellent bitumen affinity, so it is strongly recommended for road surfacing.
- All engineering parameters are comparable to AASHTOO, ASTM, and BS standards, indicating that the Samana Suk Formation limestone is the potential aggregate source.
- The area requires detailed remote sensing mapping and GIS technique to differentiate distinct lithological differences, including limestone, dolomites, and marls.
- In Pakistan, the aggregate material is extracted using the traditional method of blasting, which results in a material loss of more than 50%. Therefore, detailed work is required on the correct processing of the aggregate.

6. Declarations

6.1. Author Contributions

Conceptualization, J.H., J.Z., X.L., K.H., S.Y.A.S, S.A., and A.H.; methodology, J.H., J.Z., X.L., K.H., S.Y.A.S, S.A., and A.H.; writing—original draft preparation, J.H, J.Z, X.L, and S.A.; writing—review and editing, J.H., J.Z., X.L., K.H., S.Y.A.S, S.A., and A.H. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.5. Conflicts of Interest

The authors declare no conflict of the interest.

7. References

[1] Rehman, G., Zhang, G., Rahman, M. U., Rahman, N. U., Usman, T., & Imraz, M. (2020). The engineering assessments and potential aggregate analysis of mesozoic carbonates of Kohat Hills Range, KP, Pakistan. Acta Geodaetica et Geophysica, 55(3), 477–493. doi:10.1007/s40328-020-00301-9.

[2] Gkouma, M., Karkanas, P., & Iacovou, M. (2021). A geoarchaeological study of the construction of the Laona tumulus at Palaepaphos, Cyprus. Geoarchaeology, 36(4), 601–616. doi:10.1002/gea.21850.

[3] Naeem, M., Zafar, T., Karim, M. A. M., Miraj, M. A. F., Sanaullah, M., Bashir, R., & Abbas, S. (2021). Aggregate prospects of pirkoh limestone from gulki-rodo area of Pakistan as a potential construction material. Himalayan Geology (42) 2, 382–387.

[4] Gorospe, K., Booya, E., Ghaednia, H., & Das, S. (2019). Effect of various glass aggregates on the shrinkage and expansion of cement mortar. Construction and Building Materials, 210, 301–311. doi:10.1016/j.conbuildmat.2019.03.192.

[5] Koukis, G., Sabatakakis, N., & Spyropoulos, A. (2007). Resistance variation of low-quality aggregates. Bulletin of Engineering Geology and the Environment, 66(4), 457–466. doi:10.1007/s10064-007-0098-x.

[6] Tanyu, B. F., Yavuz, A. B., & Ullah, S. (2017). A parametric study to improve suitability of micro-deval test to assess unbound base course aggregates. Construction and Building Materials, 147, 328–338. doi:10.1016/j.conbuildmat.2017.04.173.

[7] Přikryl, R. (2021). Geomaterials as construction aggregates: a state-of-the-art. Bulletin of Engineering Geology and the Environment, 80(12), 8831–8845. doi:10.1007/s10064-021-02488-9.

[8] Naeem, M., Khalid, P., & Anwar, A. W. (2015). Construction material prospects of granitic and associated rocks of Mansehra area, NW Himalaya, Pakistan. Acta Geodaetica et Geophysica, 50(3), 307–319. doi:10.1007/s40328-014-0087-z.

[9] Ndukauba, E., & Akaha, C. T. (2012). Engineering-Geological Evaluation of Rock Materials from Bansara, Bamenda Massif Southeastern Nigeria, as Aggregates for Pavement Construction. Evaluation, 2(5), 107–111. doi:10.5923/j.geo.20120205.01.

[10] Huang, Y., Bird, R., & Heidrich, O. (2009). Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. Journal of Cleaner Production, 17(2), 283–296. doi:10.1016/j.jclepro.2008.06.005.

[11] Gondal, M. M. I., Ahsan, N., & Javid, A. Z. (2009). Engineering Properties of Potential Aggregate Resources from Eastern and Central Salt Range, Pakistan. Geological Bulletin of Punjab University, 44, 97–104.

[12] Naeem, M., Khalid, P., Sanaullah, M., & Zia ud Din. (2014). Physio-mechanical and aggregate properties of limestones from Pakistan. Acta Geodaetica et Geophysica, 49(3), 369–380. doi:10.1007/s40328-014-0054-8.

[13] Khan, S. (2000). Study of the Geology of Kirana Group, Central Punjab and Evaluation of its Utilization and Economlc Potential as Aggregate. PhD Thesis, University of the Punjab, Lahore, Pakistan.

[14] Ullah, R., Ullah, S., Rehman, N., Ali, F., Asim, M., Tahir, M., Ullah, S., & Muhammad, S. (2020). Aggregate Suitability of the Late Permian Wargal Limestone at Kafar Kot Chashma Area, Khisor Range, Pakistan. International Journal of Economic and Environmental Geology, 11(1), 89–94. doi:10.46660/ojs.v11i1.418.

[15] Ersoy, H., Karahan, M., Kolaylı, H., & Sünnetci, M. O. (2020). Influence of Mineralogical and Micro-Structural Changes on the Physical and Strength Properties of Post-thermal-Treatment Clayey Rocks. Rock Mechanics and Rock Engineering, 54(2), 679–694. doi:10.1007/s00603-020-02282-1.

[16] Gu, X., Li, X., Zhang, W., Gao, Y., Kong, Y., Liu, J., & Zhang, X. (2021). Effects of HPMC on Workability and Mechanical Properties of Concrete Using Iron Tailings as Aggregates. Materials, 14(21), 6451. doi:10.3390/ma14216451.

[17] Zarif, I. H., & Tuǧrul, A. (2003). Aggregate properties of Devonian limestones for use in concrete in Istanbul, Turkey. Bulletin of Engineering Geology and the Environment, 62(4), 379–388. doi:10.1007/s10064-003-0205-6.

[18] Nweke, O. M., & Okogbue, C. O. (2021). Geotechnical evaluation of the quality and durability of argillites from Abakaliki Metropolis (Southeastern Nigeria) as road aggregates. Arabian Journal of Geosciences, 14(22). doi:10.1007/s12517-021-08613-y.

[19] Ramsay, D. M., Dhir, R. K., & Spence, I. M. (1974). The role of rock and clast fabric in the physical performance of crushed-rock aggregate. Engineering Geology 8(3), 267–285. doi:10.1016/0013-7952(74)90002-7.

[20] Lees, G., & Kennedy, C. K. (1975). Quality, Shape and Degradation of Aggregates. Quarterly Journal of Engineering Geology and Hydrogeology, 8(3), 193–209. doi:10.1144/gsl.qjeg.1975.008.03.03.

[21] Abbas, S. M. (2012). Geology and Structure of the Westernmost Hill Range, Sadda Area, Kurram Agency, Northwest. Master Thesis, National Centre of Excellence in Geology, University of Peshawar, Peshawar, Pakistan.

[22] Gansser-Biaggi, A. (1964). Geology of the Himalayas. London, Interscience Publisher, New York, United States.

[23] Badshah, M. S., Gnos, E., Jan, M. Q., & Afridi, M. I. (2000). Stratigraphic and tectonic evolution of the northwestern Indian plate and Kabul block. Geological Society Special Publication, 170(1), 467–476. doi:10.1144/GSL.SP.2000.170.01.25.

[24] Meissner, C. R., Hussain, M., Rashid, M. A., & Sethi, U. B. (1975). Geology of the Parachinar Quadrangle, Pakistana. U.S. Govt. Print. Off. doi:10.3133/pp716f

[25] Beck, R. A., Burbank, D. W., Sercombe, W. J., Khan, A. M., & Lawrence, R. D. (1996). Late cretaceous ophiolite obduction and paleocene india-asia collision in the westernmost himalaya. Geodinamica Acta, 9(2–3), 114–144. doi:10.1080/09853111.1996.11105281.

[26] Davies, L. M. (1930). The fossil fauna of the Samana Range and some neighbouring areas, The Palaeocene Foraminifera/by LM Davies. Calcutta Publishers, Kolkata, India.

[27] Shah, S. (1977). Stratigraphy of Pakistan, volume 12 of the Geological Survey of Pakistan Islamabad, Director General, Geological Survey of Pakistan, Western City, Pakistan.

[28] Fatmi, A. N. (1974). Lithostratigraphic units of the kohat-potwar province, Indus basin, Pakistan: a report of the stratigraphic committee of Pakistan. Geological Survey of Pakistan, Western City, Pakistan.

[29] ASTM D75-87. (1992). Standard practice for sampling aggregates. ASTM International, Pennsylvania, United States.

[30] AASHTO, (2014). Standard specifications for transportation materials and methods of sampling and testing. AASHTO provisional standards. The American Association of State Highway and Transportation Officials, Washington, United States.

[31] ASTM C125-03. (2003). Standard terminology relating to concrete and concrete aggregates. ASTM International, Pennsylvania, United States.

[32] Johnson, R.B., & DeGraff, J. V. (1988). Principles of engineering geology. John Wiley & Sons, New Jersey, United States.

[33] Dunham, R. J., (1962). Classification of Carbonate Rocks According to Depositional Texture. Classification of Carbonate Rocks—A Symposium, American Association of Petroleum Geologists, Oklahoma, United States. doi:10.1306/M1357.

[34] Kandhal, P. S., Mallick, R. B., & Huner, M. (2000). Measuring bulk-specific gravity of fine aggregates: Development of new test method. Transportation Research Record, 1721(1721), 81–90. doi:10.3141/1721-10.

[35] Tsikouras, B., Pomonis, P., Rigopoulos, I., & Hatzipanagiotou, K. (2005). Investigation for the suitability of basic ophiolitic rocks from the Mikroklissoura Grevena area as anti-skid aggregate material and railroad ballast. In Proc. of the 2nd Conference of the Committee of Economical Geology, Mineralogy and Geochemistry, Athens, Greece, 347-356.

[36] Mpalatsas, I., Rigopoulos, I., Tsikouras, B., & Hatzipanagiotou, K. (2010). Suitability assessment of gretageous limestones from Thermo (Aitolokarnania, Western Greece) for their use as base and sub-base aggregates in road-construction. Bulletin of the Geological Society of Greece, 43(5), 2501-2509. doi:10.12681/bgsg.11656.

[37] Jethro, M. A., Shehu, S. A., & Olaleye, B. (2014). The suitability of some selected granite deposits for aggregate stone production in road construction. Geology, 60(431), 0011.

[38] AASHTO T 85, (2014). Standard Method of Testing for Specific gravity and absorption of coarse aggregate. The American Association of State Highway and Transportation Officials, Washington, United States.

[39] BS-812-105.1 (1989). Testing aggregates. Methods for determination of particle shape flakiness index. British Standards Institution, London, United Kingdom.

[40] BS 812-105.2 (1990). Testing aggregates. Methods for determination of particle shape. Elongation index of coarse aggregate (British standard). British Standards Institution, London, United Kingdom.

[41] ASTM C131-06. (2006). Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine. ASTM International, Pennsylvania, United States.

[42] AASHTO-T-104-99. (2007). Standard method of test for soundness of aggregate by use of sodium sulfate or magnesium sulfate. The American Association of State Highway and Transportation Officials, Washington, United States.

[43] BS-812-112. (1990). Testing aggregates method for determination of aggregate impact value (AIV). British Standards Institution, London, United Kingdom.

[44] BS-812-110. (1990). Testing aggregates methods for determination of aggregate crushing value (ACV). British Standards Institution, London, United Kingdom.

[45] ASTM C29 (2009). Standard test method for bulk density ("Unit Weight") and voids in aggregate. American Society for Testing and Materials, Annual Book, Pennsylvania, USA.

[46] AASHTO-T-182-84. (2002). Standard method for coating and stripping of bitumen-aggregate mixtures. The American Association of State Highway and Transportation Officials, Washington, United States.

[47] Irfan, T. Y. (1996). Mineralogy, fabric properties and classification of weathered granites in Hong Kong. Quarterly Journal of Engineering Geology, 29(1), 5–35. doi:10.1144/GSL.QJEGH.1996.029.P1.02.

[48] Ahsan, N., & Gondal, M. M. I. (2016). Aggregate suitability studies of limestone outcrops in Dhak pass, western Salt range, Pakistan. International Journal of Agriculture and Applied Sciences (Pakistan).

[49] Flügel, E. (2004). Depositional Models, Facies Zones and Standard Microfacies. Microfacies of Carbonate Rocks, 657–724. doi:10.1007/978-3-662-08726-8_14.

[50] Peng, J., Wu, X., Ni, S., Wang, J., Song, Y., & Cai, C. (2022). Investigating intra-aggregate microstructure characteristics and influencing factors of six soil types along a climatic gradient. CATENA, 210, 105867. doi:10.1016/j.catena.2021.105867.

[51] Chen, J. S., Shiah, M. S., & Chen, H. J. (2001). Quantification of Coarse Aggregate Shape and Its Effect on Engineering Properties of Hot-Mix Asphalt Mixtures. In Journal of Testing and Evaluation 29(6), 513–519. doi:10.1520/jte12396j.

[52] Ahsan, N., & Gondal, M. M. I. (2016). Aggregate suitability studies of limestone outcrops in Dhak pass, western Salt range, Pakistan. International Journal of Agriculture and Applied Sciences, 4(2), 69-75.

[53] Blyth, F.G.H. and De Freitas, M.H. (1974). A Geology of Engineers. ELBS and Edward Arnold, London, United Kingdom.

[54] Lees, G., & Kennedy, C. K. (1975). Quality, Shape and Degradation of Aggregates. Quarterly Journal of Engineering Geology and Hydrogeology, 8(3), 193–209. doi:10.1144/gsl.qjeg.1975.008.03.03.

[55] Hassan, E. U., Hannan, A., Rashid, M. U., Ahmed, W., Zeb, M. J., Khan, S., … Ahmad, A. (2020). Resource assessment of Sakesar limestone as aggregate from salt range Pakistan based on geotechnical properties. International Journal of Hydrology, 4(1), 24–29. doi:10.15406/ijh.2020.04.00222.

[56] Croney, D., & Croney, P. (1991). The design and performance of road pavements. McGraw Hill Professional, New York, United States.

[57] Zhang, D., Cheng, Z., Geng, D., Xie, S., & Wang, T. (2022). Experimental and Numerical Analysis on Mesoscale Mechanical Behavior of Coarse Aggregates in the Asphalt Mixture during Gyratory Compaction. Processes 10(1), 47. doi:10.3390/pr10010047.

[58] Carlos, A., Masumi, I., Hiroaki, M., Maki, M., & Takahisa, O. (2010). The effects of limestone aggregate on concrete properties. In Construction and Building Materials, 24(12), 2363–2368. doi:10.1016/j.conbuildmat.2010.05.008.

[59] Pouranian, M. R., & Haddock, J. E. (2018). Determination of voids in the mineral aggregate and aggregate skeleton characteristics of asphalt mixtures using a linear-mixture packing model. In Construction and Building Materials 188, 292–304. doi:10.1016/j.conbuildmat.2018.08.101.

[60] Williams, S. G., & Cunningham, J. B. (2012). Evaluation of aggregate durability performance test procedures. Final Report, TRC-0905, University of Arkansas, Arkansas, United States. Available online: https://www.ardot.gov/wp-content/uploads/2020/11/TRC0905_Evaluation_of_Aggregate_Durability_Performance_Test_Procedures.pdf (accessed on December 2021).

[61] Fournari, R., & Ioannou, I. (2019). Correlations between the properties of crushed fine aggregates. Minerals 9(2), 86. doi:10.3390/min9020086.

[62] Kazmi, D., Serati, M., Williams, D. J., Qasim, S., & Cheng, Y. P. (2021). The potential use of crushed waste glass as a sustainable alternative to natural and manufactured sand in geotechnical applications. Journal of Cleaner Production 284, 124762. doi:10.1016/j.jclepro.2020.124762.

[63] Bayane, B. M., & Yanjun, Q. (2017). Evaluation of physical and mechanical properties of quarry stones in the southern Republic of Benin. Journal of Sustainable Development of Transport and Logistics 2(1), 61–66. doi:10.14254/jsdtl.2017.2-1.6.

[64] Neville, A. M. (1995). Properties of concrete (4^{th} Ed.). Longman Scientific and Technical, London, United Kingdom.

[65] Smith, M.R., Collis, L. (2001). Aggregates: sand, gravel and crushed rock aggregates for construction purposes (3^{rd} Edi.). Geological Society, London, United Kingdom, Engineering Geology Special Publications, 17(1). doi:10.1144/gsl.eng.2001.017.

[66] Mitchell, C. (2007). GoodQuarry Quarry Fines and Waste. British Geological Survey, London, United Kingdom.

[67] Demez, A., & Karakoç, M. B. (2020). Mechanical properties of high strength concrete made with pyrophyllite aggregates exposed to high temperature. Structural Concrete, 22(S1), E769–E778. doi:10.1002/suco.201900381.

[68] Fookes, P. G., Gourley, C. S., & Ohikere, C. (1988). Rock weathering in engineering time. Quarterly Journal of Engineering Geology and Hydrogeology, 21(1), 33–57. doi:10.1144/gsl.qjeg.1988.021.01.03.

[69] Verma, A., Babu, V. S., & Arunachalam, S. (2022). Characterization of recycled aggregate by the combined method: Acid soaking and mechanical grinding technique. Materials Today: Proceedings, 49, 230–238. doi:10.1016/j.matpr.2021.01.842.

[70] West, G. (1996). Alkali-aggregate reaction in concrete roads and bridges. In Alkali-aggregate reaction in concrete roads and bridges. Thomas Telford. doi:10.1680/aricrab.20696.

[71] Masad, E., Panoskaltsis, V. P., & Wang, L. (2006). Asphalt Concrete: Simulation, Modeling, and Experimental Characterization. In Proceedings of the R. Lytton Symposium on Mechanics of Flexible Pavements (June 1-3, 2005), Louisiana, United States. doi:10.1061/9780784408254.

[72] Read, J., & Whiteoak, D. (2003). The shell bitumen handbook (5^{th} Edi.). Thomas Telford, London, United Kingdom.

[73] Abo-Qudais, S., & Al-Shweily, H. (2007). Effect of aggregate properties on asphalt mixtures stripping and creep behavior. Construction and Building Materials (Vol. 21, Issue 9, pp. 1886–1898). doi:10.1016/j.conbuildmat.2005.07.014.

[74] Hamedi, G. H., Sahraei, A., & Esmaeeli, M. R. (2021). Investigate the effect of using polymeric anti-stripping additives on moisture damage of hot mix asphalt. European Journal of Environmental and Civil Engineering (Vol. 25, Issue 1, pp. 90–103). doi:10.1080/19648189.2018.1517697.

[75] Li, Q., Xu, F., Zheng, H., Shi, J., & Zhang, J. (2022). Experimental Study on Freeze-Thaw Effects on Creep Characteristics of Rubber Concrete. Advances in Materials Science and Engineering (Vol. 2022). doi:10.1155/2022/9182729.

[76] Hussain, J., Zhang, J., Fitria, F., Shoaib, M., Hussain, H., Asghar, A., & Hussain, S. (2022). Aggregate Suitability Assessment of Wargal Limestone for Pavement Construction in Pakistan. Open Journal of Civil Engineering, 12(01), 56–74. doi:10.4236/ojce.2022.121005.