CORRELATION BETWEEN SLAKE DURABILITY INDICES AND STRENGTH OF COAL FROM KARAGANDA COAL BASIN

by

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DECLARATION

‘I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at Nazarbayev University or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.’

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ABSTRACT

The uniaxial compressive strength is a very important parameter in mine design. For weak rocks such as coal, it is particularly difficult to obtain cores for mechanical testing. Especially for the weak rocks, another possibility of obtaining strength can be slake durability test (SDT) that is quick and inexpensive. A laboratory testing project was designed and carried out to characterize some physical (porosity and bulk density) and mechanical properties (UCS and PLI) and also slake durability indices (SDI). Coal samples obtained from three different mines of the Karaganda Coal Basin with corresponding coal seams: Tentekskaya (D6), Kuzymbayev (K12) and Kazakhstanskaya (D6 and D11). The main objective of this work was to establish relations between the SDI and strength parameters of the tested coals such as UCS test and PLT. For the studied coal samples, there is a positive and strong correlation between SDI and UCS when specimen tested load applied perpendicular to the bedding. A relationship between the PLI parallel and SDI values show a moderate correlation. Nevertheless, a very strong and positive correlation exists between the PLI perpendicular and SDI. In general, the SDI values show weaker correlations with physical properties than mechanical properties. Coal strength obtained in this research work from the relationship between PLT perpendicular and SDI data from cycles 2-5 has the highest accuracy and reliability among all of the mechanical properties presented. It was estimated by using the correlation coefficients between strength parameters and slake durability cycles that there should be four cycles of tests to identify SDI is necessary, but no further cycles are needed. The data and relationships obtained in this is research work indicates that the UCS and point load strength indices of samples from Karaganda coal mine can be estimated using slake-durability test. It should be mentioned that obtained results are based on a limited number of samples; due to tis should be used with care in the pre-investigation stage of the relevant projects.

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1 INTRODUCTION

In this chapter and in the following sub-sections first, a brief description of slake durability is given then the research problem statement and the research questions addressed in this research project are presented. Then, the importance of conducting this study and the possible implications of the findings of this research project are discussed, briefly. Next, the aims and objectives of this research work are described. This is followed by explanations of the research methodology designed to achieve the corresponding research objectives. In the last part, organization, structure, and content of different chapters in this dissertation are explained.

1.1 STATEMENT OF PROBLEM

The material mass ability to resist the effects of cyclic wetting and drying forces on the physical breakdown or disintegration of the rock into smaller aggregate sizes are described as slake durability. Disintegration here means scratching, wearing, or tearing away of particles. This process is due to material removal or displacement from the surface. The disintegration of rock in the water can be measured using the slake durability test (SDT). Slake durability test measures the resistance to weakening and disintegration of rock in the water. Slake Durability Index (SDI) is calculated using standard cycles of drying and wetting. The slake durability index is used for investigating the short-term effects of weathering agents on a rock, which is a percentage ratio of final to initial dry weights of rock in the drum (Franklin and Chandra, 1972). Several factors affect slake durability of coal including some physical and mechanical properties such as pore structure, permeability, reaction with water, and rock strength. Liang et al. (2014) reported that with an increase in weathering state, the material's strength generally deteriorates. In addition, the estimation of UCS and other parameters using SDI is also possible for sedimentary rocks with weathering states beyond the slightly weathered state.

For very weak material, the slake durability test shows better correlation with UCS compared with stronger rocks (ibid, 2014). Due to the fact that most coals are soft and sample preparation, especially obtaining cores, for strength tests such as UCS is a very difficult task establishing correlations between the slake durability of coal and its mechanical properties for quick estimation of these parameters can be very valuable. Hence, this issue was the main motivation behind the present research work. This can be considered as a preliminary step towards a better understanding of the performance of coal under conditions of wet and dry states, as well.

Investigation of coal slake durability raises the following set of questions related to coal testing:

- What are the impacts of coal slake durability on its strength?
- How can physical properties of coal affect its Slake Durability Index (SDI)?
- How does SDI of coal correlate to its physical and mechanical properties?

1.2 Relevance to industry

Coal is one of the major fossil energy resources for generation of electricity especially in China, India, and Kazakhstan (William, Paul and Mead, 2018). The majority of coking coal production in Kazakhstan comes from underground coal mining in the KCB and coal for electric power generation from Ekibastuz Coal Basin (ibid, 2018). Laboratory investigation of slake durability of coal can enable us to examine the susceptibility of coal for slaking when exposed to water during underground mining activities (Varley, 1990). More importantly, strength parameters of coal are important input parameters for geomechanical mine design. Considering the fact that most coals are classified as a soft rock then preparing core samples from such weak rocks for mechanical testing is very difficult. At the other hand, SDT is a relatively easy test with almost no effort for sample preparation. Hence, establishing correlations between UCS and SDI can make an estimation of the UCS based on SDI a useful tool.

1.3 Aims and objectives

Laboratory investigation as an experimental research approach is one of the ways of understanding and characterizing the slake durability, physical, and strength properties of coal. Physical properties of coal which is necessary for coal characterization include density and porosity. Efforts will also be made to establish relationships between the physical properties of coal and slake durability (SDI) along with the mechanical properties of coal from KCB, particularly strength is investigated. At first, determine the physical and strength properties of the coal samples and then assess the durability of the samples by conducting slake durability tests. In the next stage, relations are established between physical and strength properties of the examined coals and slake durability to investigate if these parameters correlated or not and if so, how strong or weak are the correlations. The specific objectives of the research are as the following: to characterize the physical and mechanical properties of the coal samples; to assess the slake durability of the coal samples through conducting slake durability test, and to establish interrelationships between strength properties and slake durability of the examined coal samples.

1.4 Research methodology

This research work is an experimental research study. The tests conducted included density, porosity, uniaxial compression strength test, point load test, and slake durability test. SDT suggested being identified by two-cycle of wetting and drying. However, there are cases when SDI identified by doing more cycles. This increase in the number of cycles in the SDT means that time to perform the test gets longer. SDT is easy to reproduce since this method consumes less time for sample preparation. Also, different tests were carried out to assess the density and strength of coal in rock mechanics laboratory. Strength parameters for coal from four different locations were determined using a uniaxial compression test and point load test. All of the tests were conducted in accordance with the suggested methods of the International Organization for Standardization (ISO), International Society for Rock Mechanics (ISRM) and American Society for Testing and Materials (ASTM). In order to conduct a laboratory test for achieving the objectives of this research, relevant standards were studied, and sample preparation was carried out based on the suggested standards: ISO (11722:1999, 5072:2013), ISRM (1979, 1981, 1985) and ASTM (C 914 – 95, D7625). Experimental methodology intended to use coal samples preparation from coring/cutting to determine SDI dependency on its physical and strength properties.

1.5 Thesis organization

Thesis work is organized in the six chapters. In Chapter 1, the problem statement, relevance to industry, objectives, and research methodology are discussed as well as a brief description of the thesis structure and chapters. Chapter 2, is the literature review for this work which includes some background information on coal geology, reserves and production. It also provides information regarding coal properties and establishes the research background. Chapter 3, contains the information on the research plan including the project schedule and excluding risk assessment. In Chapter 4, the methodology and the experimental procedures are discussed. It describes the coal sampling as well as testing procedure of apparatus. Chapter 5 is the Results and Discussion of this research work. First, the data generated are presented in graphs and tables and then data analysis, and discussion of the results are presented. Chapter 6 is dedicated to Conclusions and Recommendations for further studies. In this chapter, the main findings of this research work are summarized, and some recommendations are provided for future research in this direction.

2 LITERATURE REVIEW

This chapter presents an overview of the data source and structure of the coal mining industry in the World and particularly in Kazakhstan. Study area details are presented with an explanation of coal classification systems, i.e. coal mark and selected for the research locations are highlighted. Other established rock classification criteria based on material characteristics of rocks are presented.

2.1 COAL RESERVES AND PRODUCTION

Most of all the energy consumed by end-users comes from fuels. Importance of electricity worldwide is crucial, and coal is a major energy source for this industry. The primary use of coal is in the energy sector. The share of coal in global power generation has not changed in the last 20 years, currently standing at 38% (BP, 2018). Coal plays a significant role in iron and steel production along with cement manufacture also. The use of coal depending on types of coal is illustrated in a chart that is shown in Figure 1.

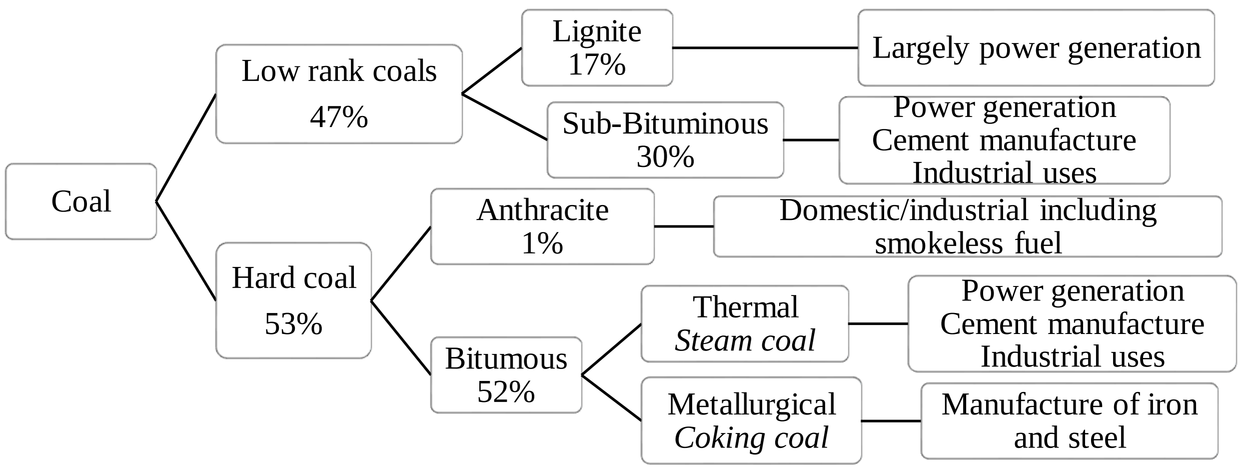

Figure 1. Types of coal and its use around the World (WCI, 2009).

Sub-bituminous and thermal bituminous (steam coal) are consumed for cement manufacture industrial use, and lignite is used for power generation. Manufacturing of iron and steel needs coal resources requires metallurgical bituminous (coking) coal. It is important to note that not all higher rank coals have coking properties. Coal is an important fossil energy resource, worldwide. Current world total resources are over seventeen times current proven reserves, and there are by the estimate of 17.7 trillion tons of hard coal, (IEA, 2018). Even though the resources are widely distributed over the world, proven coal reserves tend to be concentrated in certain countries. Their common feature is their reliance on coal for domestic energy or export revenue. According to the U.S. Energy Information Administration, these five countries have about 3/4 of the world's coal reserves (EIA, 2018), they are the United States of America—21%, Russia—14%, Australia—9%, India—8% and China—23%.

2.1.1 The coal mining industry in Kazakhstan

Central Asia's largest recoverable coal reserves are present in Kazakhstan territory. Kazakhstan's total proved hard coal, meaning anthracite and bituminous coal reserves at the end of 2017 is 25,605 million tonnes (BP, 2018). Coal is one of the commodities used in the industry sector as mineral fuels. Reserves-to-production (R/P) ratio for Kazakhstan is 230 years (BP 2018), meaning that with the current coal production rate the reserves will last more than two centuries. World proved coal reserves are much higher than the R/P ratio for oil and gas and this is the same scenario for Kazakhstan. During 2017, 111.1 tonnes of coal were produced in Kazakhstan as seen in Figure 2, and this indicates a rise in comparison with the previous two years. The initiative of increasing the coverage of geological studies in the territory of the Republic of Kazakhstan was implemented in 2014; new studies were conducted in the mineral complex. The target was to increase from 78% in 2009 to 95% in 2014 the percentage of coverage available for regional geological surveys. According to the data published by the Ministry for Investments and Development of Kazakhstan, Division of solid minerals geology the inferred resources of coal in the country on the regional and geological survey is estimated additional 170 million tonnes with this extensive study of regions (KZ resources, 2018). Considering this immense resource and the need for identifying new prospective areas, there are several prospecting, exploration, and resource delineation projects underway.

The committee of geology and subsoil use under the Ministry for Investments and Development of the Republic of Kazakhstan initiated a pilot project that presents to the public the results of preliminary geological studies. There is a project in the form of database, where all studies of areas for minerals are collected. It is accessible in the form of an interactive map that provides the details about the country's mineral resources. Input data of this project are the results of the geological studies in the whole territory of the country. Figure 2 represents the interactive map (Map, 2018) with certain search outputs with different deposit types. In this map, the regions with studies developed for hydrocarbon raw material are presented in purple. Their location is in the western part of the country in particular for petroleum products, fuel and gas.

In the region under the red circle, shown in blue areas are mainly coal mining regions located: East and Central Kazakhstan.

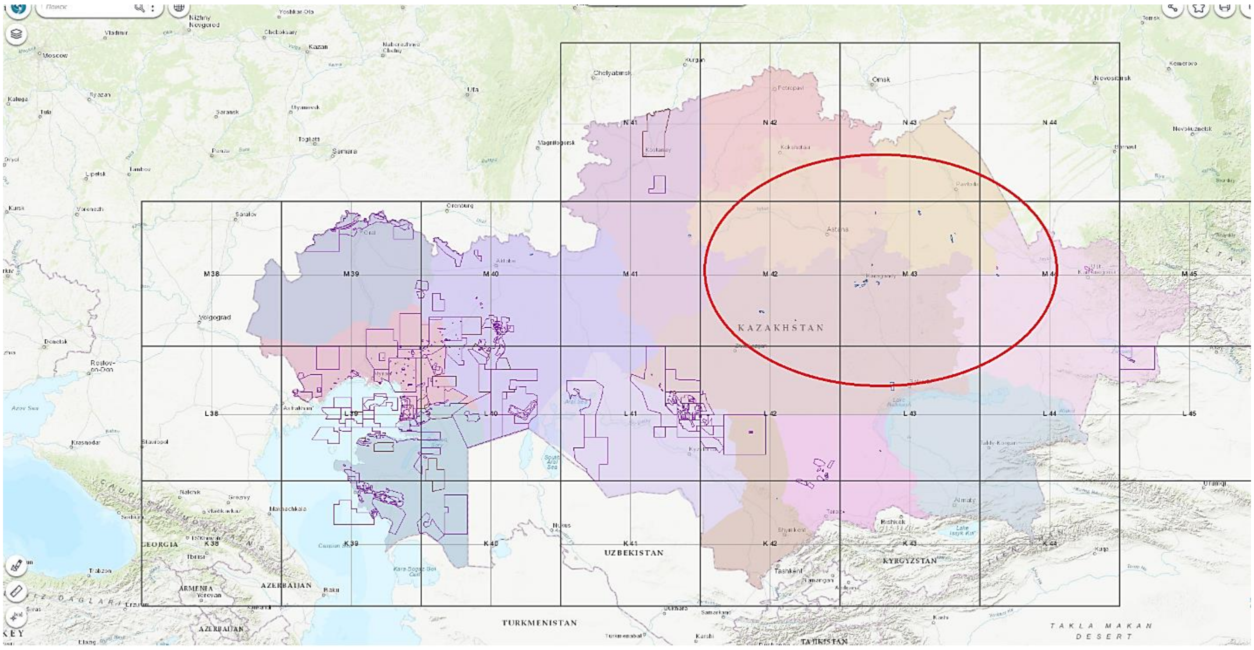

Figure 2. Contract territories in the Republic of Kazakhstan for hydrocarbon raw materials and coal production (Map, 2018).

As one of the competitive and fast growing sectors of Kazakhstan's mining industry attracts foreign investors. Private companies together with state-owned corporations are the main producers of mineral products in Kazakhstan (OECD, 2018). There are partly and fully private companies that produce coal: ERG and ArcelorMittal, they operate in different regions of the country.

2.1.2 Study area and geology

KCB has long been Kazakhstan's main coal supplier. There are eight underground coal mines located in the Karaganda coal basin that is owned and operated by ArcelorMittal Temirtau (AMT). Names of these mines are Kostenko, Kuzembaeva, Saranskaya, Abayskaya, Kazakhstanskaya, Lenina, Shakhtinskaya and Tentekskaya. Figure 3 shows a regional map by indicating the location of mines where AMT operates and specifying underlined locations as a selected one for the purpose of this study.

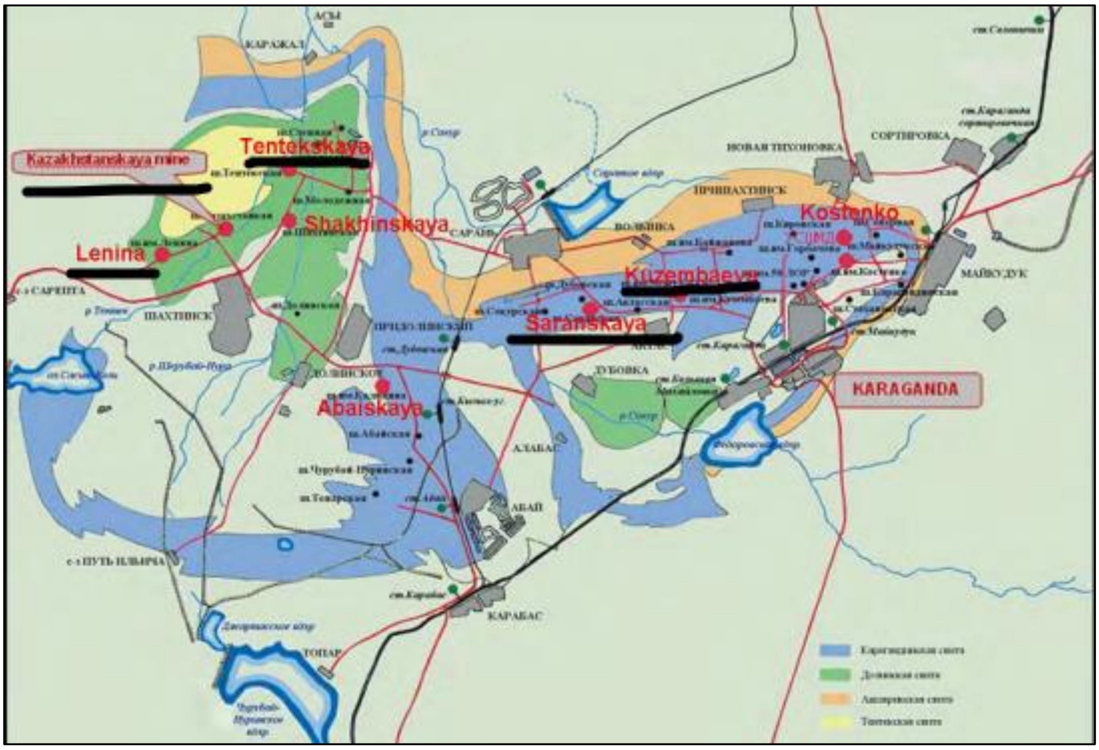

Figure 3. Map of KCB with indicating locations of selected samples (EPA, 2017).

Coal samples are collected for the testing from seven locations from currently being developed coal seams (4) and mines (5). A more detailed description of each seam and coal mine is presented in Table 1. There are grade composition of Zh, KZh, K and OS coal grades overall within the KCB; however, for the current study selected coals were corresponding into only first two "coal marks". The corresponding meaning to these coal grades is by Coal Classification System (PM-Files, 2019): Zh mark coals are the most valuable coking coals, KZh - "coke fat coal", K - "coke coal" and OS – "semi-lean caking coal."

Table 1

Summary of Mine and Coal Seam Characteristics (Ulinich, 2019).

Karaganda coal basin mine	*Coal seams*	*CODE*	*Coal grade*	*North latitude*	*Eastern longitude*
Lenina	D6	D6L	KZh	49° 44' 38.2810"	72° 31' 2.8622"
Tentekskaya		D6T	KZh	49° 47' 9.7585"	72° 34' 15.4879"
Kazakhstanskaya		D6K	KZh	49° 44' 33.2158"	72° 32' 24.3694"
Kazakhstanskaya	D11	D11K	KZh	49° 46' 4.0262"	72° 33' 21.3462"
Saranskaya	K7	K7S	K		
Saranskaya	K12	K12S	K	49° 46' 24.7396"	72° 57' 12.6448"
Kuzymbayev		K12K	K	49° 48' 17.2666"	73° 0' 6.8403"

According to EPA (2017), the boundaries of operating mines mainly occupied by coking bituminous coals if not consider some discontinuous beds of brown coals. Within the area of coal basin increase of metamorphism, intensity detected from the north-east to the south-west in addition from overlying seams to underlying seams. It should be noted that samples collected in the top face of the seam section for each location since coal there has better quality. Due to the general data obtained from coal layers coal grade “KZh” were selected to be investigated and for comparison of grade effect on the result's samples from location, K12K was added. So, coal samples from the K7 and K12 seams of Saranskaya coal mine were not included for the further studies as well as Lenina mine, but latter due to the obtaining enough samples from its corresponding seam D6. There is a case where these samples were used while doing the UCS test.

2.2 Classification of coal

Characteristics of rock material according to Goel and Singh (2011) can be grouped by physical and mechanical properties. Physical characteristics are porosity; texture, grain size and shape; color; mineral, chemical composition; as well as density. These quantitative characteristics also include mechanical properties like durability, plasticity and swelling potential; brittle behavior, violent failure, fracture mechanics, and strength. Coal is a unique rock type. It is described as an organic sedimentary rock (Riazi and Gupta 2016), which also belongs to the category of soft rocks (Kanji, 2014). Soft rocks are recognized as the critical geomaterial because of these types of problems associated with working on soft ground. Issues in soft rocks are highlighted by Kanji (2014) are:

- Soft rocks demonstrate undesirable behavior;
- have strength in between soils (UCS < 1 MPa) and hard rocks (UCS > 20 MPa) – Intermediate strength needs well characterization of their properties;
- Issues with site investigation and sampling;
- The necessity forupdate existing or adoption of new geomechanical classification for practically continuous soft rock masses.

Coal is a complex mixture of substances, consists of organic and mineral, derived from plant debris (Marsh and Reinoso, 2006). These organic components called macerals: Liptinite, Vitrinite and Inertintite. One of the primary components of coal that over geological time periods changes predictably with heating. Pan et al. (2013) argue that a vitrinite reflectance value is more advantageous than vitrinite content for assigning rank, texture and strength.

2.3 Slake durability

According to Maia and Xavier (2014), the SDT shows a direct correlation of wear property with the increasing rotation, and this relationship is approximately linear when prepared samples undergo cycles of wetting and drying processes in the laboratory. Simple procedures are performed for the slake-durability test, but there are complicated mechanisms in slaking processes that contribute to the result of the SDT. There is a significant change in values of SDT results depending on coal specimen's geometry selected for the test. Agustawijaya (2003) states mechanisms related reduction of the slake-durability index of the rocks: reduction contributed by drum rotations influence is particularly substantial for irregularly shaped samples, also the presence of microstructures, clay minerals and gypsum. It is advised to choose the samples more rounded than irregular since the latter has lower values of SDT results than former according to Agustawijaya (2003). The ranges of SDI after the second cycle is used to characterize the rock's durability see Table 2.

Table 2

Slake durability classification based on SDI value.

Classification for durability	*SDI by Gamble (1971)*		*SDI by Franklin and Chandra (1972)*
Group name	1st cycle Slake Durability Index (%)	2nd cycle Slake Durability Index (%)	2nd cycle Slake Durability Index (%)
Extremely high	-	-	95-100
Very high durability	>99	>98	90-95
High durability	98-99	95-98	75-90
Medium high durability	95-98	85-95	-
Medium durability	85-95	60-85	50-75
Low durability	60-85	30-60	25-50
Very low durability	<60	<30	0-25

SDI was also used to "assess the vulnerability of rocks to changes in moisture content and was correlated to point load values (Whateley, 2002)." For this century's innovations coal geology when measuring, understanding and visualizing coal characteristics difficulties on measuring moisture content by a reproducible method. "Moisture not only affects density estimation but also handleability of coal during processing and transportation. Handleability also depends upon the amount of fines (ibid, 2002)."

2.4 Strength of coal

The uniaxial compressive strength (UCS) is a very important parameter in geomechanical mine design, roof support design, column stability analysis, CBM. However, obtaining UCS in the laboratory for coal is extremely difficult due to the coals nature. Size effect was a topic of study by testing large diameter samples because coal is a very variable material. This method establishes mechanical properties from the triaxial test on 61, 101, 146 and 300 mm diameter samples for quantifying the variability of laboratory coal strength data (Medhurst and Brown, 1998). Due to the fact that most coals are classified as a soft rock (i.e., UCS ranging from less than 1 MPa to 20 MPa), sampling and coring of soft rocks are very problematic. In addition, coal can be intensely fractured due to a high level of stresses or tectonic forces which makes obtaining core samples extremely difficult. The strength of the studied rock units obtained from Uniaxial Compressive Strength (UCS) test. For this purpose, the blocks were cored to give cylindrical specimens, and this preparation along with the test procedures completed by following the ISRM suggested methods (1979). There are relatively not difficult tests like PLT, and P-wave velocity can be employed in both the site and laboratory, they characterize and determine the strength and dynamic properties of rock, respectively. Point Load Index ($I_{s(50)}$) is assessed in accordance to suggested guidelines from the same institutions standard (ISRM, 1985) for determining point load strength. Strength of coal depends on mineralogy and composition. The study of Pan *et al.* (2013) reveals how coal microstructures influence the mechanical properties of coal, predominantly the UCS and Young's modulus. Several tests were conducted on long flame coal, a bituminous (⅓ coking) coal, anthracite coal samples to measure the mechanical properties related to coal rank, compressional velocity and maceral composition. Their laboratory tests on core were conducted to get results of UCS directly, and a secondary measure for strength is found by using correlations from acoustic/sonic compressional velocity (p-wave). Results of coal specimen tested under uniaxial compression condition (Pan *et al.*, 2013) as presented in Figure 4.

As one can see from Figure 4, UCS and Young's modulus are affected by the physical and chemical properties of the coal. There is not a unique correlation for different coal ranks as shown by authors using different relationships for different coal types. For instance, pore structure development in coal depends on coal type and rank (i.e., maceral composition). Hence, as coal rank or vitrinite reflectance increases then coal has less microporous structure (i.e., lower porosity) and higher UCS (Pan et al., 2013).

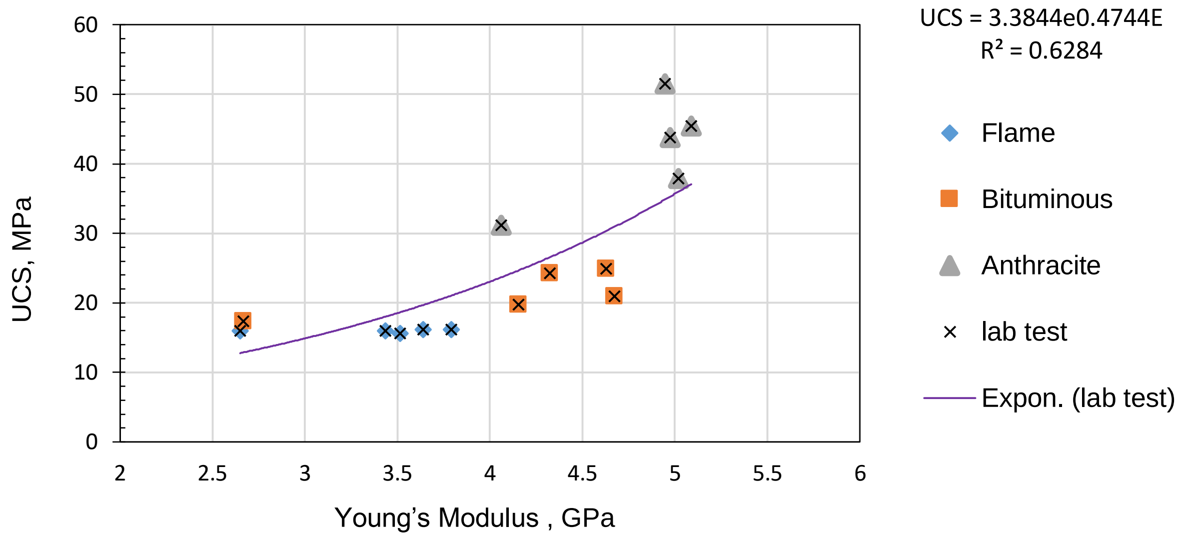

Figure 4. The relationship between UCS and Young's modulus (Pan et al., 2013).

There is also an economic point of view exploring relatively less costly alternatives by taking into account that the UCS is expensive to test. Because of samples preparation requirement to prepare in certain shape and geometry and quantity too, whereas there are tests that do not require special arrangements for preparing specimen and just irregular lumps are used. Especially for the weak rocks, another possibility of obtaining strength can be SDT that is quick and cheap. UCS and point load strength index of samples from Karaganda coal mine can be estimated from slake-durability values by using simple and easy mathematical relations. These equations are practical and simple enough to apply for the determination of different properties of coal.

2.5 Physical properties of coal

The dominant coal properties to characterize the qualities of this material are the strength of intact rock and microstructural and textural features which affect the durability of rock (Riazi and Gupta, 2016).

2.5.1Density

Coal density has several terms and definitions due to the coal being not homogeneous by its nature. Varieties of determining this property Depending on the situation where it is used there are true relative (TRD), apparent relative density (ARD) and bulk density (BD) for. In order to give more distinction for brown coals and lignite regarding different density types ISO 5072 (2013) suggests the following definitions: "the TRD is a ratio of the mass of a sample of dry coal ground to pass through a 212µm sieve to the mass of an equal volume of water at a specified temperature. ARD is a ratio of the mass of dry coal to the mass of a volume of water equal to the apparent volume of the coal at a specified temperature.” The bulk density (BD) is the ratio of total mass to the volume that coal occupies. For the same coal sample, the values of the BD less than the value of ARD and the value of TRD being the highest. Since the results of the volume are more accurate when the liquid waxes ability to closely mold into the surface pore of the specimen, Crawford (2013) suggests using wax immersion method. This way of determining density is better than the caliper method, instantaneous water immersion method and wax-shrink wrap immersion.

2.5.2 Coal surface area and porosity

The surface area consists of internal and external surface areas; a difference between these two is the latter being a small portion of coal. The fine capillaries and pores are formed within coal during coal generation, so the coal internal pore structure is entirely the coal internal surface area. The pores are widely and deeply distributed to form a complex and well-developed internal structure. Many pores are enclosed in coal. The total volume of these pores over the entire coal volume is the measure of porosity. The value can be represented in percentage or as the void volume in a unit mass of coal. The porosity of coal is tested in equipment that requires no liquid media.

2 RESEARCH APPROACH AND PROJECT PLAN

In this chapter, the first hypothesis to conduct the research study is stated. It is experimental research, which includes laboratory testing. To achieve the aims and objectives of this research scope of work must be planned. This is followed by a research plan that includes planning for literature review, sampling, specimen preparation, and testing. A scheduled project plan assigns tasks and activities, so to accomplish them accordingly, risk management and contingency plan were applied. Project completion becomes possible once all the action steps were accomplished. To achieve the objectives of the current study several tasks need to be completed:

- Review of the previous works on the slake durability test and relating those to coal;
- Identifying the standard test procedures that are carried out on coal and requirements for the specimen;
- Designing a research plan and schedule;
- Creating a risk management plan for the research project.

3.1 HYPOTHESIS

In this thesis project, slake durability along with other methods for determination of physical and mechanical properties of the rock are used to investigate slake durability of coal. The hypothesis of this research is that the physical and mechanical properties of coal affect its slaking behavior. There is a possibility to develop correlations to estimate some of these properties using the slake durability test data.

3.2 TASKS AND ACTIVITIES

The required tasks and activities of this research are divided into steps to establish logic and required time evaluation. Significant tasks and essential activities for the successful completion of the experimental part of the mining research project are specified in a schematics for tasks shown in Figure 6. The necessary steps for accomplishing the current research objectives: conducting a literature review, work on the experimental part and data analysis as shown in Table 3.

Table 3

Research schedule steps.

Steps	*Action*
Literature Review	The topic proposal. Research plan; Background info: slake durability; Review on physical properties of coal; Background research: Coal in Kazakhstan; Review on mechanical properties of coal; Ensuring that laboratory equipment is available and set up for tests; Description of tests to be conducted; Preparing the project plan; Determining the required number of samples and their dimensions.
Experimental part	Contact with AMT company for mine visit, collecting coal samples from KCB for laboratory testing; Additional articles and paper review; Working on the feedback: all chapters; Creating a database for results. **Rock mechanics laboratory**: Sample collection; Follow the specifications for representative coal samples; Samples preparation according to standards; Conduct laboratory testing.
Data analysis	Results interpretations and discussion; Finalizing the thesis including all results; Comparing results with results from the literature review.
Delivery	Preparation for the thesis defense; Discussing results with supervisor; Sharing of results of the experiments to the interested public.

3.3 Research plan

This research project consists of four major parts: a theoretical part, an experimental part, analysis of results as well as a delivery part. There is a context established for project management in the form of the scope of work in Table 3. As a part of this project, overall management measures were prepared, and it includes project schedule and risk management plan for those treats with high risks. There is a high level of confidence with this schedule to achieve the project outcomes on time, also to keep at a minimum any probable limitations in the research outputs. The risk management plan is an important tool to navigate the stages of the research project. The effectiveness of SDI improved by understanding processes with geomechanical properties of coal. Considerations that need to be made are summarized in the flow chart shown in Figure 5.

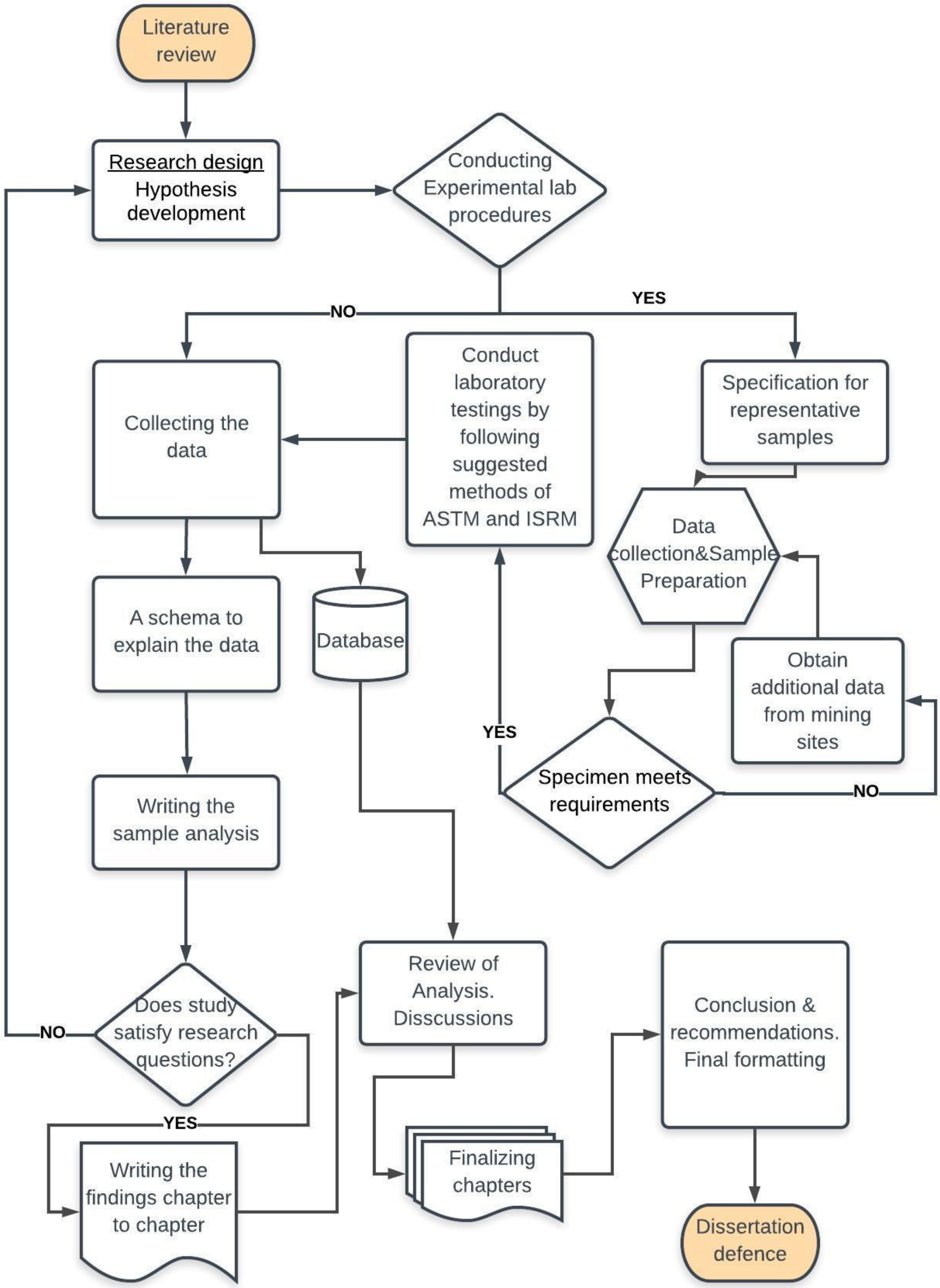

Figure 5. Flowchart with processes of the research project.

3.3.1 Equipment and material requirements

The laboratory facility of the university has the necessary testing equipment; its installment and components should be in place. The use of manual and standards to correctly perform experiments during research. Most of all, samples for conducting laboratory testing in the university must be stored properly once obtained from the mine site. Preparation of samples is possible by using certain equipment. These and all equipment types for selected tests are listed in Table 4.

Table 4

List of equipment used.

Test type	Equipment
Density, slake durability test	Scale, hammer, oven, container
Pore structure	Nitrogen Porosimeter
Uniaxial Compressive Strength test Sample preparation: Cutting, Coring and Grinding	Unconfined strength test apparatus Cut-off saw RLS-100, The GCTS RCD-200 Heavy Duty Laboratory Core drilling machine Screw-cutting lathe Knuth V-Turn 410/1000
Indirect strength: PLT	PLT-2W Point Load Testing Apparatus
Slake durability test	Slake Durability Apparatus

3.3.2 Other required resources for research

Conduct research effectively means having all equipment, material and other types of resources necessary to complete the project. They are: laptop or/and computer for writing, exchanging correspondence, and reviewing the available literature. Apart from the tangible resources, there are important components: contacts of mining company representatives, agreements of collaboration. For directing request on communication with mines regarding the providing coal samples for this research, there is procedural requirement exist. At every stage of the mining research project, the pile of documents used or reviewed will be saved into the binder or in the case of online documentation by using the secure cloud space Dropbox for a database to be created to retrieve when needed. There is an essential role that the library plays for the course of the project. Its database of electronic and hard copy materials are a great aid for review of the literature.

3.4 Project plan

In a flowchart shown in Figure 5 that identifies several milestones in between starting and ending of the mining research project: literature review and defense of the thesis, respectfully.

This is the basis to identify risks events and their causes. To analyze risks in terms of consequence and likelihood of each risk event, the list of occasions should be recorded. Evaluating risks comes from prioritization of risk events for management. Then it turns to treat risks by the implementation of strategies to manage risk events. Constant monitor and review the effectiveness of the project risk management processes are essential for the successful completion of the project.

3.4.1 Planning the specimen preparation

This research project aims to evaluate the physical-mechanical properties of intact rocks and the correlation of slake durability with the density, uniaxial compressive strength (UCS), Point Load Index ($I_{s\,(50)}$), porosity (n). For describing coal samples dimensioning for each procedure according to the number of tests and sample geometry the schematic shown in Figure 6 is prepared.

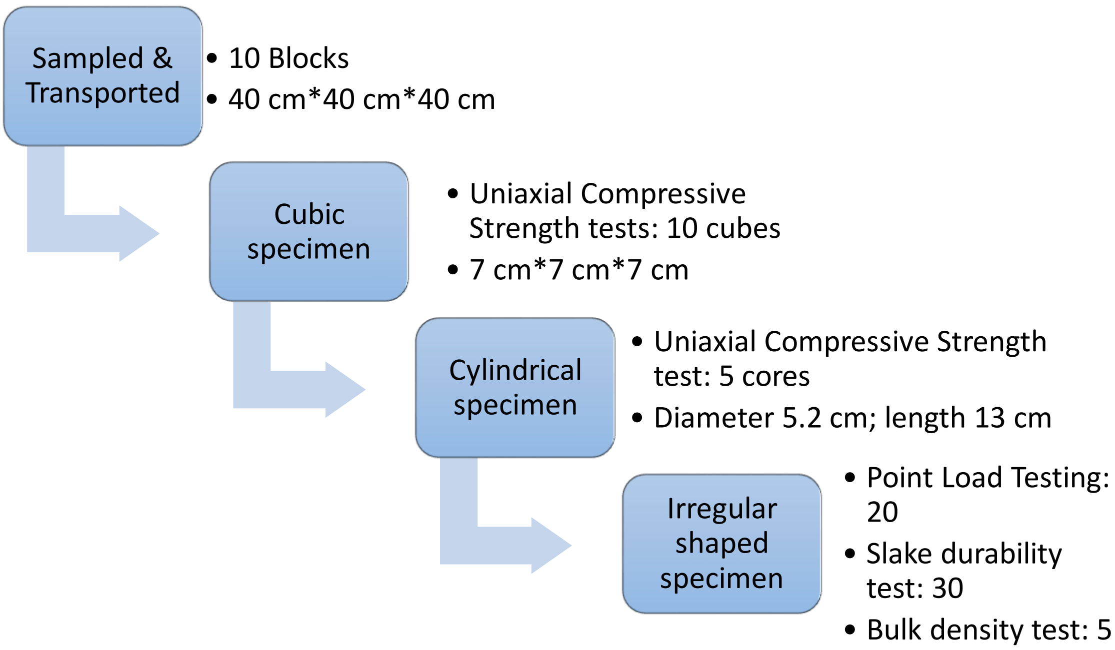

Figure 6. Specimen size and shape for different tests.

Planning the laboratory core preparation for testing the key coal properties represents the certain order of arrangements shown in Figure 7. These procedures are followed to produce the core speciemens: sample selection, transportation, coring/cutting, final preparation (cutting to the length and grinding faces) and inspection that might affect to the end results of the tests. Also, the sequence of sample preparation order is considered while planning with the intention of providing detailed documentation about intact rocks under different condition of obtaining coal specimens.

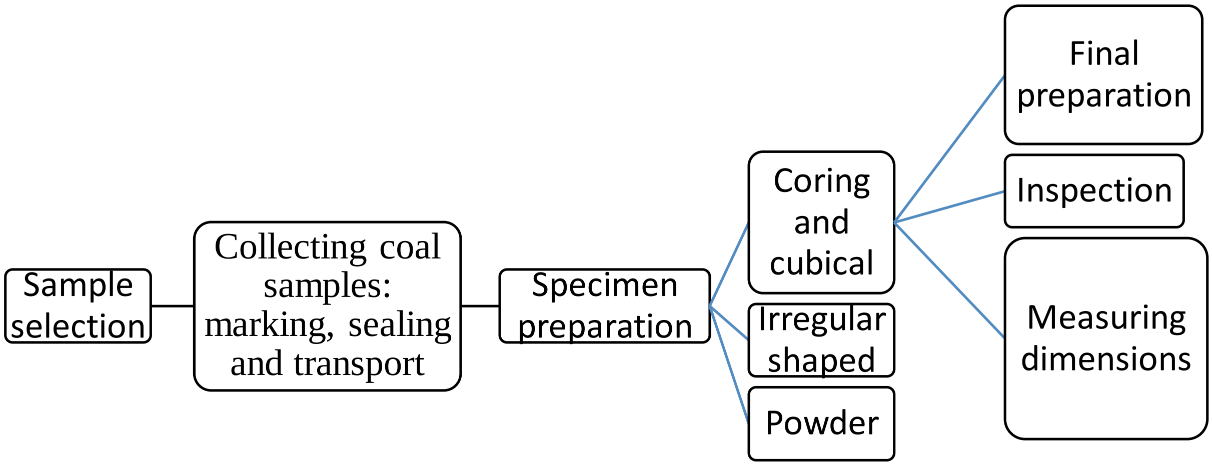

Figure 7. Laboratory coal sample preparation steps.

3.4.2 Planning the testing procedures

Laboratory investigation sequence for a determination of different physico-mechanical properties requires laboratory testing of coal samples. This part of the project plan involves the arrangement of the order of the tests as shown in Table 5, starting tests from measuring physical properties then strength properties of coal. Regarding the density of coal, several methods can be used. Bulk density of cubic and core specimen was obtained before UCS. Also, test on waxed sample submerging into the water was performed on residual coal samples after the destructive tests. The porosity and surface area are tested on the powder. Since the specimen preparation for UCS takes the longer time it was conducted on later stages; meanwile point load test and slake durability tests are performed.

3.4.3 Planning the data analysis

Once all the results are obtained from the experimental part, the database is created to record all the values. From the database, the values of different test are considered for different relationships between existing parameters. By using data from the literature and combining the results obtained new database is created. Pearson r coefficient of correlation and its classification to identify some parameters are applied. Apart from estimating correlation and regression, there are graphs and tables to summarize the values obtained from tests. This will follow with in depth discussion of the results, their value and prediction of some parameters.

Table 5

Summary of coal testing procedures for a specimen from one location.

Results of coal properties	*Standard procedure*	*Shape*	*Size (dimension or mass)*	*Number of samples*
Density	IRSM (1979) and ASTM C 914 – 95	Irregular lump, Cylindrical Core or cube	varies	5
Porosity		Powder	5g	1
UCS (cubic) parallel, perpendicular	ASTM D2938 and ISRM SM (1979)	Cube	L=70mm, W=70mm, H=70mm	5 for each bedding direction
UCS (core)		Cylindrical core	D=52mm H=130mm	5
Point load test(PLT)	ASTM D5731 - 16 and ISRM SM (1985)	Irregular lump	D=50mm, L>0.5D 0.3<D/W<1	10 for each bedding parallel, perpendicular direction
Slake durability test	IRSM (1979)	Irregular lump	450-550g	30

3.5 PROJECT SCHEDULE

By setting the due date to each of these actions a proper schedule of the work can be constructed and with following the plan accurately the project could be succeeded. The project schedule is presented in a Gantt chart from Figure 8. Identified all project milestones were assigned by the calendar date and delivery. After writing the literature review, the project's critical path includes execution of these tasks: revisiting research design, collecting the data that meet the specifications, sample preparation and equipment setup, conducting laboratory testing, creating a dataset for results. The samples will be collected shortly after identifying the specifications for the representative sample; this allows the experimental part. For the schedule performs to be suitable for realistic situations it should be updated promptly. The only track should be kept for completed tasks without considering major practical adjustments. There are loops and alternate options in Figure 5, by using them it is possible to make the accuracy of planning in details with considering all tasks grouped into a certain stage.

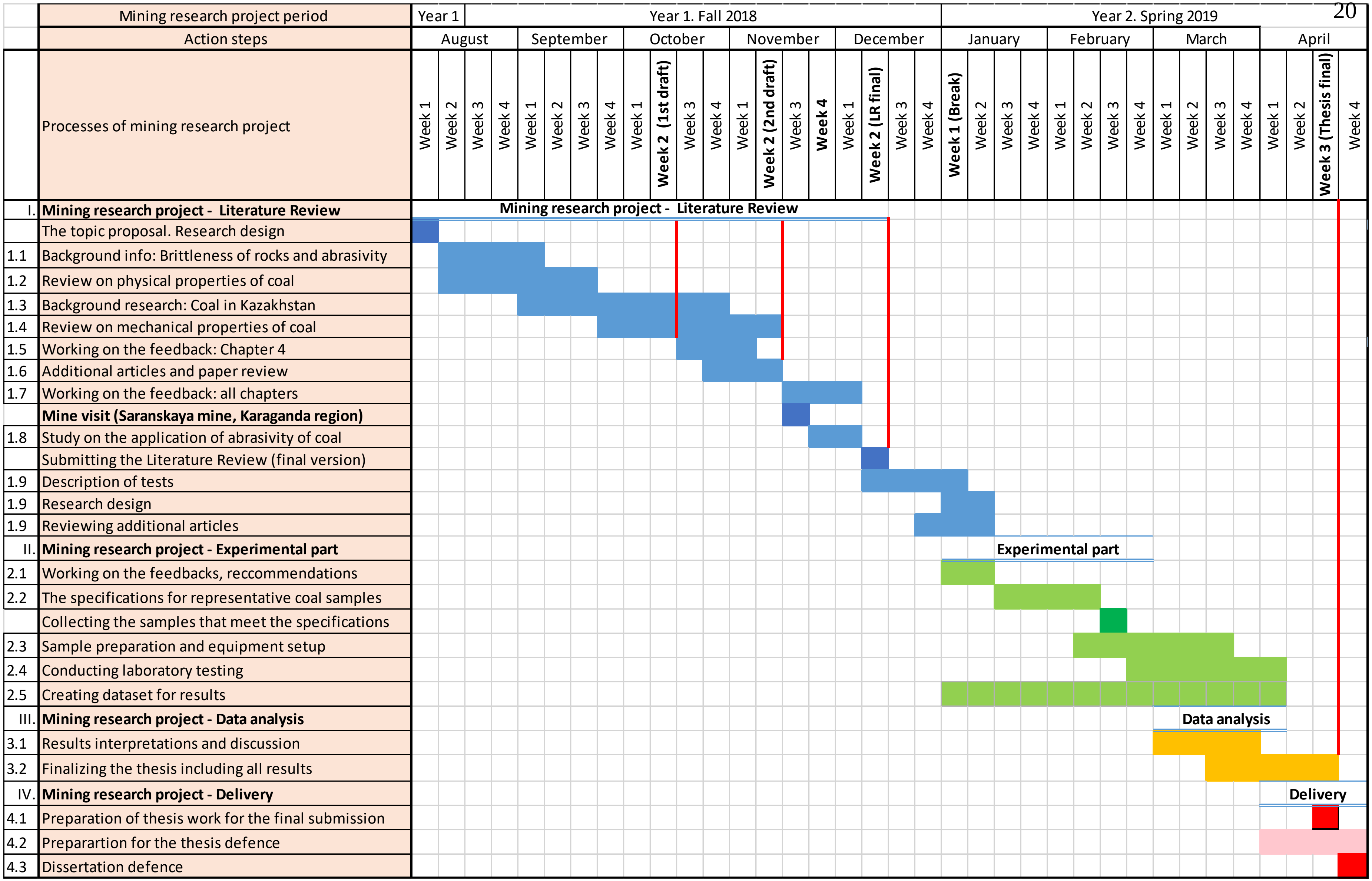

Figure 8. Gantt chart with processes of a mining research project

3.6 RISK ASSESSMENT

Risk management adds value to research projects. Risk management is a detailed and systematic method of identifying, analyzing and responding to risks to achieve the project goals. The advantages of risk matrix involve recognizing, analyzing and mitigating risks, and enhancement of project management processes and efficient utilization of resources. The main principle here is certain risk value resulting when multiplying consequence to likelihood. The accurate risk assessment procedure requires a description of both risk impact; they are determined in Table 6. Regarding the probability of occurrence the following description of risk occurrence Likelihood applied. For risks that have a high chance to occur during the research project - frequent (4), may or may not occur – somewhat frequent (3), low chance to occur – occasional (2) and rare (1) for risks that are very likely not to occur.

Table 6

Description of risk severity.

Consequences	*Description*
Very Low	No consequence, no significant risks
Low	Probable minor physical injury, minor delay (less than a week) in research schedule with no effect on the whole project.
Moderate	Possibility of moderate injury, lack of time that delay of the project (several weeks), inaccurate results.
High	Potential significant injury, sickness resulting on delay (month) in research schedule, loss of resources (samples, information and documents).
Very High	Lethal outcomes, physical disability to work; regarding the project body: unfinished research or no account of results.

Project delivery should be presented by a healthy student on a date as scheduled with a complete set of quality information by specified marking criteria. The severity of the risk can be controlled by these factors. After the risks and their likelihood of occurrence and severity are identified, the risk value can be estimated. The risk matrix is presented in Table 7, which helps to identify the importance of each risk impact based on likelihood and impact ratings. The horizontal line represents the impact consequences of the risks to happen, while the vertical line shows the level of risk's probability. Moreover, it shows a combination of the consequence and likelihood which produce risk priority zones based on risk levels indicted in Table 8. Rating risk as assigned for distinct risk factors in the identified risk categories calculated: red zone risks are of the high priority, risk impact decreasing by orange zones to yellow zones, where the risks are lowest for the green zone.

Table 7

Risk matrix.

	Risk Value	*Consequence impact*				
		1-Very Low	2-Low	3-Moderate	4-High	5-Very High
Likelihood	1-Rare		E1	PM3	H2	E3
	2-Occasional		H4	T2, D3, H5	O3	H1, O4
	3-Somewhat Frequent		PM1	D2, O1	E2	D1, H3
	4-Frequent			T1, O2	PM2	

Table 8

Calculation of risk levels.

Risk rating	*Value*	*Priority*
Negligible	1-3	
Moderate	4-9	
Significant	10-12	
Extreme	15 - 20	

Twenty project hazards from six risk categories were considered to be critical for this project. Table 9 demonstrates six main risk categories (each with their sub-categories) grouped as follows: design risks, external risks, health risks, organizational risks, project management risks and time-bound risks. This risk analysis method can help to identify which one of the following actions should be applied, either perform further analysis for risk or find a response. As one can see from the risk matrix shown in Table 7, these are the risks located in the red zone: D1, PM2, H3. From the design risk category, design errors and omissions meaning the missing of project design step(s) (D1) parameter has a high rate of impact for the duration of the overall research project. Under the project management risk category, misconduct issue due to improper referencing of the material (i.e. plagiarism) (PM2) has a high impact on the submission of high quality work. From the student's physical health related risks illness like the inability to complete the work due to physical health issues (H3) parameter has a very high rate of impact and should be in the first priority. All of these parameters on the table results on the poor quality of work, delays and different losses. As a result, these risks should be carefully considered, while risks from the red zone should be immediately analyzed using quantification and aggressive risk management and proper treatment with suitable mitigation plan should be applied.

Table 9

Risk categories and risk value.

Code	*Categories of research project hazards*	*Likelihood* *	*Impact* **	*Risk value*
	Design Risks			
D1	Design errors and omissions: project design step(s) missing	3	5	Extreme
D2	Required late changes into research project design	3	3	Moderate
D3	Failure to carry out the research works by research design	2	3	Moderate
	External Risks			
E1	Remarks from the company emerge by requesting some adjustments	1	2	Low
E2	Unavailability of the laboratory or testing equipment	3	4	Significant
E3	Course completion requirements changes	1	5	Moderate
	Student's physical health-related risks			
H1	Exhaustion: Low energy due to the work overload and lack of sleep	2	5	Significant
H2	Eye-strain: excess use of computer screen and extended hours in front of the monitor	1	4	Low
H3	Illness: inability to complete the work due to physical health issues	3	5	Extreme
H4	Injury: problems with back can occur due to sited position or injury in a lab	2	2	Moderate
H5	Stress from an overwhelming amount of work leads to mental health problems	2	3	Moderate
	Organizational risks			
O1	Incorrect interpretation of laboratory testing results, mistakes in reporting	3	3	Moderate
O2	Issues during laboratory tests: lack of samples for test or bad quality	4	3	Significant
O3	Loss of the information in the database	2	4	Significant
O4	Lack of protection: damage of samples during storage/transportation	2	5	Extreme
	Project management risks			
PM1	Failure to comply with the quality requirements of project delivery	3	2	Moderate
PM2	Misconduct: improper referencing of the material, plagiarism	4	4	Extreme
PM3	Conflicts between company and student, or supervisor and student	1	3	Low
	Time-related risks			
T1	Acceptance of unrealistic deadline	4	3	Significant
T2	The process takes longer than anticipated	2	3	Moderate

*Likelihood:1 (Rare)-4 (Frequent), ** Impact: 1 (Very Low)-5 (Very High)

3.7 Risk management plan

There is the flowchart in Figure 5 that can assist in making a list of all possible negative outcomes and a table with risk value parameters, which presents hazards associated with every single group of risks. Since reasons for all of the possible delays and difficulties are known it is possible to identify action steps to eliminate risk or prevent the obstacles that might bring complications for completing the initiated research. The flowchart specifies the major issue regarding this, so if the answer is changed to the no test conducting then the data collection will refer only to data that can be obtained from the literature. Other concerns of any risk occurring during the project are not meeting the requirement for available samples. In such cases processes before the current one will be conducted by the use of the loop to make an iterative procedure. The continuous trials with sufficient allowance given to contingencies should be avoided.

The extreme risk category has three hazards, which have to be prevented or in the case of occurrence have alternative option to be performed to mitigate its consequences. Inability to complete the work due to physical health issues (H3) can be prevented by consuming healthy food, doing regular exercises for body and eyes.. The study environment where good lighting and quiet exists and assigning systematic breaks during the working day. From the risk value having extreme risk category, the project management problem related misconduct issue due to improper referencing of the material (i.e. plagiarism) (PM2) has a high impact on the submission of high quality work. This could be managed by using citation tools. In the case of many similarity cases with the original texts, significant attention needs to be apportioned for progressing in academic writing skills. Since there is a high rate of impact for the duration of an overall research project because of errors and omissions in the research plan (D1), the use of flowchart given in Figure 5 as well as project schedule given in Figure 8 is helpful. The major concern of extreme risk relates to creating a database, reporting the findings and writing chapters to finalize the mining research project. At the start doing literature review is essential; then communicate and consult with interested parties during the course of the project, whom might be an advisor or other professors, admin staff and representatives of coal mines.

The risk management plan includes project management issues relevant to conducting an experimental work. The following arrangements need to be monitored to obtain viable results. The main focus of this project relies on the data obtained from the field: i.e. samples of coal from the KCB. The consecutive steps for experimental procedures should be carefully organized: testing materials being sampled, conditions of transportation, measures used to conduct the test and to gather obtained data. Control of documents related to the thesis, unsaved information for saving all documents and results, regularly check access to the database. The list of all other required activities in the case of a problem occurring with the few of above-mentioned procedures:

- Revising and re-adjusting the research design due to certain limitations with research;
- Requesting additional samples from the same mine site explaining the shortage;
- Performing the theoretical work from the available results of previous studies.

4 EXPERIMENTAL PROCEDURES

The experimental part of the research is structured by the specification of equipment for testing as well as the existing methods of standardized testing procedures. The following sections contain information on procedures used for sampling and performing the tests. The procedure of testing plays a great role in the overall mining research plan. Material characterization is possible from the sample's physical parameters that give more details on coal like density, specific gravity, porosity and water content. UCS and PLT tests are conducted to see the correlation of these properties of coal: strength, and slake durability. Test procedures are described step by step with the samples preparation section is discussed, separately.

4.1 Sample selection

Sample shape and dimensions are specified for each testing as well as specimen conditions and the number of samples required. Sample selection marks certain requirements for shape and size and to obtain specifically unweathered, joint and fracture free coal bulk masses. Collected samples are the representative of the average field characteristics; therefore, careful handling is required to avoid damage from deterioration when stored and also avoiding delays while collecting them. The most appropriate way of confusion avoidance is labelling them after sealing in specific bags. Marking serves to fulfil two purposes: identification of the site of origin and representation of the accurate orientation of the sample's geological location (Singh and Ghose, 2006). For example, Kuzembayeva K12 corresponding to a coal mine and seam site, also upper layer regarded as samples' orientation relative to the parent geology. Loading and unloading samples performed by use of a loader-piler (stacker) is an essential part of sample transportation as well as carrying the load in vehicle protected from sun and snow. For containing samples in a dry and dark place before proceeding to conduct any undertakings in the laboratory, samples are placed in storage.

4.2 Specimen collection

Coal samples of specified sizes will be collected such that all experiments listed in the diagram shown in Figure 6 can be performed. Coal mines and currently operating seams in Karaganda Region are Tentekskaya (D6), Kuzymbayev (K12) and Kazakhstanskaya (D6 and D11); this is a list of coal mine seams belonging to ArcelorMittal Temirtau JSC. Coal minefields are the area of interest from where the samples are collected. There should be paid careful attention to the coal samples handling as well as for their transportation. For sample handling, transportation, and storage processes these are important parameters to be considered: the source of samples, sampling date, method of preserving samples during transport and storage.

4.3 Specimen preparation

Since the specimens of different shapes and sizes are needed the matter of importance to separate samples for cube, chunk and core recovery. Dimensions of specimens are key parameters to consider when preparing the samples as well as its amount. Preparation of every specimen dimension as specified for each test requires the use of coring and cutting machine. Slake durability representative samples should have a total mass of 450-550g, for which ten lumps that are roughly spherical in shape are chosen that gets rounded during preparation. The use of hammer helped for trimming angular parts of those obtained samples.

4.3.1 Preparation of coal specimens for physical tests

Regarding samples preparation, the porosity test the samples were crushed since the powdered sample was required. For testing the density irregular lump shaped specimen were used. Specimen selected for this test is placed into water that is in a container shown in Figure 9; therefore, the coal sample's shape should be less tan the diameter of the vessel.

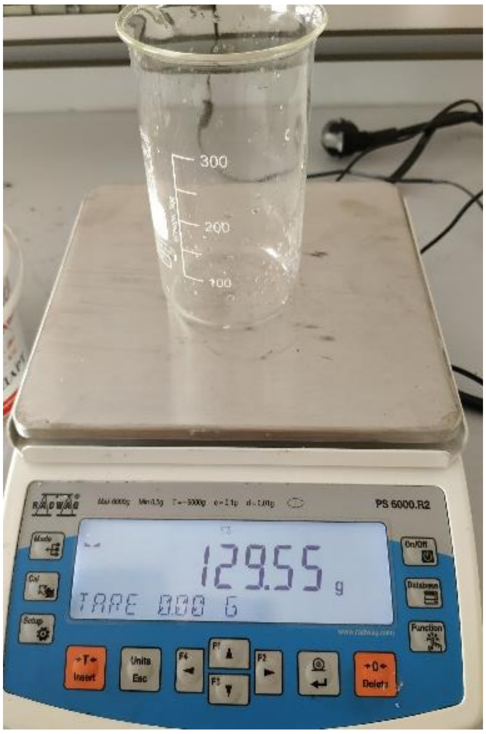

Figure 9. Scale and container for density test.

4.3.2 Preparation of coal specimens for mechanical tests

Configuration requires test specimens with smooth, flat and parallel faces. The specimens prepared for Point – Load test had the form of irregular lumps. Problems of core recovery from coal block are a separation occurring along with the bedding plane. This happens when coring both parallel and perpendicular to the bedding due to weak stratification. By following ISRM (1979), core specimen is prepared for UCS test. For this purpose diamond, pacific lapidary slab saws and a coring machine were used. The size and condition of samples have played a critical role in inserting the blocks into the apparatus for cutting shown in Figure 10.

Figure 10a (SMG, 2019)

Figure 10b (GCTS, 2019)

Figure 10. Specimen preparation equipment: a) cutting and b) coring machine.

The factors affecting the quality of specimens are identified to minimize the intact core recovery issues apart from the condition of sample material. They are machine characteristics, drilling parameters applied and selection suitable coring bits. The drilling machine characteristics are deliberately selected to encounter fewer issues while actual performing drilling. Coring machine type having certain stiffness and capacity allows obtaining core with minimum vibration, by the independent load applied to the bit at peripheral speed and rotation.

Next criteria about drilling parameters are essential for operating on the selected machine; it is a fluid flushing rate. The rate of flushing affects to the penetration rate, 16 liters/min is optimum rate until which the rate of penetration increases afterwards with the buoyancy of flushing fluid the rate reduces (Singh and Ghose, 2006). Several specimens were obtained by replacing the fluid of the apparatus with water while keeping the rate of flushing as for cases of using specific fluid. Since the most important parameter is the amount of obtained quantity and good quality specimen out of sample other criteria were varying and played less significance to the result.

Pre-coring preparation considers the placing of the coal sample on the apparatus for drilling. The machine having the sample locating area and securing clamps simplifies the procedure. However, this way of fastening the sample to hold tight for safe work condition might apply extra strength to the sample. The imposed stress affecting the result cannot be detected as well as if it was negligible. There is a plastic gate for ensuring the safety of the operating personnel in cases of breakages of coal parts. For coal recommended drillability parameters are using a drill bit of 38 mm extra thin wall diamond impregnated at 1000 rpm speed with bit load being 650-850 kN and flushing rate of fluid 12 liters/min (Singh and Ghose, 2006). This set of specifications was changed for the actual core recovery. According to IRSM (1979), NX core specimen with a diameter of 54 mm should be prepared. Due to the required core diameter being larger from available drill bits there was chosen the one type that has this parameter: diameter of 52 mm. Afterwards, the obtained core undergoes the final preparation stages, where the cutting and grinding equipment are used. The surface of coal that will be placed to the testing apparatus are inked with white correction marker; this is the same procedure common for both cubic and core samples as shown in Figure 11a and Figure 11b respectively. Procedure to make a smooth surface for cubic is shown in Figure 11c and, the equipment in Figure 11d was used for core samples.

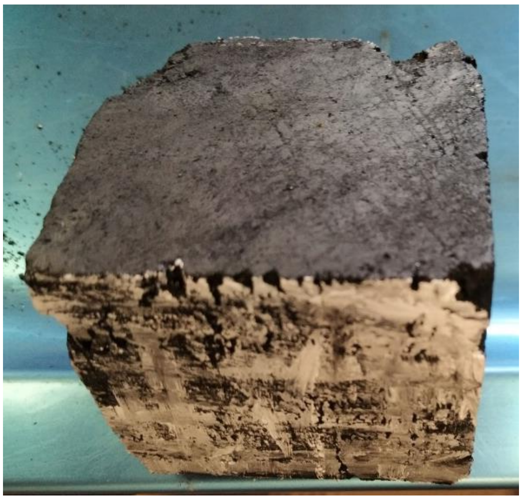

Figure 11a

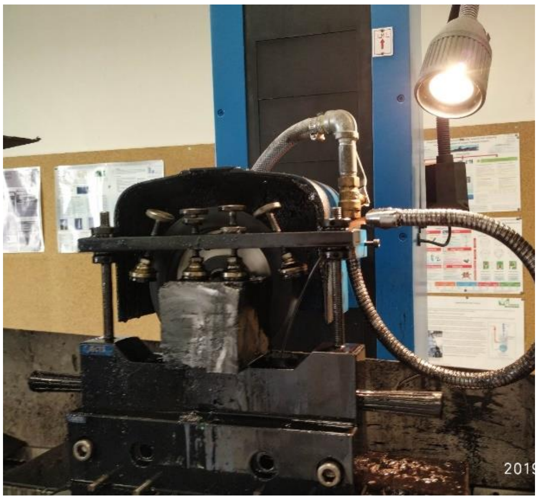

Figure 11c

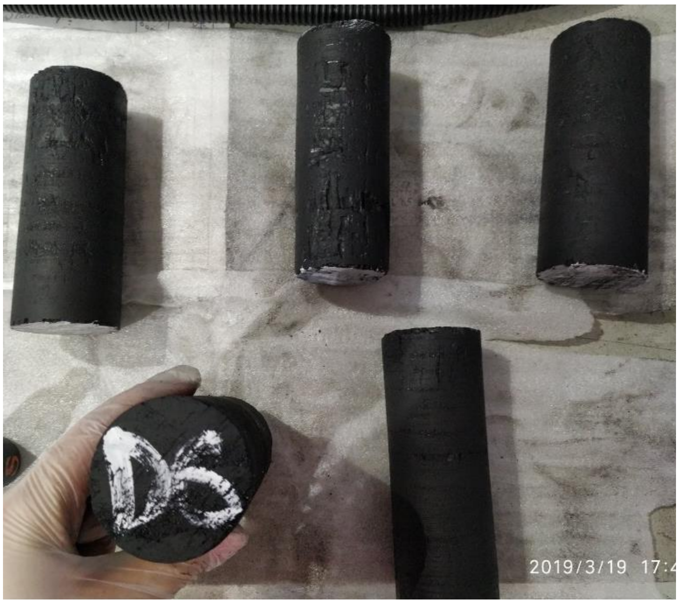

Figure 11b

Figure 11d

Figure 11. Final preparation: a)Cubic and b)Core specimens with marked surfaces, and Grinding machine for c) cubic specimens and d) for core specimens.

For checking the perpendicularity to the axis of the specimen to be less than 0.001 radians (about 3.5 min) or 0.05 mm in 50 mm and flatness of opposite sides to 0.02 mm apparatus shown in Figure12 is used: Figure 12a shows core specimen and Figure 12b for the cubic specimen. The samples finally ready to the testing with careful inspection of the specimen under the jig, only left issue is about appropriate labelling.

Figure 12a

Figure 12b

Figure 12. Specimen flatness check under the specimen inspection jig: a) Cylindrical sample and b) Cubic sample.

4.4 TEST METHODS

This section describes the equipment description and equations used for determining the property value from the collected test results. Rock mechanical properties testing equipment are PLT apparatus, UCS apparatus, slake durability testing apparatus, Nitrogen Porosimeter, they are from different providers. Conducting tests and data analysis after specimen preparation will be directed according to the ISRM suggested methods, ASTM for coal samples in the laboratory. After collecting the results from the experimental procedure, the database is created. From the set of definite data estimate of each property is generated to be presented in the results section in the next chapter.

4.4.1 Slake durability

Slake durability index is found by conducting the SDT. The suggested method describes the two standard cycles of rock sample tested to assess the resistance to weathering and disintegration by using the apparatus shown in Figure 13a. This Slake durability test equipment consists of two test drums joined to the motor drive, additionally an oven shown in Figure 13b needed for drying and scale with an accuracy of 0.5 g. The scale is the same as used for density measurement shown in Figure 9. The drum is a sufficiently strong 2.00 mm mesh cylinder assembled horizontally into the motor drive that rotates at the constant speed of 20 RPM for the 10min period. Calculation of the SDI is by following Equation 1:

$$I_{d(N)} = \frac{W_{d(N)} - D}{W_{d(0)} - D} * 100\% \qquad 1)$$

N – Number of cycles, N={1…5};
$I_{d(N)}$ – Slake durability index (N-th cycle), %;
$W_{d(0)}$– Weight of the initial samples, g;
D – Weight of the drum, g.

Figure 13a Figure 13b

Figure 13. Equipment used for Slake Durability Index determination (a) Drums and (b) Drying oven.

4.4.2 Density

The density of the substance is a measure of mass per volume as shown by Equation 2.

$$\rho_C = m_C / V \qquad 2)$$

Standard test method for bulk density by wax immersion ASTM C 914 – 95 gives the guidelines for apparent density calculation. It involves the use of paraffin wax, measuring container for water and wax melting pot for being placed into the oven. It is preferable to have a lab grade paraffin wax that melts at approximately 57°C and has a density of 0.87-0.91 g/cm^3.To obtain the volume of the sample with a wax coating, V_{Total} take the difference between the original dry weight, W, and the suspended weight, S_{Wax} or S. This relation is shown in Equation 3.

$$V_{Total} = P - S \qquad 3)$$

V_{Total}= Volume of the Sample with wax coating, cm^3;
P= Weight of Sample coated in wax, g;
S= Suspended weight of the coated sample, g.

The volume of the wax coating, V_{Wax} is obtained as calculated in Equation 4:

$$V_{Wax} = \frac{P-W}{K_{wax}} \tag{4}$$

V_{Wax} = *Volume of Wax Coating, cm*$^{3;}$
P= Weight of Sample coated in wax, g ;
W= Weight of dried Sample, g;
K_{wax}= *Density of the wax in* g/cm^3 *[*K_{wax}*=0.9* g/cm^3*]*

The volume of the test specimen, V is found by subtracting the result found by Equation 4 from the total volume as calculated in Equation 5:

$$V = V_{Total} - V_{Wax} \tag{5}$$

4.4.3 Porosity

The effective porosity of rock specimens is determined using a gas expansion method. Dry unit weights and effective porosity of the coal specimens is determined using automated gas sorption analyzer. The temperature that sample can withstand for degassing: 110 degrees. The laboratory testing of coal specimen is conducted by using Nitrogen Porosimeter designed by Quantachrome Instruments. Coal pore volume, V_{pore}, coal surface area and pore size are obtained when a specimen is placed into the apparatus. Coal porosity then can be determined by using Equation 6.

$$n_C = \frac{V_{pore}}{V} \tag{6}$$

n_C – Coal porosity, % ;
V_{pore} – pore volume, cm^3.

4.4.4 Uniaxial compressive strength

The uniaxial compressive strength (UCS) of the sample is the load carried by the sample before failure over the original cross-sectional area as calculated by Equation 7. Depending on the shape of samples guidelines to follow differs. For core specimens, IRSM Suggested Methods for Determining the UCS and Deformability of Rock Materials and for measuring UCS of cubic specimen Standard Test Method for Compressive Strength of Dimension Stone is used. According to IRSM (1979) core specimen with D, the diameter of 52 mm and length equals to 130 mm was prepared. Core specimen shall be placed into the apparatus in between steel platens are having Rockwell hardness of not less than HRC58, its thickness D/3 and diameter between D and D + 2 mm. Maximum load during the test were obtained by subjecting each cylindrical specimen to incremental loading at about constant rate within limits of 0.5-1.0 MPa/s in IRSM (1979), whereas ASTM C 170 – 90 suggests the rate of loading not exceeding 0.69 MPa/s. Equipment load rate of 0.5 MPa/s was set. As for cubic specimens, the test method is the same with the exception of the coal specimen dimensions and number: for ten specimens since to observe the effect of anisotropy specimens of two kinds of bedding to the loading direction are prepared. Figure 14 shows uniaxial compressive strength testing apparatus and screen monitor for recording the value of load and displacement. Different stages of determination of UCS of coal sample in the laboratory one can see from Figure 14, there is cylindrical sample before a) and after b) the load applied in the direction perpendicular to the bedding.

$$UCS = \frac{F_{peak}}{A} \qquad 7)$$

F_{peak} – peak load, kN;
A – area of the surface load applied, mm^2.

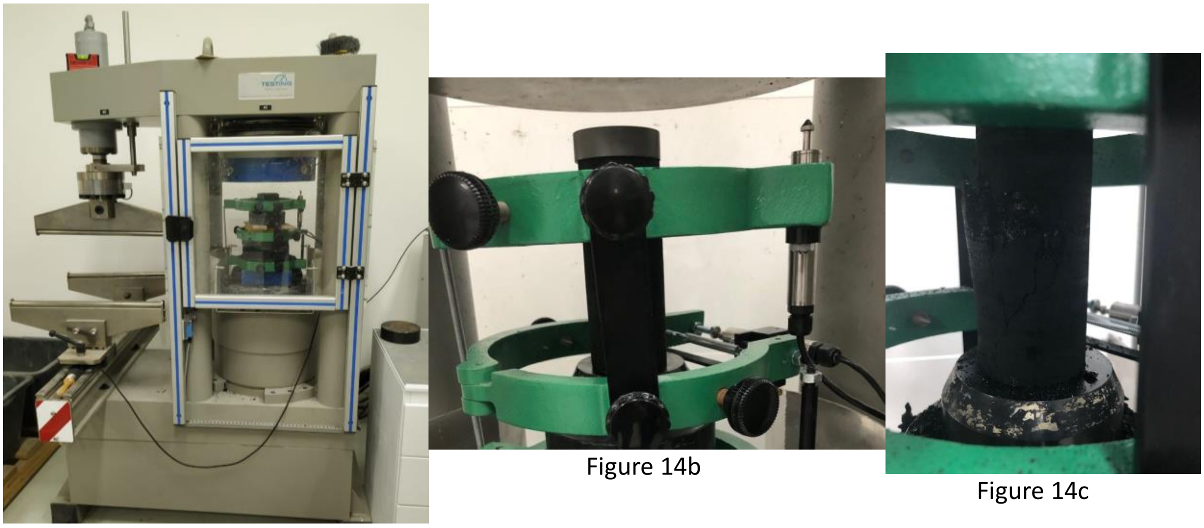

Figure 14a Figure 14b Figure 14c

Figure 14. UCS apparatus (a) with the cylindrical sample (b) before and (c) after the UCS test.

4.4.5 Point load test

Point load test apparatus is designed by Geotechnical Consulting and Testing Systems (GCTS). The testing of coal specimen strength is conducted by using PLT-2W Point Load Testing Apparatus; this laboratory testing equipment is presented in Figure 15. Point Load Strength Index $I_{s\,(50)}$ was derived from the results of both perpendicular and parallel direction of bedding. The $I_{s\,(50)}$ of the specimens was determined by mounting each specimen between two platens of a point load tester to be tested under the same loading conditions. The peak load under which specimen breaks then used for calculating PLI by using Equation 8, where ${D_e}^2$ can be estimated by using Equation 9.

Figure 15. PLT-2W Point Load Testing Apparatus (GCTS, 2019).

$$I_{s\,(50)} = \frac{F_{peak}}{{D_e}^2}\ [-] \qquad 8)$$

$${D_e}^2 = \frac{4}{\pi}(W * D) \qquad 9)$$

D_e – Equivalent diameter, mm;
$W$and D – Dimensions (width and height) of irregular shaped specimen, mm.

4.5 Test procedures

Depending on the method of test selected detailed description of each test is given in the next section. These procedural explanations of each laboratory test might serve as a basis for detailed standard operating procedures. Since the porosity test were not performed at Rock mechanics lab its procedural steps are not described in this Section.

4.5.1 Determining $I_{d(N)}$ from slake durability test

Procedure for SDT is according to ISRM SM (1977) as follows:

- Step 1. Scale the drum and record this weight as D, the weight of drum. It should be brushed clean before its mass is recorded;
- Step 2. Place the sample in the drum to dry at a temperature of 105 degrees for 6hr;

- Step 3. After cooling scale the sample and record this weight as A, the initial weight of coal sample with drum;
- Step 4. Mount the drums containing the samples to buckets and couple them with the motor;
- Step 5. Fill the buckets with the slaking fluid, which is the tap water to a level of 20mm below the horizontal axis of the drum;
- Step 6. Set a timer for 10min to detect the rotation of the motor; at this period 200 revolutions of drums are expected;
- Step 7. Remove the drum with a retained portion of the coal samples and place to dry into the oven for 6hr;
- Step 8. Scale the sample and record this weight as B after cooling, the initial weight of coal sample with the drum;
- Step 9. Empty the basket and fill four times again to repeat procedures in steps 1-9, since overall five measurements should be done. Accordingly, next recordings of the retained mass within the bucket is D, F and E for 3rd, 4th and 5th cycles;
- Step 10. Calculate the slake durability index as the percentage ratio of final to initial sample masses as shown in Equation 1.

4.5.2 Determining ρ_C from wax immersion density test

Procedure for identifying the density of coal:

- Step 1: Select sample and dry at room temperature to remove any excess moisture from its surface;
- Step 2: Scale the sample and record this weight as W, the dry weight of the coal sample;
- Step 3: Take the wax and melt it in the pot;
- Step 4: Take a coal sample to be used for testing to determine its density and dip the sample into the wax pot to coat the sample, if necessary apply the extra coating by dipping of the sample into the wax. Once the coating of the sample achieved without any air bubbles trapped in the wax, remove the sample from the wax and let the hardening of wax to occur;
- Step 5. Scale the sample coated in wax and record this weight as P, the weight of sample coated in wax;
- Step 6. Fill the water tub to the level deep enough to fully cover the sample in the basket and set up the scale to be bottom loading. The water should be at room temperature, so

check that the water is at 20-23°C and set a specific gravity of approximately 1 for water;

- Step 7. Attach the sample basket to the bottom of the scale. Make sure to tare the scale before beginning testing and allow the scale to come to a complete rest before taking the measurement;
- Step 8. Place the sample into the basket and record this weight as S_{Wax}, the weight as the suspended weight;
- Step 9. Calculate the volume of the coal sample, V as in Equation 5;
- Step 10. Calculate apparent density results to two decimal places from the average mas and volume of coal sample, by Equation 2;
- Step 11. Empty the basket and fill four times again to repeat procedures in step 1-10, since overall five measurements should be done.

4.5.3 Determining σ_c from Uniaxial Compressive Strength test

Procedures followed to test the strength are described below:

- Step 1. Prepare the specimen and record the dimensions. Ensure the perpendicularity to the axis of the specimen and flatness (see in the previous sub-section);
- Step 2. Place the sample to the apparatus where steel platens in the form of discs are placed at the specimen ends;
- Step 3. Start loading continuously at 0.5 MPa/s rate;
- Step 4. Record the maximum load on the specimen in kN to within 1%;
- Step 5. Calculate the UCS by using Equation 7;
- Step 6. Empty the apparatus from broken pieces and repeat four more times procedures in steps 1-5, since overall five measurements should be done. When testing for anisotropic rock, there is a small adjustment that for the specimens with another bedding plane the procedures are repeated.

4.5.4 Determining $I_{s(50)}$ from Point Load Test

According to suggested methods for rock characterization ISRM (1985), determining point load strength index to identify strength means following these procedures:

- Step 1. Prepare the specimen of selected shape – an irregular lump of necessary size and direction of beddings;

- Step 2. Follow to the set of actions to place the specimen: relieve pressure by turning the knob counter-clockwise; remove pins while holding crosshead, then move crosshead to the desired position; push the cylinder down;
- Step 3. Place specimen between points before measuring its dimensions and indicating its anisotropy, type the dimensions, D and W accordingly to the screen of a device, later these values used to calculate D_e according to Equation 9;
- Step 4. Close the valve by turning the knob clockwise, place the pump reservoir cap in the "Vent" position, pump the handle to apply just enough pressure to hold the specimen in place;
- Step 5. Record the distance on the screen as D;
- Step 6. Record the values of load, gap, and peak load;
- Step 7. Report the results provided by the main screen. It is the basic information to make their calculations later on by using Equation 8;
- Step 8. Repeat procedures in steps 1-7 using other specimens.

5 RESULTS AND DISCUSSION

In this chapter, first results from conducting different experiments on coal samples taken from the Karaganda Coal Basin (aka KCB) are presented. The experiments conducted in the course of this research work included tests for determination of physical properties of the coal specimens such as porosity and bulk density. The rock mechanics laboratory testing program also included the uniaxial compression strength test, point load test, and sonic velocity test. Slake durability tests were also conducted as the major test to understand the of durability coal. This is followed with analysis, interpretation, and discussion of the experimental data generated during this research work. At the final stage, interrelationships between some of these parameters are investigated, and some correlations are developed and presented. The strength and statistical significance of the developed correlations are also discussed based on the Pearson r product-moment correlation coefficient. In the end, the technical, scientific, and practical implications of such correlations are discussed in the context of quick, economical, and reliable estimation of physical-mechanical properties of coal.

5.1 RESULTS

In this section, results obtained from different laboratory tests conducted on coal specimens obtained from the KCB for determining some of their physical and strength properties are presented. The specimens were prepared and tested in accordance with the ISRM or ASTM standards for the purpose of this research work as discussed in Chapter 4. During the sample preparation, the core samples were difficult to obtain due to the softness of the coal samples and presence of a lot of micro fractures in the block samples which made obtaining long samples for UCS extremely difficult. Instead, cubic samples were prepared and tested to obtain the UCS. Using cubic samples made conducting the experiments easier and investigation of strength anisotropy of coal with testing samples perpendicular and parallel to the bedding plane possible. Due to the coal samples, shortage of coal blocks from Lenina mine was grouped together with the coals from Tentekskaya mine considering the fact that their depth only differs 10-15 meters. The name, location, and code used for each coal seam are presented in Table 10.

Table 10

Name, depth, and code used for each coal mine and seam in the Karaganda Coal Basin.

Coal seams	*Mine for samples collecting*	*Location CODE*	*Depth (m)*
D11	Kazakhstanskaya	D11K	515
D6	Kazakhstanskaya	D6K	520
K12	Kuzymbayev	K12K	555
D6	Tentekskaya	D6T	612
	Lenina	D6L	625

5.1.1 Slake durability test

To obtain Slake Durability Index or SDI for the coal specimens taken from each of the tested coal seams, slake durability tests were conducted three times on specimens from 4 different depths and locations. In total, 12 samples were prepared and tested for five cycles using the slake durability test equipment. The SDI values reported in Table 11 are the average values of each set of three tests shows the range of parameters for each location and each cycle.

Table 11

Descriptive statistics of averaged slake durability indices with a standard deviation.

Specimen code	*% retention after 1st cycle*	*% retention after 2nd cycle*	*% retention after 3rd cycle*	*% retention after 4th cycle*	*% retention after 5th cycle*
D11K	96.91±0.534	94.56±1.44	92.79±2.27	91.37±2.86	89.90±3.65
D6K	95.87±1.03	93.15±1.85	90.81±2.88	89.34±3.30	87.58±3.56
K12K	96.15±1.44	94.52±1.07	92.34±1.09	90.91±1.34	89.70±1.49
D6T	97.52±0.310	95.84±1.11	95.06±1.83	94.17±2.02	93.60±2.04

From three samples taken for each location, its average is obtained to be the representative value. As one can see from Figure 16, the average of D6K sample has the value that is almost similar to one of the tests, namely D6K02. However, this is not a common case for other locations results. In Table 11 these values are shown with the averaged values of those three tests. Therefore, the deviations from average for corresponding specimen relatively higher, around 2% to 3.65%. This deviation from average was inspected, and some discrepancies were solved.

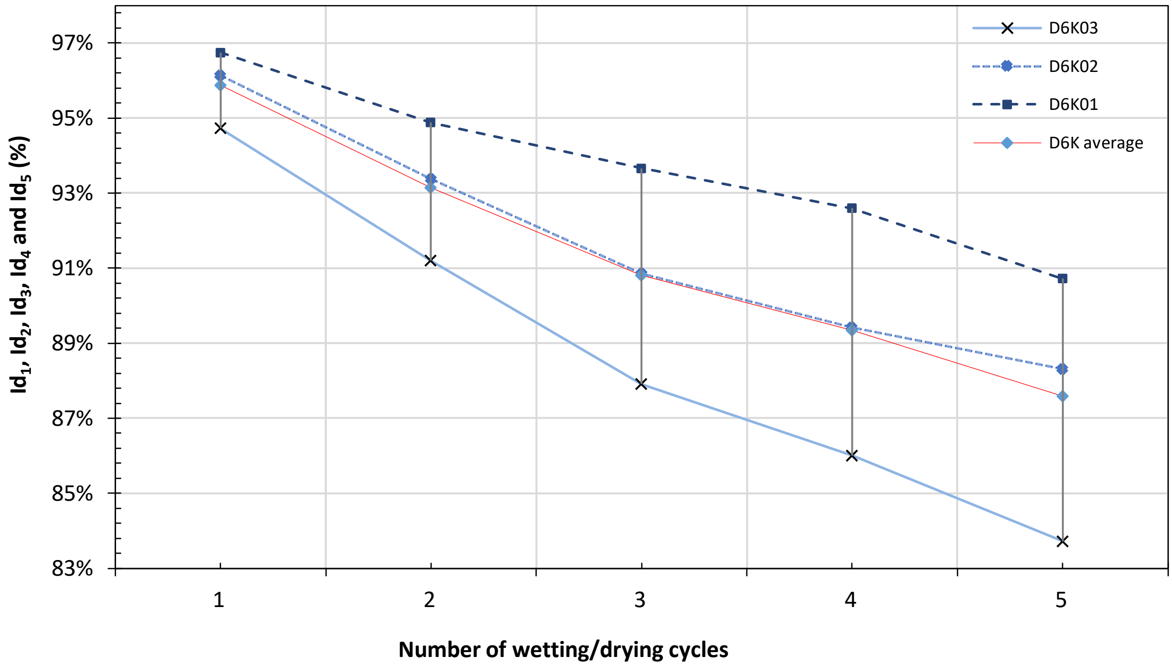

Figure 16. Slake durability indices (SDI) obtained for d6K from three samples.

Descriptive statistics results of the SDT from three tests for each location is shown in Table 12. There is a discrepancy among very few of the SDI values as highlighted in bold in the table for **D6T01** and **D11K02** samples. These values are invalid as there might be an error in conducting the tests. Hence, the average SDI values are calculated and used without these values for their corresponding specimen code. For taking out the values for 1st test for values for D6T location percentage of retention after 2 (Id_2=95.92 %) and after 3 (Id_3=96.02 %) are considered. Since the value should be in decreasing order by each cycle, but this is not the case for these tests. For the D11K02 case, this sample has a higher value in comparison with the other two samples; this characteristic of coal might be due to the effect of coal rock texture.

The photos representative of samples collected and testes for SDI are shown in Table 28 in Appendix 2. They are demonstrating each class of slaking behavior, resulting from the analysis of fragments retained in the drum before the test and after the fifth cycle slake durability test, also given the initial weight of a sample as well as SDI values after each cycle.

Table 12

Descriptive statistics of SDT results of three tests.

Specimen code	*SDI (%)* / *# of cycles*	*Samples* 1	2	3	*Average SDI (%)* *Mean*	*Std. dev.*	*Recalculated average SDI (%)* *Mean*	*Std. dev.*
D11K	*Id_1*	96.33	**97.38**	97.01	96.91	0.53	96.67	0.48
	Id_2	93.45	**96.19**	94.04	94.56	1.44	93.75	0.42
	Id_3	91.22	**95.39**	91.78	92.79	2.27	91.50	0.40
	Id_4	89.38	**94.64**	90.08	91.37	2.86	89.73	0.49
	Id_5	87.53	**94.10**	88.07	89.90	3.65	87.80	0.38
D6K	*Id_1*	96.74	96.14	94.73	95.87	1.03	95.87	1.03
	Id_2	94.88	93.37	91.20	93.15	1.85	93.15	1.85
	Id_3	93.66	90.86	87.90	90.81	2.88	90.81	2.88
	Id_4	92.60	89.43	86.00	89.34	3.30	89.34	3.30
	Id_5	90.72	88.31	83.72	87.58	3.56	87.58	3.56
K12K	*Id_1*	94.51	97.25	96.67	96.15	1.44	96.15	1.44
	Id_2	93.37	95.47	94.73	94.52	1.07	94.52	1.07
	Id_3	91.08	92.82	93.10	92.34	1.09	92.34	1.09
	Id_4	89.37	91.84	91.52	90.91	1.34	90.91	1.34
	Id_5	88.08	91.01	90.00	89.70	1.49	89.70	1.49
D6T	*Id_1*	**97.45**	97.85	97.25	97.52	0.31	97.55	0.43
	Id_2	**95.92**	96.90	94.69	95.84	1.11	95.80	1.57
	Id_3	**96.02**	96.21	92.95	95.06	1.83	94.58	2.30
	Id_4	**95.15**	95.51	91.85	94.17	2.02	93.68	2.59
	Id_5	**94.58**	94.96	91.25	93.60	2.04	93.11	2.62

The average SDI values for cycles 1-5 obtained for all four sampling locations were calculated plotted against some data from the literature on SDI of coal as presented in Figure 17. In both of those cases Anand and Giri (2015), and Swain (2010) estimated SDI after two cycles show lower durability than the current study.

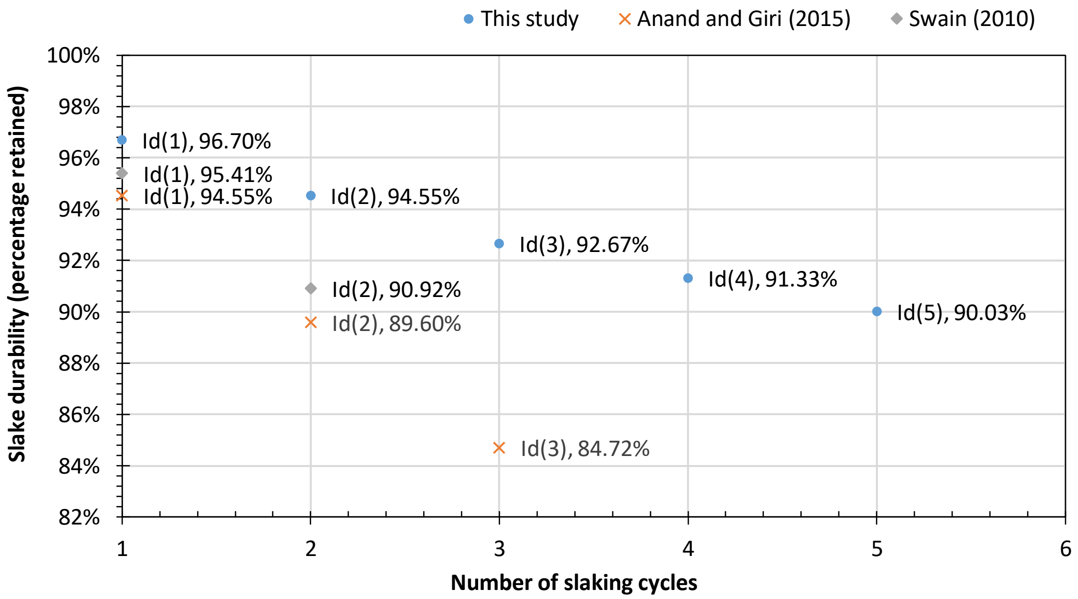

Figure 17. Comparison between the number of slaking cycle results tests from this and other studies.

5.1.2 Bulk density

The average of the density values for each layer was obtained from the bulk density calculation using a caliper in addition to the wax immersion method test, which has values lesser than calculated by the former method. Their values are presented accordingly in Tables 28–30 in Appendix 1. Average values and standard deviations are shown in the descriptive statistics for coal density in Table 13.

Table 13

Descriptive statistics of density by using both methods.

Density (g/cm3)	mean	std. dev.	max	min
from dimensions and weight (dry)	1.32	0.073	1.54	1.19
from waxed sample water immersion	1.27	0.030	1.34	1.23

Since by bulk density has an average value of 1.322±0.076 g/cm^3, the set to limit of the highest value of density is 1.396 g/cm^3 for the KCB coal. The results of 4th and 5th samples from d6T location and 1st sample of the d11K location showed extremely high values as one can see from Figure 18. These values exceed the range of dry density reported for coal. Hence, these three values (1.51 g/cm^3, 1.38 g/cm^3 and 1.67 g/cm^3, respectively) are reported invalid and omitted from the calculation of the average. Therefore, KCB coal has corrected values of density ranging from 1.23 to 1.34 g/cm^3, with an average value of 1.27±0.030 g/cm^3.

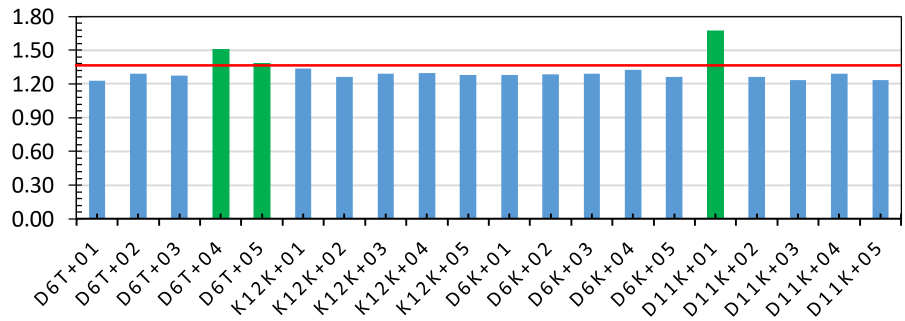

Figure 18. Bulk density distribution in the tested coal samples.

5.1.3 Porosity

Quantachrome® ASiQwin™ Automated Gas Sorption Data was used to determine the porosity of the testes coal samples. Results of nitrogen injecting porosity test are given in Appendix 1. The reported parameters include the surface area in m²/g, pore volume in cm^3/g, and pore diameter in nm units. The porosity of coal specimens was calculated, and the tabulated results for each location comes from one test each as shows, in Table 14. In order to estimate the recalculated porosity the averaged values of density found by wax immersion method is used from Table 30.

Table 14

Porosity of the testes coal samples.

No	*Specimen code*	*Depth (m)*	*Porosity (%)*	*Pore Diameter (nm)*	*Pore volume (cm^3/g)*	*Surface area (m^2/g)*	*Weight of sample*	*Volume of the tested sample*	*Density*
1	D11K	515	16.96	3.935	0.051	3.121	0.31	0.24	1.25
2	D6K	520	5.07	3.720	0.016	3.947	0.39	0.30	1.29
3	K12K	555	8.02	3.138	0.022	3.465	0.33	0.26	1.26
4	D6T	612	1.34	3.931	0.005	0.650	0.47	0.13	1.26

From Table 15 it is possible to obtain a connection between pore size and coal rank; therefore, by pore diameter coal rank can be characterized.

Table 15

Relationship between pore size and coal rank (Rodrigues and Lemos de Sousa, 2002).

Type	*Pore size*	*Coal rank*
Micropores	Less than 2 nm	High volatile bituminous coal A and higher
Mesopores	In between 2 nm and 50nm	High volatile bituminous coal (C + B)
Macropores	More than 50nm	Lignites + sub-bituminous

According to Table 15, the relationship between pore size and coal rank (Rodrigues and Lemos de Sousa, 2002) is classified: the testes coal samples are high volatile bituminous coal (C + B) since it refers to for mesopores (in between 2 nm and 50 nm) where KCB pore diameter being in between 3.138 and 3.935 nm.

5.1.4 Uniaxial compressive strength

A number of UCS tests both on cylindrical and cubic coal samples were prepared for the purpose of this study. Some of the tests were conducted with a loading direction perpendicular and some parallel to the coal seam bedding or stratification. In addition to ten cylindrical specimens prepared for Kazakhstankaya mine five for each seam, there were also cubic specimens prepared from the block samples using the cutting-trimming machine. It was not feasible to take core samples from the coal blocks due to the friable nature and low strength of the coal tested. This is why it was not possible to obtain cores for the majority of the coal seams tested. Instead, cubic samples were prepared and tested. 29 specimens in total were tested to determine the UCS of the coal samples. The specifications and dimensions of the samples are presented in Table 28 for the core samples and in Table 29 for the cubic samples shown in Appendix 1. Since directly applying Equation 7 means disregarding of the shape affect that is not acceptable for proper reporting of the result. The values of width and length for cubic specimen should be converted to the equivalent diameter of a rectangular. These Equation 9 can serve as a conversion equivalent. Therefore, no difference between finding the areas are considered. Data used for the calculation of UCS value is shown in Table 31 in Appendix 1 for each specimen.

The UCS tests results are presented in Table 16. Specimens prepared from the seam D6T with a loading direction perpendicular to the bedding plane are replaced by the D6L samples. This is due to the fact that these two seams are located only 15 meters apart from each other. The range of UCS obtained for the cubic samples tested with the loading direction perpendicular to the bedding plane and tested with the loading direction parallel to the bedding plane is from 3.05 MPa to 15.07 MPa and 1.53 MPa to 13.28 MPa, respectively. As one can see from Table 17, or the core samples testes, the range of UCS is from 3.01 MPa to 15.13 MPa.

Table 16

UCS values for specimen tested perpendicular to the bedding plane.

Loading direction	*Specimen code*	*SPECIMEN NUMBER*	*Strength, MPa*	*Average UCS, MPa*	*Range, MPa*
Perpendicular to the bedding plane	D6K	D6K+01	3.01	8.09	4.53-11.18
		D6K+02	13.92		
		D6K+03	4.58		
		D6K+04	3.78		
		D6K+05	15.13		
	D11K	D11K+1	4.76	4.53	
		D11K+2	5.53		
		D11K+3	3.49		
		D11K+4	4.24		
		D11K+5	4.63		
	D6T	**D6L+01**	**9.15**	11.18	
		D6L+03	**12.90**		
		D6L+05	**6.41**		
		D6L+07	**12.38**		
		D6T+09	15.07		
	K12K	K12K+06	3.20	4.53	
		K12K+07	3.05		
		K12K+08	4.13		
		K12K+09	5.28		
		K12K+10	7.00		

Table 17

UCS values for specimen tested parallel to the bedding plane.

Loading direction	*Specimen code*	*SPECIMEN NUMBER*	*Strength (MPa)*	*Average UCS (MPa)*	*Range (MPa)*
Parallel to the bedding plane	K12K	K12K+01	1.53	5.09	5.09-6.68
		K12K+02	12.59		
		K12K+03	3.98		
		K12K+04	2.24		
	D6T	D6T+02	13.28	6.68	
		D6T+04	9.70		
		D6T+06	4.37		
		D6T+08	2.22		
		D6T+10	3.84		

5.1.5 Point load test

Point Load Index and investigation of its relationship with UCS and DSI were one of the objectives of this research work. Hence, a number of PLT tests on irregular shape coal specimens with a height to width ratio of 0.3<D/W<1 were conducted, and the results are presented in Table 32 in Appendix 1. Again, some of the tests were carried out with loading condition perpendicular and also parallel to the bedding plane to catch the strength anisotropy, if any. From the ten tests on one specimen results for half of the tests were selected to be the true measure of the test, since according to ISRM (1985) mean value for coal calculated with deleting the two highest and two lowest values. In some cases where valid tests are less than ten only the highest and the lowest were not considered, there are cases where D/W is more than 1. The results of average values for the PLI is given in Table 18 for the case when loading direction perpendicular to the bedding and in Table 19 for parallel.

Table 18

PLI for specimen tested perpendicular to the bedding plane.

$I_{s(50)}$ *(%)*	*Mean*	*Std. Dev.*	*Max*	*Min*
D11K	0.961	0.651215	2.19	0.378
D6K	0.829	0.361784	1.27	0.412
K12K	0.976	0.18317	1.28	0.759
D6T	1.59	0.584999	2.38	0.63

Table 19

PLI for specimen tested parallel to the bedding plane.

$I_{s(50)}$ *(%)*	*Mean*	*Std. Dev.*	*Max*	*Min*
D11K	0.755	0.177	0.893	0.522
D6K	1.25	0.595	2.00	0.347
K12K	0.569	0.265	0.905	0.272
D6T	1.58	0.377	2.13	0.974

5.2 Discussion

In this section, the results obtained in this research work and presented in Section 5.1 are analyzed, interpreted, and discussed. Attempts also are made to investigate interrelationships between different parameters with emphasis on the relationships between SDI with other parameters such as UCS and PLI. Relationship between coal parameters and slake durability test are discussed in the following sub-sections in terms of correlation coefficient (r) that is a measure of linear association. This should be distinguished from the concept of R^2, which is the coefficient of determination obtained from the trend lines and also presented on the figures. A summary of the results obtained from the testing program is presented in Table 20. This table shows the physical and mechanical properties of coal samples tests including bulk density, porosity, PLI, SDI, and UCS. These are average values for each coal seam tested. An interpretation and discussion of the results obtained from each test and the interrelationships between the parameters of interest for the purpose of this research are presented in the consequent sections.

Table 20

Summary of data used in the analysis.

Specimen	***z***	ρ_C	***ρ=m/V***	n_C	σ_c ***(MPa)***	
	(m)	*(g/cm³)*	*(g/cm³)*	*(%)*	*parallel*	*perpendicular*
D11K	515	1.25	1.33	17.0	-	4.53
D6K	520	1.29	1.27	5.07	-	8.09
K12K	555	1.29	1.34	8.02	5.09	4.53
D6T	612	1.26	1.33	1.34	6.68	11.2

Table 20. Continued

Specimen	***z***	***PLI***		***Slake durability Index***				
	(m)	*parallel*	*perpendicular*	***Id_1*** *(%)*	***Id_2*** *(%)*	*Id_3 (%)*	*Id_4 (%)*	*Id_5 (%)*
D11K	515	0.76	0.961	96.67	93.75	91.50	89.73	87.80
D6K	520	1.25	0.829	95.87	93.15	90.81	89.34	87.58
K12K	555	0.57	0.976	96.15	94.52	92.34	90.91	89.70
D6T	612	1.58	1.59	97.55	95.80	94.58	93.68	93.11

5.2.1 Slake durability test

The SDI data obtained in this research work are presented the number of test cycles for all of the tested samples. Deterioration in coal durability with an increase in the number of cycles can be clearly observed from Figure 19. The same can be observed when not average values are used for data presentation but for all twelve tests as presented in Figure 20.

The slake durability indices obtained for each cycle (5 cycles) for each seam is presented in Figure 18. Gamble's classification for slake durability (Gamble, 1971) is used here to classify the durability of the testes coal samples based on SDIs obtained. Note that based on results of SDI 2nd-cycle (Id_2) SDT results all of the samples can be classified as "medium high durability" group (85%-95%), except for samples taken from D6T location (95.80%) that corresponds "high durability" group (95%-98%). To classify results for each the location based on the SDI according to Franklin and Chandra's classification for slake durability (Franklin and Chandra, 1972) (Table 4), the tested coal samples can be classified as "very high durability" materials (90%-95%).

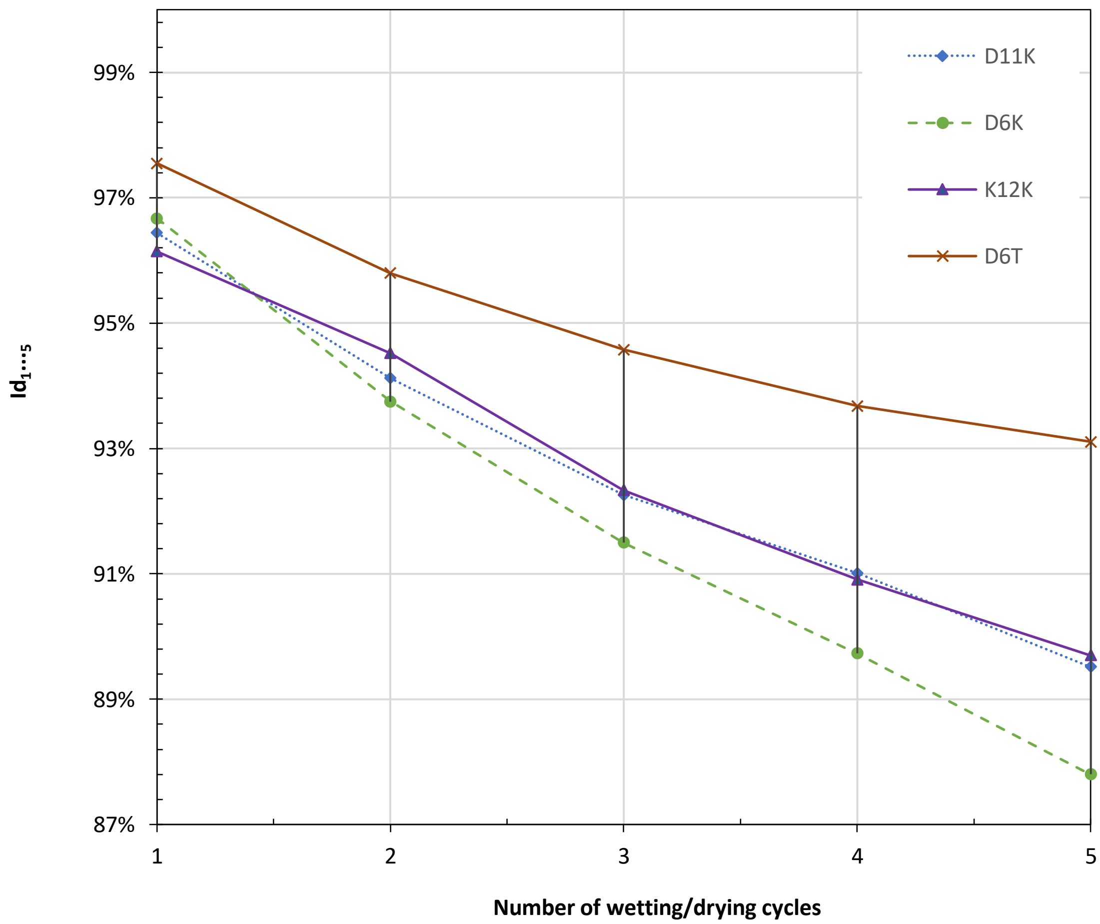

Figure 19. Slake Durability Indices vs. a number of wetting/drying cycles for the tested samples.

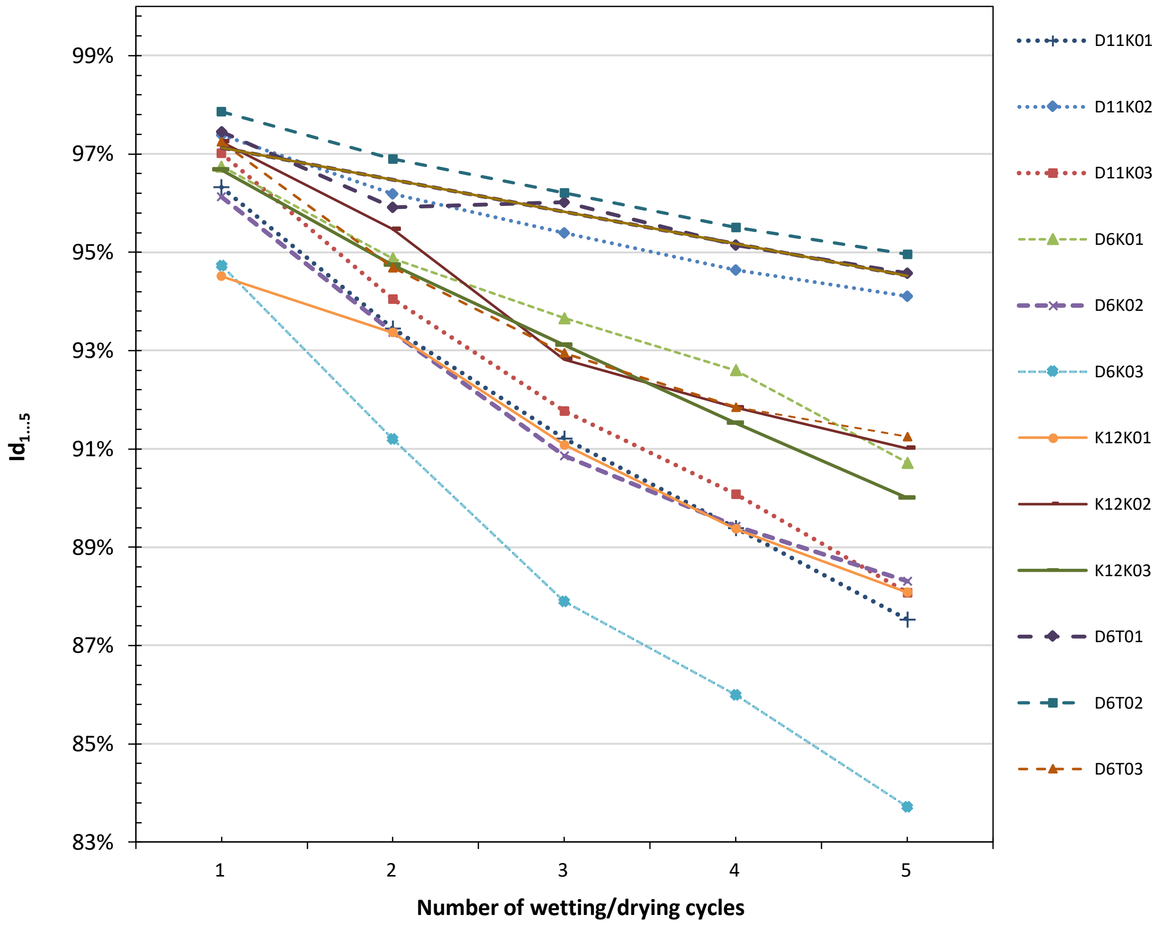

Figure 20. Effect of number of slaking cycle for tested samples

The SDI value for cycles 2,3,4, and 5 are plotted versus the corresponding first cycle SDI values in Figure 20. An attempt is made here to correlate these data as the equations, R2 values are presented on the graph. In addition, the corresponding r values are presented in Table 21. with their corresponding R^2 values. The SDI value for cycles 2,3,4, and 5 are plotted versus the corresponding first cycle SDI values are presented in Figure 20. As can be seen here, the third cycle results can be estimated by using the first cycle slake durability index where there is a very strong correlation (r=0.87) among these parameters. In addition, SDI for cycles 2,4, and 5 can be estimated by using the first cycle slake durability index where there is a strong correlation (r = 0.84, 0.85 and 0.82) among these parameters. A correlation between SDI values from cycles 2-5 vs SDI values from 1st cycle SDI values for seven types of carbonate rocks and the corresponding r values all showing very strong correlations is also reported by Yagiz (2011) as presented in Table 22. This confirms a strong relationship between SDI results from all cycles ranging from strong to very strong correlations. It can be concluded here that for the studies coal samples, there is a strong correlation between the SDI values from cycles 2-5 vs

SDI values from 1st cycle SDI values and very strong correlation between the SDI values from 3rd cycle vs SDI values from 1st cycle SDI.

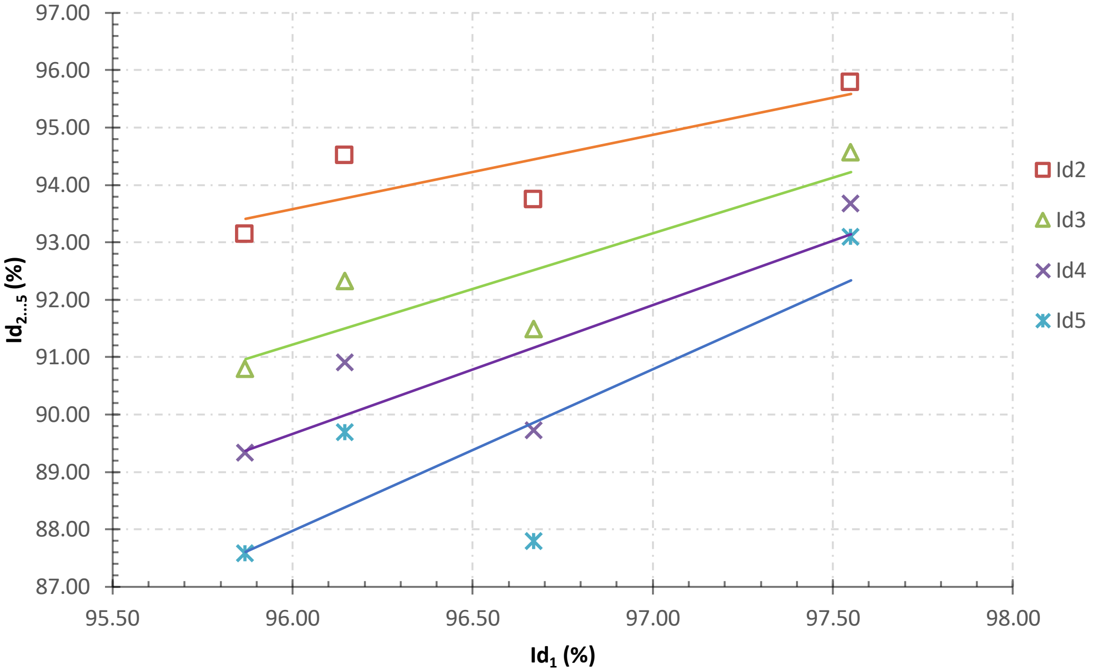

Figure 21. SDI values from cycles 2-5 vs SDI values from 1st cycle SDI values for the tested coal samples.

Table 21

This study's predictive equations, R^2 and r values from a correlation between cycles 2-5 and the first cycle SDT values.

Current study	R^2	*r*
$Id_2 = 1.29\ Id_1 - 30.6$	0.701	0.84
$Id_3 = 1.94\ Id_1 - 94.8$	0.765	0.87
$Id_4 = 2.25\ Id_1 - 126$	0.722	0.85
$Id_5 = 2.82\ Id_1 - 182$	0.665	0.82

Table 22

Predictive equations and r values from a correlation between cycles 2-5 and the first cycle SDT values (Yagiz, 2011).

Yagiz (2011)	*r*
$Id_2 = 1.430\ Id_1 – 42.97$	0.99
$Id_3 = 1.81\ Id_1 – 81.39$	0.98
$Id_4 = 2.129\ Id_1 – 112.98$	0.97
$Id_5 = 2.44\ Id_1 – 144.11$	0.97

5.2.2 Density

The relationship between slake durability indices for the testes coal samples vs bulk densities are presented in Figure 22; there are the SDI values from cycles 2-5 are given.

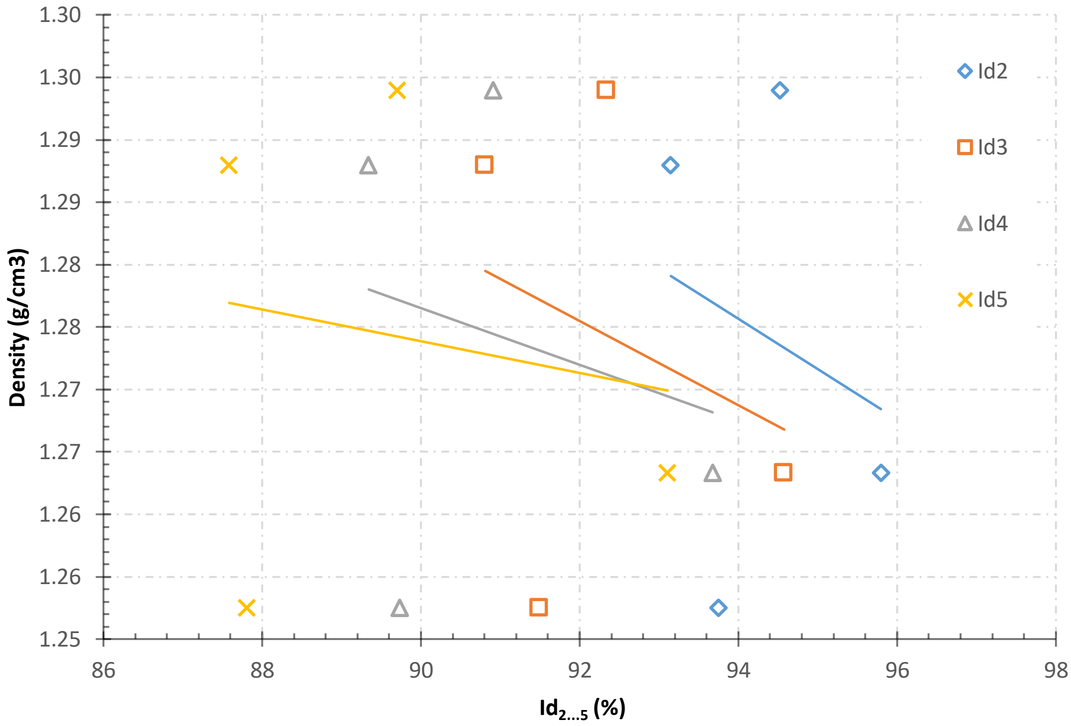

Figure 22. Slake durability indices for the testes coal samples vs density.

As can be seen in Figure 21 a weak correlation also exists between the SDI results for 2nd cycle (r=-0.30), 3rd cycle (r=-0.279) and 4th cycle (r=-0.225). There is also a very weak correlation (r=-0.165) between the 5th cycle SDI results and the bulk density of coal. SDI values are negatively correlated with bulk density.

5.2.3 Porosity

The porosity of coal specimen was determined in the core facilities using two different methods: Gas porosimetry and mercury injection porosimetry. The results obtained from Gas porosimetry which are conducted on one sample from each seam are presented vs SDI values in Figure 23. The determined porosities range from 1.34% to 17.0%. There is a big discrepancy among the porosity values obtained, and even some exceed the range of typical porosities for different coals based on the rank of the coal. Therefore, these numbers are used with caution, and new experiments are necassary to determine the porosity for each coal seam adequately. Nevertheless, this test results can be used as a basis for the semi-quantitative classification by Anon (1979): porosities less than 1 % can be considered as very low porosity, values in between

1% and 5% as low porosity, values in between 5 % and 15 % as medium porosity and values in between 15 % and 30 % indicates high porosity. Specimens D6K (5.07%) and K12K (8.02%) can be classified as medium, also D11K (16.96 %) and D6T (1.34 %) as high and very low porosity coal, respectively.

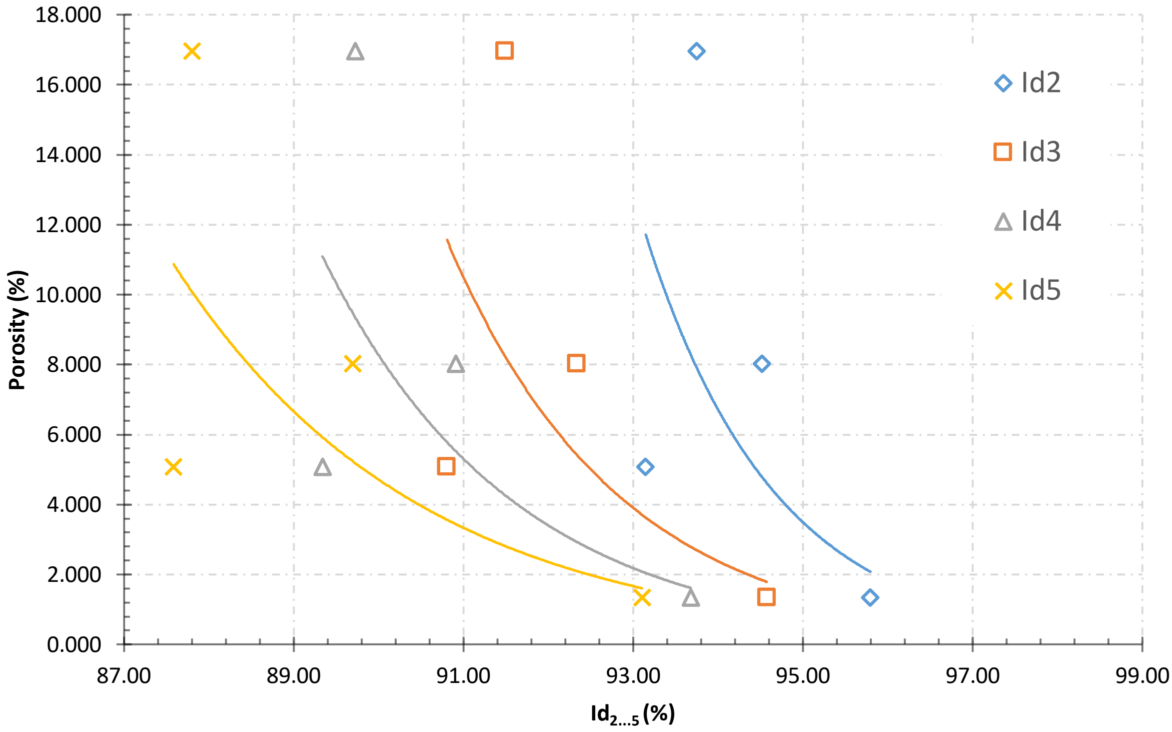

Figure 23. Relationship between the SDI values from cycles 2-5 vs porosity.

There is a negative correlation between the porosity and SDI value, further moderate to strong correlation obtained from the 2nd cycle (r=-0.505), 3rd cycle (r=-0.549), 4th cycle (r=-0.623), and 5th cycle (r=-0.658).

5.2.4 Uniaxial Compressive Strength

Uniaxial Compressive Strength or UCS for intact rock is considered as one of the most important parameters in Rock Mechanics and efforts has been made to investigate the relationship between this parameter and several other physical, chemical, and mechanical parameters of rock. The UCS values obtained for the tested coal samples from different layers with loading direction parallel and perpendicular to the bedding plane are presented versus depth in Figure 24. Each data point is the average of five tests. According to Anon (1979), the tested coal samples can be classified as “weak rock” with UCS ranging from 4.53-11.18 MPa.

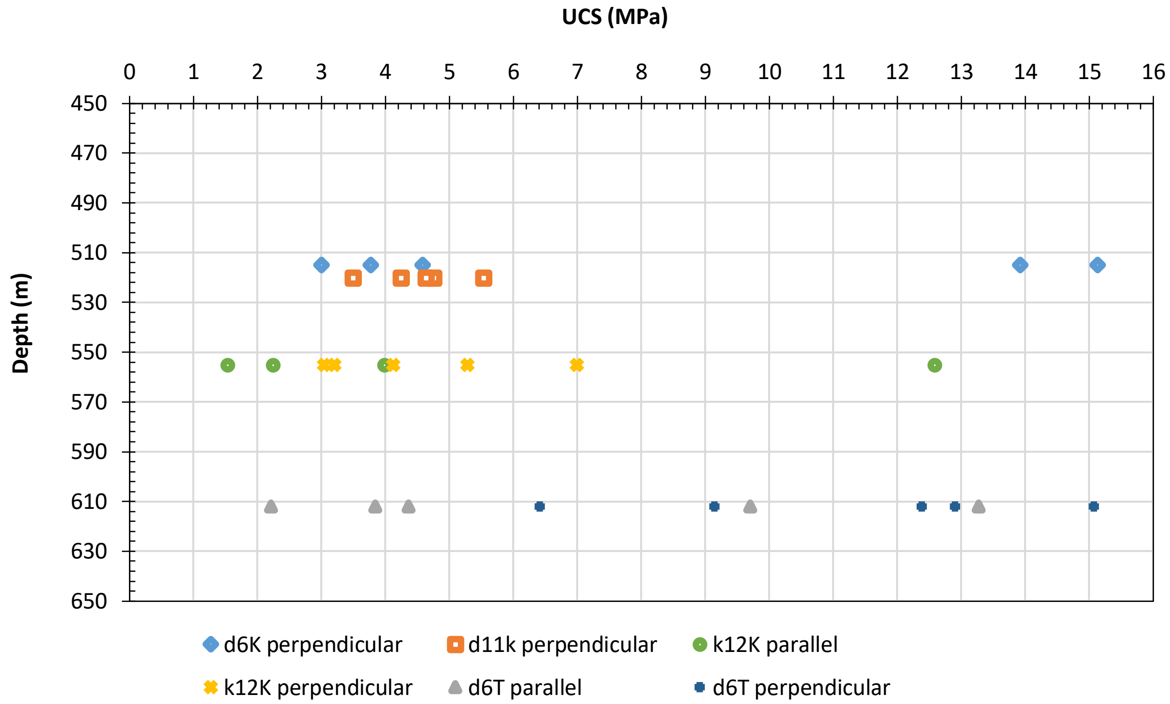

Figure 24. UCS vs depth for the tested samples from different depth, coal seams, and with different loading directions.

An attempt is made here to establish correlations between the SDI values from cycles 2-5 obtained for the tested coal specimen and UCS test data. The relationship between the SDI values from cycles 2-5 obtained for the tested coal specimen and UCS test data for the loading condition perpendicular to the bedding plane is presented in Figure 25. The equations obtained with their corresponding R^2 and r values with the meaning of r value in terms of correlation value are presented in Table 23.

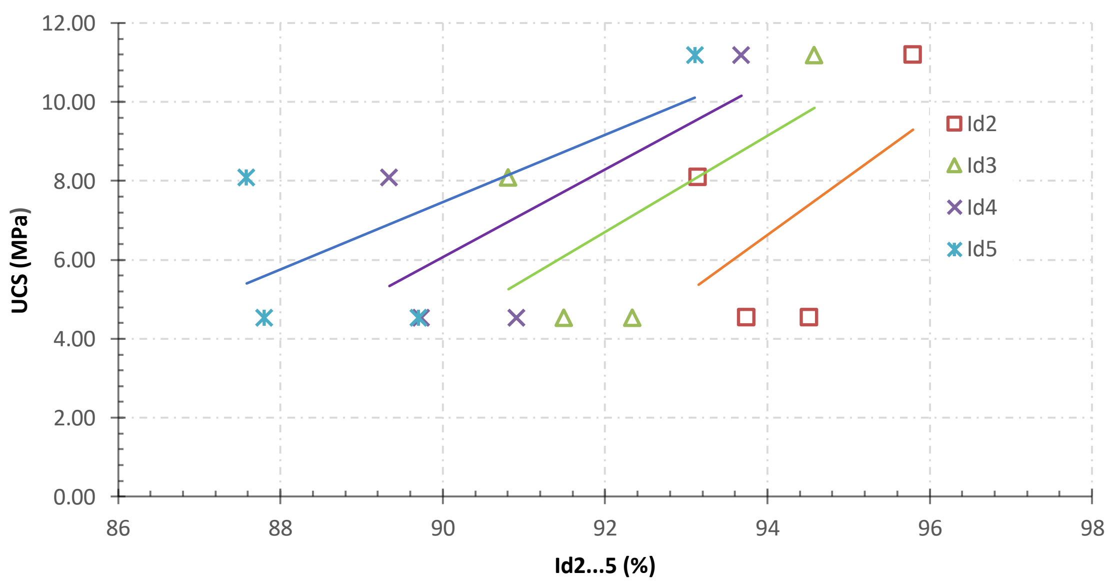

Figure 25. Relationship between the SDI and UCS (perpendicular).

Table 23

UCS vs SDI equations, R^2 and r values.

UCS (perpendicular) vs SDI	*Predictive equations and R2*	*Correlation*	*r values*
UCS vs Id_2	UCS = 1.4858 Id_2 - 133.03 R^2 = 0.2806	moderate	0.530
UCS vs Id_3	UCS = y = 1.2153 Id_3- 105.09 R^2 = 0.3862	strong	0.621
UCS vs Id_4	UCS = 1.1107 Id_4 - 93.894 R^2 = 0.4605	strong	0.679
UCS vs Id_5	UCS = 0.8523 Id_5- 69.235 R^2 = 0.4613	strong	0.679

As can be seen from Figure 25 and Table 23, there is a positive correlation between SDI and UCS (perpendicular). However, based on the r values, the correlations are moderate for 2nd cycle (r=0.530), are strong for 3rd cycle (r=0.621), for the 4th cycle (0.679) and for the 5th cycle (r=0.679). It should be pointed out that UCS for loading in parallel directions are not used for obtaining relations between UCS and SDI due to the lack of data.

5.2.5 Point Load Test

The point load test is a fast, easy, and reliable method for determining Point Load Index, I_s and estimating the UCS of intact rock. The test itself is very flexible, and it can be done on samples with different geometry. The relationship between the PLI values obtained with different loading direction with the bedding plane versus SDI values from cycles 2-5 is presented in Figures 26 and 27. As can be seen from these figures, there is a strong correlation between these parameters in general. However, it seems that the correlations obtained between PLI perpendicular versus SDI values are much stronger. The equations obtained with their corresponding R^2 and r values are presented in Table 24.

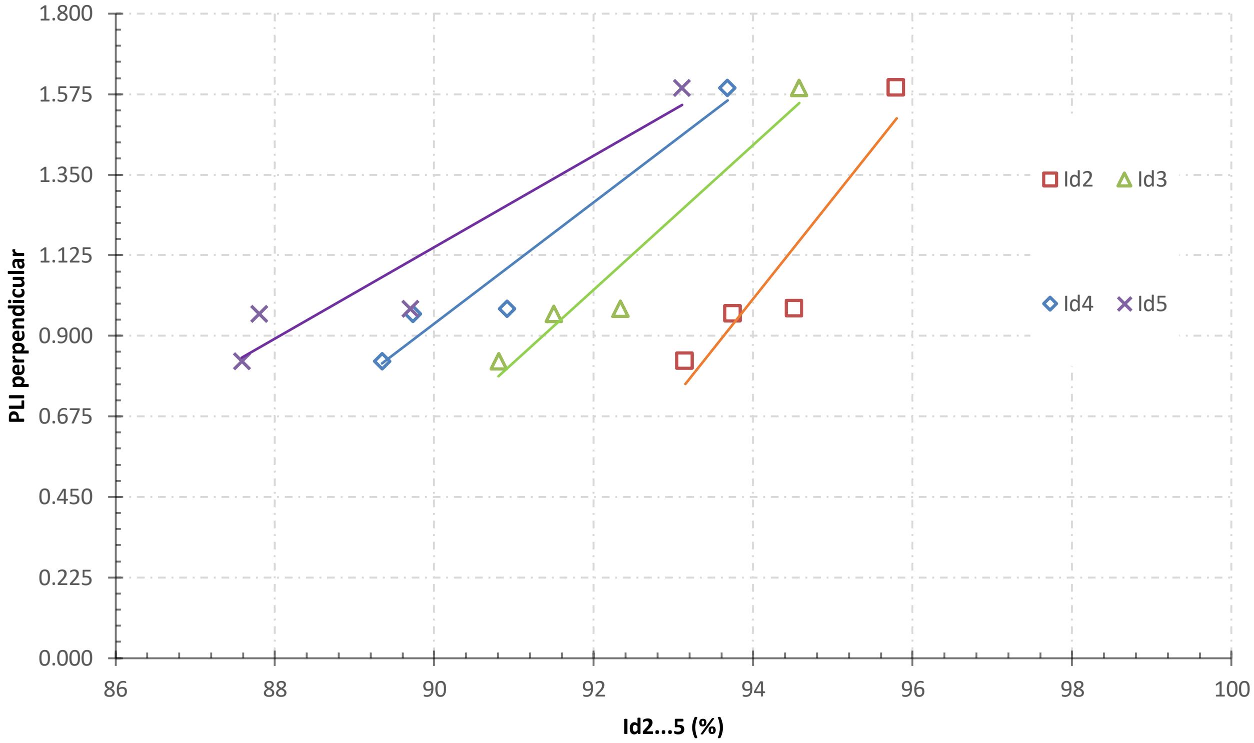

Figure 26. Relationship between the SDI values and PLI (perpendicular).

As once can see from Figure 25, a very strong and positive correlation exist between the PLI perpendicular and SDI. The correlation coefficients obtained for 2nd cycle (r=0.93), for 3rd cycle (r=0.97), 4th cycle (r=0.97), 5th cycle (r=0.96) indicate that there is a very strong correlation between these two parameters.

Table 24

SDI vs PLI (perpendicular) equations, R^2 and r values.

PLI (perpendicular) vs SDI	*Predictive equations and R^2*	*Correlation*	*r values*
PLI vs Id_2	$PLI = 0.28\ Id_2 - 25.311$ $R^2 = 0.8789$	very strong	0.93
PLI vs Id_3	$PLI = 0.2024\ Id_3 - 17.591$ $R^2 = 0.945$	very strong	0.97
PLI vs Id_4	$PLI = 0.1694\ Id_4 - 14.312$ $R^2 = 0.9454$	very strong	0.97
PLI vs Id_5	$PLI = 0.128\ Id_5 - 10.369$ $R^2 = 0.9175$	very strong	0.96

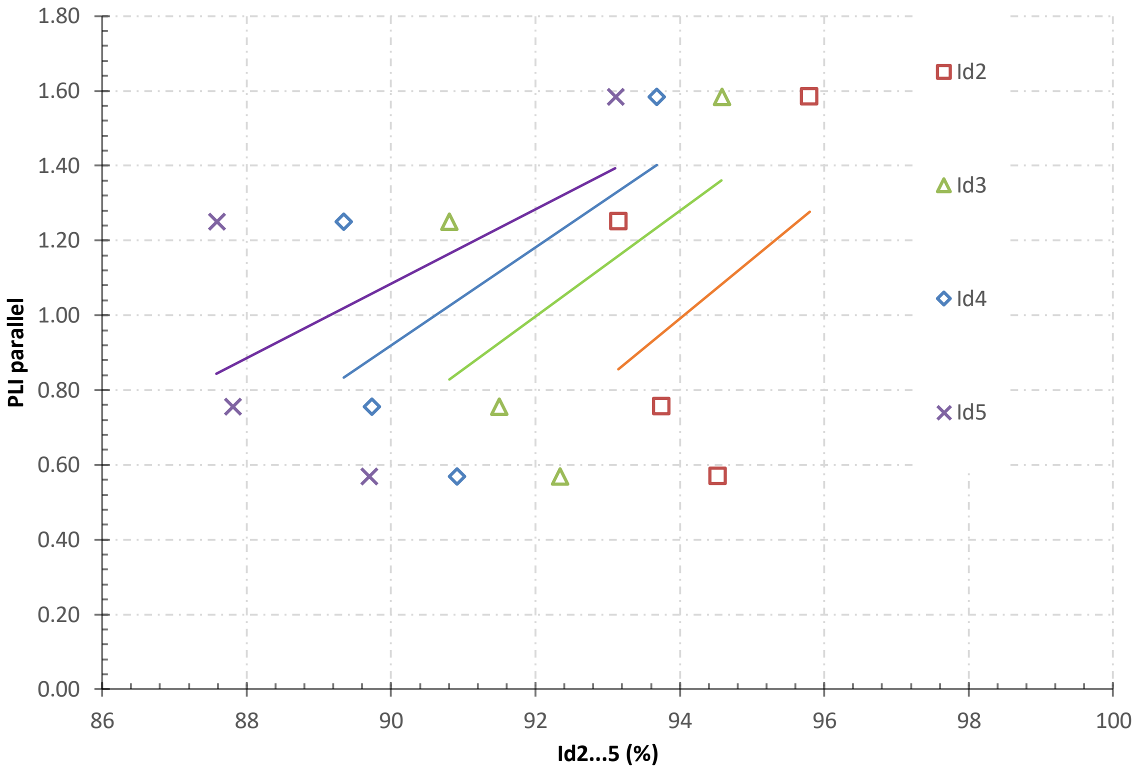

Figure 27. Relationship between the SDI values and PLI parallel.

As can be seen from Figure 27, there is a weak to moderate and positive correlations between the PLI parallel versus SDI values for cycles 2-5. The obtained the 3rd cycle (r=0.50) 4th cycle (r=0.55) and 5th cycle (r=0.55) show a moderate correlation. However, SDI data from the 2nd cycle (r=0.39) show a weak correlation with PLI when the load applied parallel to the bedding.

Table 25

SDI vs PLT parallel equations, R^2 and r values.

PLI (parallel) vs SDI	*Predictive equations and R^2*	*Correlation*	*r values*
PLI vs Id_2	PLI = 0.1592 Id_2 - 13.969 R^2 = 0.1544	weak	0.39
PLI vs Id_3	PLI = 0.1408 Id_3 - 11.961 R^2 = 0.2487	moderate	0.50
PLI vs Id_4	PLI = 0.1312 Id_4 - 10.891 R^2 = 0.3082	moderate	0.55
PLI vs Id_5	PLI = 0.0994 Id_5 - 7.8657 R^2 = 0.3011	moderate	0.55

5.3 Summary of Results and Discussions

According to Pearson r value of the coefficient of correlation which gives a quantitative measure to determine whether two parameters correlate and the strength of the correlation, a correlation with r values between 0 to 0.19 is classified as “very weak” and a correlation with r values between 0.2 to 0.39, 0.4-0.59, 0.6 to 0.79, and 0.8 to 1 is classified as “weak”, "moderate", "strong" and "very strong", respectively. Table 26 provides a summary of r coefficient of correlation for all of the attempted correlations between the different physical and mechanical properties of coal obtained in this study and cycles 2-5 of the slake durability test.

Overall, it can be concluded here that, the SDI shows weaker correlations with physical properties than mechanical properties. As can be seen from Table 26, the correlation between the SDI values obtained from cycles 2-5 and PLT perpendicular is very strong. In addition, the correlation between the SDI values obtained from cycles 2-5 and UCS perpendicular are strong (r=0.621, 0.679, 0.679) except for 2nd cycle (r=0.52). The moderate correlation exists between the SDI values obtained from cycles 2-5 and PLI parallel. Coal strength estimated using the correlations obtained for PLT perpendicular and SDI data from cycles 2-5 has the highest accuracy and reliability among all of the mechanical properties data obtained and presented in this research work.

Table 26

Summary of correlation coefficients.

r	*Id(2)*	*Id(3)*	*Id(4)*	*Id(5)*	
Density (g/cm^3)	-0.233	-0.279	-0.225	-0.165	linear
Porosity (%)	-0.505	-0.549	-0.623	-0.658	exponential
UCS perpendicular (MPa)	0.530	0.621	0.679	0.679	linear
PLI parallel	0.393	0.499	0.555	0.549	linear
PIT perpendicular	0.938	0.972	0.972	0.958	linear

This work gives a good correlation to estimate UCS from SDI. The UCS of coal samples showed a linear relationship with slake durability value; after the 3rd cycle of SDT, there are strong correlations. The same tendency is observed for PLI results being strongly correlated with SDI values only when the specimen tested with a load applied to parallel to the bedding plane. As for perpendicular bedding, there is a very strong correlation between PLI and SDI starting from the initial cycles. Taking into consideration that UCS discussed in this study is also measured in the perpendicular direction to the bedding plane, this indicates that there is also a good correlation between the UCS and PLI. These and previously inspected results indicate that SDI can be an accurate and easy alternative for strength tests.

It was estimated after which cycle of the SDI the increment on r value between the strength properties (like, UCS and PLI) and slake durability indices is not significantly varying. This can be observed after the fourth cycle of wetting/drying as shown in Figure 28. The increment on the coefficient of correlation is constant after fourth cycle as reported by Yagiz (2011). Therefore, in order to make an estimate of SDI for coal, it is suggested to conduct the SDT till four cycles.

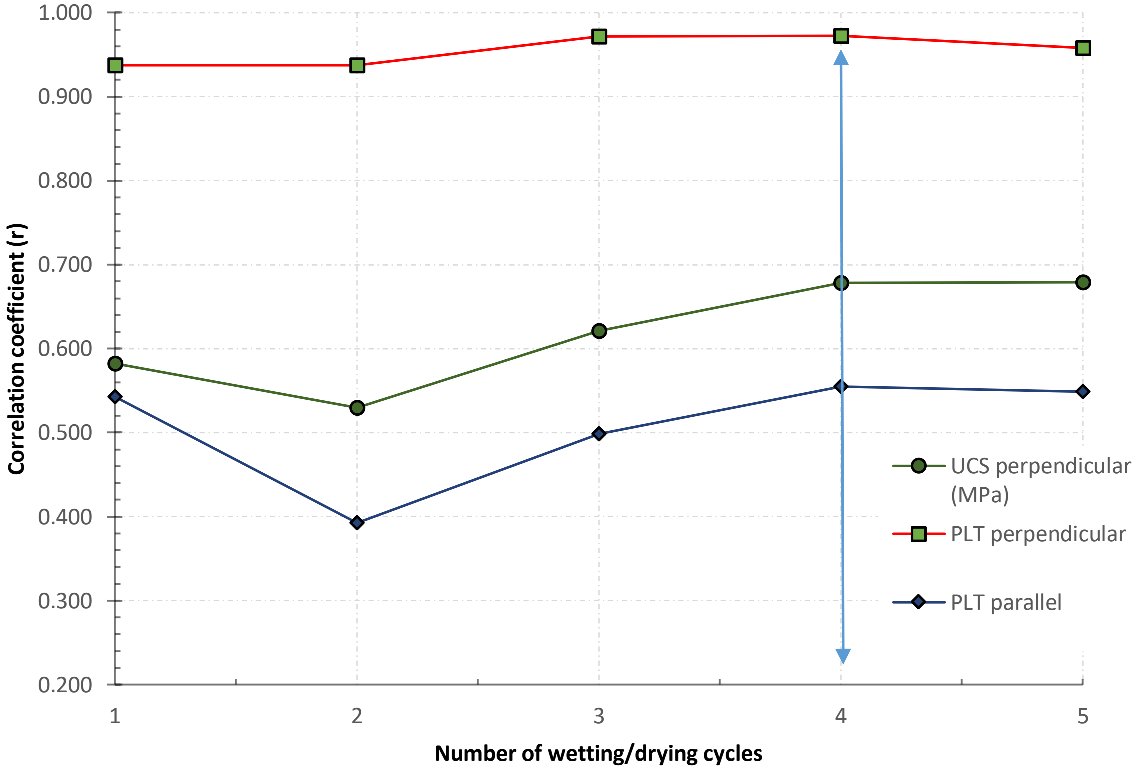

Figure 28. Relationships between the wetting/drying cycles and different rock properties.

The uniaxial compressive strength plays a very important role for mine geomechanical design, whether it is roof supporting or pillar design. Strength of the rock material depends on the method of testing (UCS or PLT), sample size, shape or geometry. Also, test procedure altogether with the specimen preparation might affect the final test result. For weak rocks, it is particularly difficult to acquire from coring since these rock material have a lot of discontinuities. When it comes to obtaining samples for measuring strength property from UCS, there are difficulties regarding the sampling arise. It is due to the coring process consuming a lot of time, even with the trimming-cutting tool preparing samples is an uneasy job. Conducting SDT and obtaining values for UCS from using the predictive equation for coal is an alternative.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

A comprehensive laboratory testing program was designed and carried out in order to first characterize some physical (porosity, bulk density) and mechanical properties (UCS and PLT) and also slake durability (SDI) of coal samples obtained from four underground mines in the Karaganda Coal Basin in Kazakhstan. The main objective of this work was to establish correlations between the SDI and strength parameters of the tested coals such as UCS and PLT. The following conclusions can be drawn based on this research work:

1. According to Anon (1979), the tested coal samples can be classified as "weak rock" with UCS ranging from 4.53-11.18 MPa.
2. Based on gas porosimetery tests, and the relationship between pore size and coal rank (Rodrigues and Lemos de Sousa, 2002) the tested coal samples can be classified as high volatile bituminous coal (C + B) since it refers to category of mesopores (in between 2 nm and 50 nm), where KCB pore diameter being in between 2.973 and 3.943m.
3. From 2nd-cycle (Id2) SDT results all of the samples can be classified as "medium high durability" group (85%-95%), except for samples taken from D6T location (95.80%) that corresponds "high durability" group (95%-98%). To classify results for each the location based on the SDI according to Franklin and Chandra's classification for slake durability (Franklin and Chandra, 1972) (Table 4), the tested coal samples can be classified as "very high durability" materials (90%-95%).
4. For the studies coal samples, there is a strong correlation between the SDI values from cycles 2-5 vs SDI values from 1st cycle SDI values and very strong correlation between the SDI values from 3rd cycle vs SDI values from 1st cycle SDI. The third cycle results can be estimated by using the first cycle slake durability index where there is a very strong correlation (r=0.87) among these parameters. In addition, SDI value for cycles 2, 4, and 5 can be estimated by using the first cycle slake durability index where there is a strong correlation (r=0.85, r=0.85 and r=0.82, respectively) among these parameters.
5. There is a positive correlation between SDI and UCS (perpendicular) indicating that the correlations are moderate for 2nd cycle (r=0.530), are strong for 3rd cycle (r=0.621), for the 4th cycle (0.679) and for the 5th cycle (r= 0.679) of SDT.
6. Also, positive correlations exist between the PLI perpendicular and SDI. There are very strong correlations between these two parameters for all cycles of SDT. Coal strength

estimated using the correlations obtained for PLT perpendicular and SDI data from cycles 2-5 has the highest accuracy and reliability among all of the mechanical properties data obtained and presented in this research work.

7. There is a weak to moderate and positive correlations between the PLI parallel versus SDI values for cycles 2-5.
8. In general, the SDI values show weaker correlations with physical properties than mechanical properties.
9. Correlation coefficients between SDI and strength properties after the 4th cycle show more constant values.

Studied coal material is a weak rock as known in the literature. As a result of this research, it is found that the SDI of coal should be performed at least four cycles, which gives better result and correlation coefficients to compare the SDI with other coal properties. However, these obtained results are valid for few locations from Karaganda coal basin and should be used with care.

6.2 Recommendations

1. Further research with additional data and studies on coal from other regions are needed to verify the proposed relationships. The quantitative relationship between PLI and SDI could provide a reference for the further study of predicting strength from other tests.
2. The coal samples testes were intensely fractured, which made obtaining core samples from the block extremely difficulty. Further research is needed to investigate the effect of microfractures on the mechanical behavior of coal. In addition, the effects and structural and geological factors controlling mechanical properties of coal can be assessed.
3. With the addition of a few more experiments, the relationship between physical and mechanical properties of coal with other important parameters such as hardness and brittleness can be investigated.

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APPENDICES

APPENDIX 1. LISTING OF TEST DATA

Table 27

Slake durability test records for all tested specimens.

No	*CODE*	*sample code*	*Initial weight with drum*	*Initial weight taken = A*	*mass of drum*	*Weight with drum after 1st cycle*	*Weight after 1st cycle = B*	*Weight with drum after 2nd cycle*	*Weight after 2nd cycle = C*	*Weight with drum after 3rd cycle*	*Weight after 3rd cycle = D*	*Weight with drum after the 4th cycle*	*Weight after 4th cycle = E*	*Weight with drum after the 5th cycle*	*Weight after 5th cycle = F*
		D11K01	1360.55	517.96	842.59	1341.53	498.94	1326.63	484.04	1315.05	472.46	1305.56	462.97	1295.97	453.38
1	D11K	D11K02	1308.43	464.95	843.48	1296.25	452.77	1290.7	447.22	1286.99	443.51	1283.53	440.05	1281.02	437.54
		D11K03	1353.64	508.72	845.04	1338.56	493.52	1323.46	478.42	1311.92	466.88	1303.28	458.24	1293.09	448.05
		D6K01	1342.45	498.5	843.95	1326.22	482.27	1316.91	472.96	1310.83	466.88	1305.55	461.6	1296.19	452.24
2	D6K	D6K02	1372.86	530.22	842.64	1352.37	509.73	1337.7	495.06	1324.4	481.76	1316.79	474.15	1310.9	468.26
		D6K03	1364.66	521.82	842.84	1337.15	494.31	1318.74	475.9	1301.54	458.7	1291.62	448.78	1279.7	436.86
		K12K01	1315.9	472.27	843.63	1289.99	446.36	1284.57	440.94	1273.79	430.16	1265.7	422.07	1259.61	415.98
3	K12K	K12K02	1305.79	463.04	842.75	1293.04	450.29	1284.81	442.06	1272.56	429.81	1268.01	425.26	1264.18	421.43
		K12K03	1299.26	456.53	842.73	1284.08	441.35	1275.21	432.48	1267.78	425.05	1260.55	417.82	1253.61	410.88
		D6T01	1331.5	488.86	842.64	1319.03	476.39	1311.54	468.9	1312.03	469.39	1307.79	465.15	1305	462.36
4	D6T	D6T02	1286.05	443.33	842.64	1276.46	433.82	1272.24	429.6	1269.15	426.51	1266.05	423.41	1263.62	420.98
		D6T03	1315.41	464.76	842.72	1294.68	451.96	1282.8	440.08	1274.71	431.99	1269.6	426.88	1266.83	424.11

Table 28

Dimensions, weight, and bulk density of core specimens (D6K and D11K).

			Density (D6K)			
No	*Sample id*	*Height (mm)*	*Diameter (mm)*	*Weight (g)*	*Volume (mm^3)*	*Density (g/cm^3)*
1	D6K+01	131.43	52.69	365.15	286431.4	1.27
2	D6K+02	133.02	51.66	339.42	278673.3	1.22
3	D6K+03	134.59	51.69	361.39	282290	1.28
4	D6K+04	131.55	50.04	333.31	258580.1	1.29
5	D6K+05	131.8	52.75	372.58	287892.3	1.29
	Average value	132.48	51.77	354.37	278678	1.27
	Standard deviation	1.34	1.1	17.06	11852.68	0.03
			Density (D11K)			
no	*Sample ID*	*Height (mm)*	*Diameter (mm)*	*Weight (g)*	*Volume (mm3)*	*Density (g/cm3)*
1	D11K+01	133.15	51.66	363.93	278945.7	1.3
2	D11K+02	134.94	51.61	390.29	282148.7	1.38
3	D11K+03	131.97	52.46	380.32	285102.8	1.33
4	D11K+04	132.76	52.67	377.35	289110.3	1.31
5	D11K+05	132.54	52.17	373.28	283177.2	1.32
	Average value	133.07	52.11	377.03	283703.8	1.33
	Standard deviation	1.13	0.47	9.65	3759.07	0.03

Table 29

Dimensions, weight, and bulk density of cubic specimens (D6T and K12K).

Density (D6T)							
No	Sample ID	Height (mm)	Width (mm)	Length (mm)	Weight (g)	Volume (mm3)	Density (g/cm3)
1	D6T+01	73.3	74.2	73.3	520.3	398684.2	1.31
2	D6T+02	71.9	73.0	74.8	545.6	392612.4	1.39
3	D6T+03	69.3	72.7	72.7	479.4	366750.9	1.31
4	D6T+04	71.1	74.2	74.8	555.0	394399.0	1.41
5	D6T+05	60.2	72.1	65.6	384.1	284744.5	1.35
6	D6T+06	71.7	76.2	76.6	542.4	418398.4	1.30
7	D6T+07	64.4	72.2	72.6	463.1	337183.8	1.37
8	D6T+08	74.6	74.1	77.2	535.3	426694.7	1.25
9	D6T+09	76.4	76.9	76.9	585.5	451682.2	1.30
10	D6T+10	72.9	70.6	72.1	479.3	370924.5	1.29
	Average value	70.6	73.6	73.7	509.0	384207.5	1.33
	Standard deviation	4.87	1.92	3.38	58.4	47721.9	0.0497

Density (K12K)							
No	Sample id	Height (mm)	Width (mm)	Length (mm)	Weight (g)	Volume (mm3)	Density (g/cm3)
1	K12K+01	72.4	75.1	74.4	521.1	404389.3	1.29
2	K12K+02	72.5	73.6	73.2	602.3	391005.1	1.54
3	K12K+03	73.4	69.6	74.0	496.4	377691.7	1.31
4	K12K+04	71.0	74.5	72.5	476.4	383490.6	1.24
5	K12K+06	70.6	72.4	66.7	472.6	340912.3	1.39
6	K12K+07	72.9	68.8	73.4	438.6	368106.1	1.19
7	K12K+08	73.0	72.7	73.1	498.4	387505.6	1.29
8	K12K+09	72.0	71.4	70.3	468.9	361380.0	1.30
9	K12K+10	72.7	72.7	73.0	576.6	386356.1	1.49
	Average value	72.3	72.3	72.3	505.7	377870.8	1.34
	Standard deviation	0.929	2.105	2.39	53.1	18726.4	0.115

Table 30

The density of specimens by wax immersion method (D6K, D6T, K12K and D11K)

	No	*Sample ID*	*Dry Weight (g)*	*Wax coated Weight (g)*	*Sus-pended Weight (g)*	*Sample with wax coating volume (cm³)*	*Sample volume (cm³)*	*Density (g/cm³)*	*Average density (g/cm³)*
D6T	1	D6T+01	31.69	34.05	28.48	2.62	25.86	1.23	1.263
	2	D6T+02	20.8	22.31	17.77	1.68	16.09	1.29	
	3	D6T+03	18.84	19.86	15.92	1.13	14.79	1.27	
	4	D6T+04	32.83	34.63	23.74	2.00	21.74	**1.51**	
	5	D6T+05	29.04	33.03	25.46	4.43	21.03	**1.38**	
K12K	6	K12K+01	37.96	40.04	30.72	2.31	28.41	1.34	1.294
	7	K12K+02	25.35	26.93	21.82	1.76	20.06	1.26	
	8	K12K+03	30.21	31.94	25.3	1.92	23.38	1.29	
	9	K12K+04	21.73	23.34	18.53	1.79	16.74	1.30	
	10	K12K+05	35.15	37.39	29.98	2.49	27.49	1.28	
D6K	11	D6K+01	13.23	14.41	11.65	1.31	10.34	1.28	1.288
	12	D6K+02	14.37	15.7	12.67	1.48	11.19	1.28	
	13	D6K+03	23.63	25.5	20.41	2.08	18.33	1.29	
	14	D6K+04	27.37	29.83	23.37	2.73	20.64	1.33	
	15	D6K+05	12.64	14.42	11.99	1.98	10.01	1.26	
D11K	16	D11K+01	18.54	20.6	13.39	2.29	11.10	**1.67**	1.253
	17	D11K+02	15.22	17.72	14.82	2.78	12.04	1.26	
	18	D11K+03	14.77	18	15.55	3.59	11.96	1.23	
	19	D11K+04	20.78	24.25	19.96	3.86	16.10	1.29	
	20	D11K+05	28.58	32.36	27.36	4.20	23.16	1.23	

Table 31

UCS test results for all tested specimens.

No	Cored specimen Sample ID	Diameter (mm)	Radius (mm)	Height (mm)	Load (kN)	Area (mm^2)	Strength (MPa)
1	D6K+01	52.690	26.345	131.430	6.552	2179.345	3.006
2	D6K+02	51.660	25.830	133.020	29.172	2094.973	13.925
3	D6K+03	51.690	25.845	134.590	9.614	2097.407	4.584
4	D6K+04	50.040	25.020	131.550	7.424	1965.641	3.777
5	D6K+05	52.750	26.375	131.800	33.059	2184.312	15.135
	D6K PERPENDICULAR	51.766		132.478			8.085
1	D11K+1	51.660	25.830	133.150	9.967	2094.973	4.758
2	D11K+2	51.610	25.805	134.940	11.566	2090.920	5.532
3	D11K+3	52.460	26.230	131.970	7.537	2160.361	3.489
4	D11K+4	52.670	26.335	132.760	9.244	2177.691	4.245
5	D11K+5	52.170	26.085	132.540	9.895	2136.541	4.631
	D11K PERPENDICULAR	52.114		133.072			4.531

No	Cubic specimen Sample ID	Height (mm)	B1M (width) (mm)	B2M (length) (mm)	Area (mm^2)	Load (kN)	Strength (MPa)
1	D6T+02	71.9	73.0	74.8	5457.5	72.5	13.3
2	D6T+04	71.1	74.2	74.8	5548.7	53.8	9.70
3	D6T+06	71.7	76.2	76.6	5835.4	25.5	4.37
4	D6T+08	74.6	74.1	77.2	5722.8	12.7	2.22
5	D6T+10	72.9	70.6	72.1	5089.5	19.6	3.84
	D6T PARALLEL	72.4	73.6	75.1			6.68
1	D6L+01	70.8	74.2	73.3	5442.5	49.8	9.15
2	D6L+03	70.4	72.7	72.7	5289.2	68.2	12.9
3	D6L+05	74.7	72.1	65.6	4730.5	30.3	6.41
4	D6L+07	69.9	72.2	72.6	5239.3	64.9	12.4
5	D6T+09	76.4	76.9	76.9	5912.1	89.1	15.1
	D6T PERPENDICULAR	72.4	73.6	72.2			11.2

No	Cubic specimen Sample ID	Height (mm)	B1M (width) (mm)	B2M (length) (mm)	Area (mm^2)	Load (kN)	Strength (MPa)
1	K12K+01	72.410	75.057	74.407	5584.716	8.537	1.529
2	K12K+02	72.523	73.617	73.237	5391.439	67.868	12.588
3	K12K+03	73.383	69.580	73.970	5146.833	20.500	3.983
4	K12K+04	71.030	74.510	72.460	5398.995	12.097	2.241
	K12K PARALLEL	72.337	73.191	73.518			5.085
1	K12K+06	70.567	72.390	66.737	5048.313	16.166	3.202
2	K12K+07	72.917	68.750	73.430	5310.963	16.183	3.047
3	K12K+08	72.963	72.663	73.090	5016.612	20.710	4.128
4	K12K+09	72.037	71.357	70.303	5313.415	28.079	5.285
5	K12K+10	72.713	72.740	73.047	5313.415	37.174	6.996
	K12K PERPENDICULAR	72.239	71.580	71.321			4.532

Table 32

PLI values for all tested specimen from KCB.

No	Specimen code	W1 (mm)	W2 (mm)	W (mm)	D (mm)	P (kN)	De^2 (mm^2)	D/W	$I_{s(50)}$ (%)
1	D11K pp01	49.2	49	49.1	34.5	0.15	2157.90	0.70	0.378
2	D11K pp02	53.2	49.5	51.35	34.8	0.34	2276.41	0.68	0.833
3	D11K pp03	42.8	54.8	48.8	48.1	0.13	2990.17	0.99	-
4	D11K pp04	55.8	39.7	47.75	25.7	0.16	1563.28	0.54	0.482
5	D11K pp05	48.5	30.9	39.7	20.5	0.27	1036.75	0.52	1.019
6	D11K pp06	66	60	63	34.6	0.36	2776.82	0.55	0.790
7	D11K pp07	66.3	31.3	48.8	53.6	0.07	3332.08	1.10	-
8	D11K pp08	24.7	36.8	30.75	53.3	0.58	2087.87	1.73	-
9	D11K pp09	55.7	52.3	54	53	1.2	3645.86	0.98	-
10	D11K pp10	51.1	57.9	54.5	38.1	0.97	2645.16	0.70	2.187
	AVERAGE					0.423			0.961
1	D11K p01	59.3	44.8	52.05	39.7	0.74	2632.34	0.76	-
2	D11K p02	57.6	63.6	60.6	55.4	0.55	4276.74	0.91	-
3	D11K p03	56.6	49.8	53.2	45.3	0.43	3070.01	0.85	0.893
4	D11K p04	74.5	70.7	72.6	28.5	0.38	2635.80	0.39	0.859
5	D11K p05	31.8	34.9	33.35	31.8	0.16	1350.99	0.95	0.522
6	D11K p06	43.2	37	40.1	33.5	0.13	1711.27	0.84	-
7	D11K p07	34.5	36.9	35.7	33.5	0.16	1523.50	0.94	-
8	D11K p08	65.8	55.5	60.65	33	0.23	2549.62	0.54	0.5292
9	D11K p09	49.8	44.8	47.3	40.4	0.36	2434.29	0.85	0.850
10	D11K p10	64.1	45	54.55	32.3	0.35	2244.54	0.59	0.864
	AVERAGE					0.349			0.755

Table 32. Continued

No	*Specimen code*	*W1 (mm)*	*W2 (mm)*	*W (mm)*	*D (mm)*	*P (kN)*	*De^2 (mm^2)*	*D/W*	$I_{s(50)}$ *(%)*
1	D6K pp01	54.7	44.4	49.55	50.9	0.94	3212.86	1.03	-
2	D6K pp02	56.4	66.7	61.55	47.4	0.54	3716.52	0.77	1.010
3	D6K pp03	56	39.8	47.9	48.8	0.6	2977.73	1.02	1.268
4	D6K pp04	45.2	28	36.6	46	0.2	2144.71	1.26	-
5	D6K pp05	49.5	39.4	44.45	41	0.17	2321.59	0.92	0.412
6	D6K pp06	42.9	27.9	35.4	44.6	0.26	2011.26	1.26	-
7	D6K pp07	46.9	33.5	40.2	43.9	0.17	2248.13	1.09	-
8	D6K pp08	38.2	37.6	37.9	38.2	0.41	1844.31	1.01	1.127
9	D6K pp09	45.7	70.1	57.9	41.4	0.25	3053.58	0.72	0.521
10	D6K pp10	47.8	39.9	43.85	47.9	0.25	2675.69	1.09	0.560
	AVERAGE					0.379			0.829
1	D6K p01	47.9	28.6	38.25	34.6	0.12	1685.92	0.90	0.347
2	D6K p02	49.9	39.1	44.5	31.5	0.74	1785.67	0.71	-
3	D6K p03	69.3	47.2	58.25	33.8	0.74	2508.09	0.58	1.718
4	D6K p04	70.1	55.5	62.8	37.4	0.95	2992.00	0.60	2.002
5	D6K p05	45.8	44.5	45.15	37.8	0.11	2174.10	0.84	-
6	D6K p06	46.6	42.7	44.65	30.4	0.34	1729.12	0.68	0.969
7	D6K p07	63	59.2	61.1	46.3	0.54	3603.73	0.76	1.027
8	D6K p08	39.6	39	39.3	38.1	0.54	1907.43	0.97	1.458
9	D6K p09	36.5	27.7	32.1	38.1	0.54	1557.97	1.19	-
10	D6K p10	39.7	35.6	37.65	47.9	0.26	2297.37	1.27	-
	AVERAGE					0.488			1.25

Table 32. Continued

No	Specimen code	W1 (mm)	W2 (mm)	W (mm)	D (mm)	P (kN)	De^2 (mm2)	D/W	$I_{s(50)}$ (%)
1	K12K pp01	72.6	73	72.8	34.4	1.65	3190.22	0.47	-
2	K12K pp02	33.2	40.4	36.8	26.4	0.27	1237.61	0.72	0.925
3	K12K pp03	57	57	57	31.6	0.34	2294.52	0.55	0.829
4	K12K pp04	46.6	47.2	46.9	31.6	0.34	1887.95	0.67	0.923
5	K12K pp05	27	32.3	29.65	32.1	0.13	1212.44	1.08	-
6	K12K pp06	44.4	53.6	49	38.9	0.54	2428.15	0.79	1.276
7	K12K pp07	53.9	44.3	49.1	38.6	0.32	2414.34	0.79	0.759
8	K12K pp08	35	63.5	49.25	35.7	0.15	2239.78	0.72	-
9	K12K pp09	34.2	38.8	36.5	23.3	0.65	1083.38	0.64	-
10	K12K pp10	51.4	50.5	50.95	26.9	0.37	1745.93	0.53	1.048
	AVERAGE					0.476			1.59
1	K12K p01	56.4	56.9	56.65	32.9	0.17	2374.25	0.58	0.407
2	K12K p02	43.9	39.9	41.9	39.4	0.49	2103.01	0.94	-
3	K12K p03	43.5	54.5	49	24.3	0.39	1516.82	0.50	-
4	K12K p04	39.7	44.1	41.9	31.6	0.14	1686.68	0.75	0.404
5	K12K p05	47	56.7	51.85	31.6	0.34	2087.21	0.61	0.873
6	K12K p06	41.4	52.6	47	35.6	0.1	2131.46	0.76	-
7	K12K p07	52.1	57.8	39.2	39.2	0.34	1957.50	1.00	0.905
8	K12K p08	41.4	53.7	47.55	29.1	0.07	1762.68	0.61	-
9	K12K p09	36.7	41.1	38.9	25.3	0.08	1253.72	0.65	0.272
10	K12K p10	59.2	48.3	53.75	51.1	0.26	3498.89	0.95	0.503
	AVERAGE					0.238			0.57

Table 32. Continued

No	Specimen code	W1 (mm)	W2 (mm)	W (mm)	D (mm)	P (kN)	De^2 (mm2)	D/W	$I_{s(50)}$ (%)
1	D6T pp01	41.2	42.5	41.85	35.7	0.17	1903.24	0.85	-
2	D6T pp02	47.4	44.8	46.1	40.7	0.56	2390.15	0.88	1.335
3	D6T pp03	67.2	68.4	67.8	43.4	1.28	3748.43	0.64	2.383
4	D6T pp04	49	51.2	50.1	43.8	1.13	2795.39	0.87	-
5	D6T pp05	48.7	40.2	44.45	33.5	0.85	1896.91	0.75	-
6	D6T pp06	60.8	57.3	59.05	36.2	0.82	2723.07	0.61	1.820
7	D6T pp07	65.3	71.7	68.5	24.8	0.25	2164.08	0.36	0.630
8	D6T pp08	54.1	52.7	53.4	40.7	2.8	2768.64	0.76	0.000
9	D6T pp09	55	53.2	54.1	23	0.16	1585.10	0.43	-
10	D6T pp10	48.6	57.6	53.1	39.8	0.88	2692.20	0.75	1.965
11	D6T pp11	67.7	66.7	67.2	37.3	0.95	3193.07	0.56	1.931
12	D6T pp12	55.2	54	54.6	38.8	0.55	2698.70	0.71	1.227
	AVERAGE					0.867			1.59
1	D6T p01	57.4	59.5	58.45	33.2	0.24	2472.03	0.57	-
2	D6T p02	45	52.3	48.65	44.1	0.44	2733.08	0.91	0.974
3	D6T p03	47.3	58.3	52.8	42.6	0.44	2865.32	0.81	-
4	D6T p04	41.5	40.5	41	34.7	0.76	1812.36	0.85	-
5	D6T p05	61.3	48.5	54.9	43.4	0.71	3035.24	0.79	1.484
6	D6T p06	40.1	34.9	37.5	32.7	0.46	1562.10	0.87	1.386
7	D6T p07	39.3	38.9	39.1	38.1	0.79	1897.72	0.97	-
8	D6T p08	50	49.1	49.55	38.32	0.64	2418.80	0.77	1.516
9	D6T p09	40.2	41.1	40.65	39.6	0.82	2050.62	0.97	2.127
10	D6T p10	37.8	38.6	38.2	28.2	0.52	1372.28	0.74	1.682
11	D6T p11	45	45	45	29.6	0.32	1696.82	0.66	-
	AVERAGE					0.558			1.58

Reports of test results for porosity of coal specimen

Quantachrome® ASiQwin™- Automated Gas Sorption Data Acquisition and Reduction
 version 3.01

Analysis Report

Operator: Dauren Date:2019/04/26 Operator: Dauren Date:2019/04/29

Sample ID: **KazakhstanskayaD11**powder Filename: KazakhstanskayaD1112_26.04.19.qps

Sample Desc: Comment:

Sample Weight: 0.3127 g Instrument: Autosorb iQ Station 1

Approx. Outgas Time:4.2 hrs Final Outgas Temp.:110 °C Extended info: Available

Analysis gas: Nitrogen Non-ideality: 6.58e-05 1/Torr CellType: 12mm

Analysis Time: 6:44 hr:min Bath temp.: 77.35 K

Analysis Mode: Standard VoidVol Remeasure:off

VoidVol. Mode: He Measure Cold Zone V: 6.96268 cc Warm Zone V: 8.54302 cc

Data Reduction Parameters

Thermal Transpiration: onEff. mol. diameter (D): 3.54 ÅEff. cell stem diam. (d): 4.0000 mm

t-Method Calc. method: de Boer

BJH/DH method Moving pt. avg.: off Ignoring P-tags below 0.35 P/Po

Adsorbate Nitrogen Temperature 77.350K

Molec. Wt.: 28.013 Cross Section: 16.200 Å² Liquid Density: 0.806 g/cc

Diameter	Pore Volume	Pore Surf Area	dV(d)	dS(d)	dV(logd)	dS(logd)
nm	cc/g	m²/g	cc/nm/g	m²/nm/g	cc/g	cc/g
3.1389	1.2048e-04	1.5353e-01	6.8451e-04	8.7231e-01	4.9460e-03	6.3029e+00
3.3176	2.4018e-04	2.9785e-01	6.5991e-04	7.9566e-01	5.0397e-03	6.0765e+00
3.5069	3.7441e-04	4.5096e-01	6.8063e-04	7.7635e-01	5.4945e-03	6.2672e+00
3.7129	5.6350e-04	6.5468e-01	8.8026e-04	9.4833e-01	7.5234e-03	8.1052e+00
3.9355	8.0100e-04	8.9607e-01	1.0310e-03	1.0479e+00	9.3397e-03	9.4928e+00
4.1756	9.3979e-04	1.0290e+00	5.5544e-04	5.3208e-01	5.3387e-03	5.1143e+00
4.4393	1.0708e-03	1.1471e+00	4.7192e-04	4.2522e-01	4.8224e-03	4.3451e+00
4.7309	1.1628e-03	1.2248e+00	3.0111e-04	2.5459e-01	3.2790e-03	2.7724e+00
5.0479	1.2730e-03	1.3122e+00	3.3537e-04	2.6575e-01	3.8967e-03	3.0878e+00
5.4138	1.3724e-03	1.3856e+00	2.4649e-04	1.8212e-01	3.0713e-03	2.2692e+00
5.8207	1.4813e-03	1.4604e+00	2.6531e-04	1.8232e-01	3.5544e-03	2.4426e+00
6.2670	1.5756e-03	1.5206e+00	1.9551e-04	1.2478e-01	2.8198e-03	1.7998e+00
6.7974	1.6626e-03	1.5718e+00	1.5042e-04	8.8517e-02	2.3529e-03	1.3846e+00
7.4103	1.7461e-03	1.6169e+00	1.2908e-04	6.9676e-02	2.2010e-03	1.1881e+00
8.1121	1.7524e-03	1.6200e+00	8.2465e-06	4.0663e-03	1.5392e-04	7.5898e-02
8.9876	1.7524e-03	1.6200e+00	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
10.0560	1.8544e-03	1.6606e+00	8.9331e-05	3.5534e-02	2.0662e-03	8.2189e-01
11.3903	1.9474e-03	1.6932e+00	6.0893e-05	2.1384e-02	1.5947e-03	5.6001e-01
13.1249	2.0862e-03	1.7355e+00	7.1474e-05	2.1783e-02	2.1561e-03	6.5710e-01
15.4882	2.2695e-03	1.7829e+00	6.5843e-05	1.7005e-02	2.3418e-03	6.0480e-01
18.7863	2.5126e-03	1.8346e+00	6.3759e-05	1.3576e-02	2.7485e-03	5.8522e-01
24.2704	2.9520e-03	1.9071e+00	6.1403e-05	1.0120e-02	3.4065e-03	5.6142e-01
34.3036	3.8662e-03	2.0137e+00	7.0809e-05	8.2568e-03	5.5264e-03	6.4441e-01
60.8018	7.3517e-03	2.2430e+00	8.6953e-05	5.7204e-03	1.1719e-02	7.7096e-01
200.4074	5.1333e-02	3.1208e+00	1.8393e-04	3.6711e-03	7.3615e-02	1.4693e+00

BJH desorption summary

Surface Area = 3.121 m²/g

Pore Volume = 0.051 cc/g

Pore Diameter Dv(d) = 3.935 nm

Analysis Report
Operator: Dauren Date:2019/04/24 Operator: Dauren Date:2019/04/25
Sample ID: **KazakhstanskayaD6#2** Filename: KazakhstanskayaD612_24.04.19.qps
Sample Desc: Comment:
Sample Weight: 0.3859 g Instrument: Autosorb iQ Station 1
Approx. Outgas Time:4.2 hrs Final Outgas Temp.:110 °C Extended info: Available
Analysis gas: Nitrogen Non-ideality: 6.58e-05 1/Torr CellType: 12mm
Analysis Time: 7:48 hr:min Bath temp.: 77.35 K
Analysis Mode: Standard VoidVol Remeasure:off
VoidVol. Mode: He Measure Cold Zone V: 7.22842 cc Warm Zone V: 8.2439 cc
Data Reduction Parameters
Thermal Transpiration: onEff. mol. diameter (D): 3.54 ÅEff. cell stem diam. (d): 4.0000 mm

t-Method Calc. method: de Boer
BJH/DH method Moving pt. avg.: off Ignoring P-tags below 0.35 P/Po
Adsorbate Nitrogen Temperature 77.350K
Molec. Wt.: 28.013 Cross Section: 16.200 Å² Liquid Density: 0.806 g/cc

Diameter	Pore Volume	Pore Surf Area	dV(d)	dS(d)	dV(logd)	dS(logd)
nm	cc/g	m²/g	cc/nm/g	m²/nm/g	cc/g	cc/g
3.1382	1.5249e-04	1.9437e-01	8.8357e-04	1.1262e+00	6.3831e-03	8.1359e+00
3.3178	3.1815e-04	3.9408e-01	8.8850e-04	1.0712e+00	6.7859e-03	8.1813e+00
3.5125	4.9416e-04	5.9453e-01	8.6662e-04	9.8689e-01	7.0072e-03	7.9797e+00
3.7198	9.4980e-04	1.0845e+00	2.1544e-03	2.3167e+00	1.8448e-02	1.9837e+01
3.9371	1.3937e-03	1.5355e+00	1.9894e-03	2.0212e+00	1.8030e-02	1.8318e+01
4.1771	1.5531e-03	1.6881e+00	6.2084e-04	5.9452e-01	5.9694e-03	5.7163e+00
4.4427	1.6877e-03	1.8093e+00	4.9038e-04	4.4151e-01	5.0148e-03	4.5151e+00
4.7308	1.8329e-03	1.9321e+00	4.8139e-04	4.0703e-01	5.2421e-03	4.4323e+00
5.0546	1.9665e-03	2.0378e+00	3.8611e-04	3.0555e-01	4.4920e-03	3.5548e+00
5.4165	2.0909e-03	2.1296e+00	3.2904e-04	2.4299e-01	4.1022e-03	3.0294e+00
5.8185	2.2240e-03	2.2211e+00	3.1256e-04	2.1487e-01	4.1856e-03	2.8775e+00
6.2786	2.3538e-03	2.3038e+00	2.6251e-04	1.6724e-01	3.7931e-03	2.4165e+00
6.8062	2.4853e-03	2.3811e+00	2.3451e-04	1.3782e-01	3.6731e-03	2.1587e+00
7.4157	2.6243e-03	2.4561e+00	2.1133e-04	1.1399e-01	3.6061e-03	1.9451e+00
8.1425	2.7768e-03	2.5310e+00	1.9173e-04	9.4187e-02	3.5918e-03	1.7645e+00
9.0150	2.9374e-03	2.6023e+00	1.6902e-04	7.4995e-02	3.5052e-03	1.5553e+00
10.0870	3.1213e-03	2.6752e+00	1.5405e-04	6.1089e-02	3.5738e-03	1.4172e+00
11.4174	3.3152e-03	2.7432e+00	1.3221e-04	4.6318e-02	3.4709e-03	1.2160e+00
13.1702	3.5878e-03	2.8259e+00	1.3370e-04	4.0607e-02	4.0464e-03	1.2290e+00
15.4906	3.9065e-03	2.9082e+00	1.2246e-04	3.1622e-02	4.3577e-03	1.1252e+00
18.8644	4.4251e-03	3.0182e+00	1.2511e-04	2.6529e-02	5.4125e-03	1.1477e+00
24.2935	5.2710e-03	3.1575e+00	1.2602e-04	2.0749e-02	7.0040e-03	1.1532e+00
34.4162	7.1204e-03	3.3724e+00	1.3665e-04	1.5883e-02	1.0688e-02	1.2422e+00
62.2243	1.6066e-02	3.9475e+00	2.1257e-04	1.3665e-02	2.9258e-02	1.8808e+00

BJH desorption summary

Surface Area = 3.947 m²/g
Pore Volume = 0.016 cc/g
Pore Diameter Dv(d) = 3.720 nm

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Analysis Report
Operator: Dauren Date:2019/03/27 Operator: Dauren Date:2019/04/08
Sample ID: **Kuzembayeva12** Filename: Kuzembayeva12_27.03.19.qps
Sample Desc: Comment:
Sample Weight: 0.3264 g Instrument: Autosorb iQ Station 1
Approx. Outgas Time:8.5 hrs Final Outgas Temp.:110 °C Extended info: Available
Analysis gas: Nitrogen Non-ideality: 6.58e-05 1/Torr CellType: 12mm
Analysis Time: 6:30 hr:min Bath temp.: 77.35 K
Analysis Mode: Standard VoidVol Remeasure:off
VoidVol. Mode: He Measure Cold Zone V: 6.9017 cc Warm Zone V: 8.63194 cc
Data Reduction Parameters
Thermal Transpiration: onEff. mol. diameter (D): 3.54 ÅEff. cell stem diam. (d): 4.0000 mm

t-Method Calc. method: de Boer
BJH/DH method Moving pt. avg.: off Ignoring P-tags below 0.35 P/Po
Adsorbate Nitrogen Temperature 77.350K
Molec. Wt.: 28.013 Cross Section: 16.200 Å² Liquid Density: 0.806 g/cc

Diameter	Pore Volume	Pore Surf Area	dV(d)	dS(d)	dV(logd)	dS(logd)
nm	cc/g	m²/g	cc/nm/g	m²/nm/g	cc/g	cc/g
3.1377	1.7841e-04	2.2744e-01	1.0298e-03	1.3128e+00	7.4383e-03	9.4825e+00
3.3171	3.3552e-04	4.1689e-01	8.4635e-04	1.0206e+00	6.4627e-03	7.7932e+00
3.5073	4.5751e-04	5.5602e-01	6.2634e-04	7.1432e-01	5.0570e-03	5.7673e+00
3.7126	6.0748e-04	7.1760e-01	6.9528e-04	7.4911e-01	5.9420e-03	6.4020e+00
3.9354	8.3831e-04	9.5222e-01	1.0041e-03	1.0205e+00	9.0956e-03	9.2450e+00
4.1771	1.0069e-03	1.1137e+00	6.6513e-04	6.3693e-01	6.3953e-03	6.1242e+00
4.4418	1.1143e-03	1.2104e+00	3.8911e-04	3.5041e-01	3.9784e-03	3.5827e+00
4.7276	1.2275e-03	1.3062e+00	3.8277e-04	3.2386e-01	4.1654e-03	3.5243e+00
5.0505	1.2580e-03	1.3303e+00	8.6932e-05	6.8850e-02	1.0106e-03	8.0035e-01
5.4139	1.3996e-03	1.4349e+00	3.7590e-04	2.7773e-01	4.6841e-03	3.4608e+00
5.8177	1.5525e-03	1.5401e+00	3.5494e-04	2.4404e-01	4.7526e-03	3.2676e+00
6.2795	1.7147e-03	1.6434e+00	3.2909e-04	2.0963e-01	4.7559e-03	3.0295e+00
6.8070	1.9121e-03	1.7594e+00	3.5111e-04	2.0632e-01	5.5000e-03	3.2320e+00
7.4191	2.1018e-03	1.8616e+00	2.8658e-04	1.5451e-01	4.8924e-03	2.6378e+00
8.1485	2.3368e-03	1.9770e+00	2.9485e-04	1.4474e-01	5.5277e-03	2.7135e+00
9.0186	2.6043e-03	2.0957e+00	2.8371e-04	1.2583e-01	5.8861e-03	2.6106e+00
10.0921	2.9216e-03	2.2214e+00	2.6350e-04	1.0444e-01	6.1159e-03	2.4240e+00
11.4431	3.2815e-03	2.3472e+00	2.4027e-04	8.3986e-02	6.3216e-03	2.2098e+00
13.1265	3.6424e-03	2.4572e+00	1.9310e-04	5.8843e-02	5.8266e-03	1.7755e+00
15.4256	4.0945e-03	2.5744e+00	1.6568e-04	4.2961e-02	5.8692e-03	1.5219e+00
18.8381	4.7529e-03	2.7142e+00	1.6075e-04	3.4133e-02	6.9453e-03	1.4747e+00
24.0827	5.8612e-03	2.8983e+00	1.7334e-04	2.8790e-02	9.5552e-03	1.5871e+00
34.4272	7.5951e-03	3.0998e+00	1.2129e-04	1.4092e-02	9.4750e-03	1.1009e+00
60.5557	9.5626e-03	3.2297e+00	5.1831e-05	3.4237e-03	6.9838e-03	4.6131e-01
203.8834	2.1577e-02	3.4654e+00	4.8310e-05	9.4779e-04	1.9516e-02	3.8289e-01

BJH desorption summary

Surface Area = 3.465 m²/g
Pore Volume = 0.022 cc/g
Pore Diameter Dv(d) = 3.138 nm

Analysis Report
Operator: Dauren Date:2019/04/25 Operator: Dauren Date:2019/04/26
Sample ID: **TentekskayaD6**#2 Filename: TentekskayaD612_25.04.19.qps
Sample Desc: Comment:
Sample Weight: 0.4656 g Instrument: Autosorb iQ Station 1
Approx. Outgas Time:2.2 hrs Final Outgas Temp.:110 °C Extended info: Available
Analysis gas: Nitrogen Non-ideality: 6.58e-05 1/Torr CellType: 12mm
Analysis Time: 5:47 hr:min Bath temp.: 77.35 K
Analysis Mode: Standard VoidVol Remeasure:off
VoidVol. Mode: He Measure Cold Zone V: 7.77354 cc Warm Zone V: 9.02199 cc
Data Reduction Parameters
Thermal Transpiration: onEff. mol. diameter (D): 3.54 ÅEff. cell stem diam. (d): 4.0000 mm

t-Method Calc. method: de Boer
BJH/DH method Moving pt. avg.: off Ignoring P-tags below 0.35 P/Po
Adsorbate Nitrogen Temperature 77.350K
Molec. Wt.: 28.013 Cross Section: 16.200 Å² Liquid Density: 0.806 g/cc

Diameter	Pore Volume	Pore Surf Area	dV(d)	dS(d)	dV(logd)	dS(logd)
nm	cc/g	m²/g	cc/nm/g	m²/nm/g	cc/g	cc/g
3.1359	5.7105e-06	7.2840e-03	3.2851e-05	4.1902e-02	2.3715e-04	3.0249e-01
3.3147	8.2830e-06	1.0388e-02	1.3999e-05	1.6893e-02	1.0682e-04	1.2890e-01
3.5048	8.2830e-06	1.0388e-02	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
3.7095	2.0519e-05	2.3582e-02	5.7421e-05	6.1918e-02	4.9032e-04	5.2872e-01
3.9311	1.1109e-04	1.1574e-01	3.9344e-04	4.0033e-01	3.5603e-03	3.6226e+00
4.1743	1.7461e-04	1.7661e-01	2.4790e-04	2.3755e-01	2.3821e-03	2.2826e+00
4.4347	1.7461e-04	1.7661e-01	0.0000e+00	0.0000e+00	0.0000e+00	0.0000e+00
4.7239	2.0115e-04	1.9908e-01	8.4590e-05	7.1628e-02	9.1976e-04	7.7882e-01
5.0494	2.2605e-04	2.1881e-01	7.3807e-05	5.8468e-02	8.5782e-04	6.7954e-01
5.4111	2.7321e-04	2.5367e-01	1.2217e-04	9.0312e-02	1.5216e-03	1.1248e+00
5.8136	3.0929e-04	2.7850e-01	8.6113e-05	5.9249e-02	1.1522e-03	7.9279e-01
6.2764	3.6305e-04	3.1276e-01	1.0611e-04	6.7628e-02	1.5327e-03	9.7682e-01
6.8014	4.0433e-04	3.3703e-01	7.5972e-05	4.4681e-02	1.1891e-03	6.9936e-01
7.3965	4.5166e-04	3.6263e-01	7.3166e-05	3.9568e-02	1.2453e-03	6.7345e-01
8.1180	4.8779e-04	3.8043e-01	4.5378e-05	2.2359e-02	8.4753e-04	4.1761e-01
8.9967	5.4482e-04	4.0579e-01	5.9330e-05	2.6378e-02	1.2279e-03	5.4593e-01
10.0816	5.8478e-04	4.2164e-01	3.3068e-05	1.3120e-02	7.6671e-04	3.0420e-01
11.3946	6.3453e-04	4.3911e-01	3.5093e-05	1.2319e-02	9.1954e-04	3.2280e-01
13.1403	7.0312e-04	4.5999e-01	3.3076e-05	1.0069e-02	9.9870e-04	3.0401e-01
15.4967	7.6794e-04	4.7672e-01	2.4562e-05	6.3399e-03	8.7430e-04	2.2568e-01
18.8087	8.5991e-04	4.9627e-01	2.3077e-05	4.9078e-03	9.9570e-04	2.1175e-01
24.2696	1.0070e-03	5.2051e-01	2.1200e-05	3.4941e-03	1.1766e-03	1.9392e-01
34.2568	1.2481e-03	5.4867e-01	1.8498e-05	2.1599e-03	1.4413e-03	1.6829e-01
58.3402	1.8064e-03	5.8695e-01	1.5892e-05	1.0896e-03	2.0686e-03	1.4183e-01
200.6522	4.9598e-03	6.4981e-01	1.2639e-05	2.5196e-04	4.9884e-03	9.9443e-02

BJH desorption summary

Surface Area = 0.650 m²/g
Pore Volume = 0.005 cc/g
Pore Diameter Dv(d) = 3.931 nm

APPENDIX 2. SAMPLES DURING TESTS

Table 33

Specimen before and after SDT.

	Before SDT	*After the 5th cycle*	*Sample code/SDI*
1			D11K01 96.33% 93.45% 91.22% 89.38% 87.53%
2			D11K02 97.38% 96.19% 95.39% 94.64% 94.10%
3			D11K03 97.01% 94.04% 91.78% 90.08% 88.07%

4			D6K01 96.74% 94.88% 93.66% 92.60% 90.72%
5			D6K02 96.14% 93.37% 90.86% 89.43% 88.31%
6			D6K03 94.73% 91.20% 87.90% 86.00% 83.72%

7

K12K01
94.51%
93.37%
91.08%
89.37%
88.08%

8

K12K02
97.25%
95.47%
92.82%
91.84%
91.01%

9

K12K03
96.67%
94.73%
93.10%
91.52%
90.00%

10

D6T01
97.45%
95.92%
96.02%
95.15%
94.58%

11

D6T02
97.85%
96.90%
96.21%
95.51%
94.96%

12

D6T03
97.25%
94.69%
92.95%
91.85%
91.25%