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Examining the Impact of Coal Gas Emissions on the Stability Analysis of Coal Pillars: A Critical Literature Review

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Review scientific paper

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Abstract

An essential component of guaranteeing the security of underground coal mines is the stability of underground areas. Coal pillars are left in place in underground coal mines to stabilize opened regions where excavations have redistributed in situ stresses. The designs of pillars have been developed in accordance with the necessary safety and economic constraints. The safe and cost-effective design of mining pillars, particularly coal pillars, is influenced by various factors. The purpose of this publication, which is a portion of a doctoral thesis, is to support a theory regarding the impact of methane emissions on the stability of coal pillars. This topic has not received much attention in the literature. The pillar design's initially effective parameters are examined and categorized in this study. The impact of coal gas emissions on the stability of coal roofs, pillars, and walls are investigated for the first time. Previous research on the mechanical behavior of coal exposed to different kinds of gases is examined for this aim. The literature's findings also showed that coal's mechanical properties will decrease when exposed to gases, including shear strength, elastic modulus, and uniaxial compressive strength. The coal texture develops joints and cracks as a result of gas adsorption and emission, which lowers the mechanical properties of the coal and causes instabilities in underground spaces. The literature suggests that gas emissions from coal pillars and walls in underground mines most likely produced unpredictable instability and outburst. To the best of the authors' knowledge and ability to determine, there is an absence of critical literature reviews on the mechanical properties of coal during gas emissions, which is the topic of this work.

Keywords: coal
mechanical properties; methane emissions; coal pilar stability; gas adsorption and desorption; rock mechanics

1. Introduction

Coal is one of the energy sources for industrial and household applications. Also, coal supplies the required materials for the steel industry. Coal layers are mined based on the depth, thickness, and slope of the coal seam in both surfaces and underground methods. In surface coal mining methods, the main challenges are related to supply chain, continuity of the coal production, and environmental issues, including the production of greenhouse gases and pollution of soil and water. However, in underground mining there are additional challenges on top of the previously mentioned, including designing a safe and economical method for coal extraction. The main factors affecting the safe and economical operations of underground mining methods depend on the stable and optimal design of underground spaces. This means the optimal and economical design of underground spaces shall meet the production continuity **(Ataei, 2015).**

Longwall, room and pillar, short wall, and top coal caving mining are examples of underground coal extraction. In the USA, Australia, and India, longwall and room and pillar mining are the most popular techniques among them. Figures 1a and b show examples of longwall mining and room and pillar mining, respectively. In these methods to stabilize constructed spaces, coal pillars are designed and remained. Part of the deposit that cannot be recovered will remain in the mine if the pillars are not designed optimally and adequately. Stability and safety factors should also be taken into account while designing pillars. Ensuring the stability of underground spaces by taking economic considerations into account is the ultimate goal of optimal underground mining.

In coal pillar design, the stability of pillars depends on several factors. These parameters can be divided into two categories: controllable and uncontrollable. Con-

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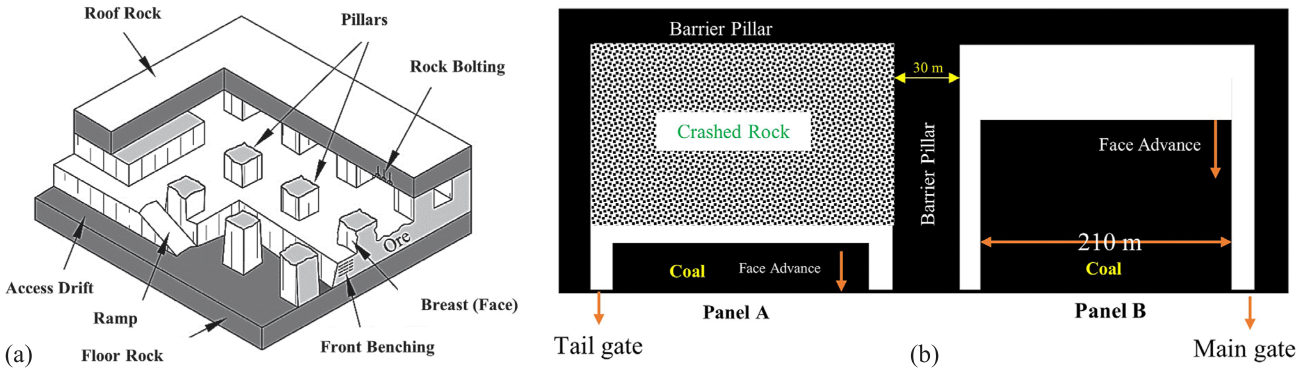


Figure 1: a) A view of room and pillar mining **(Zhang and Ni, 2018). b)** A view of longwall mining **(Ardehjani et al. 2020).**

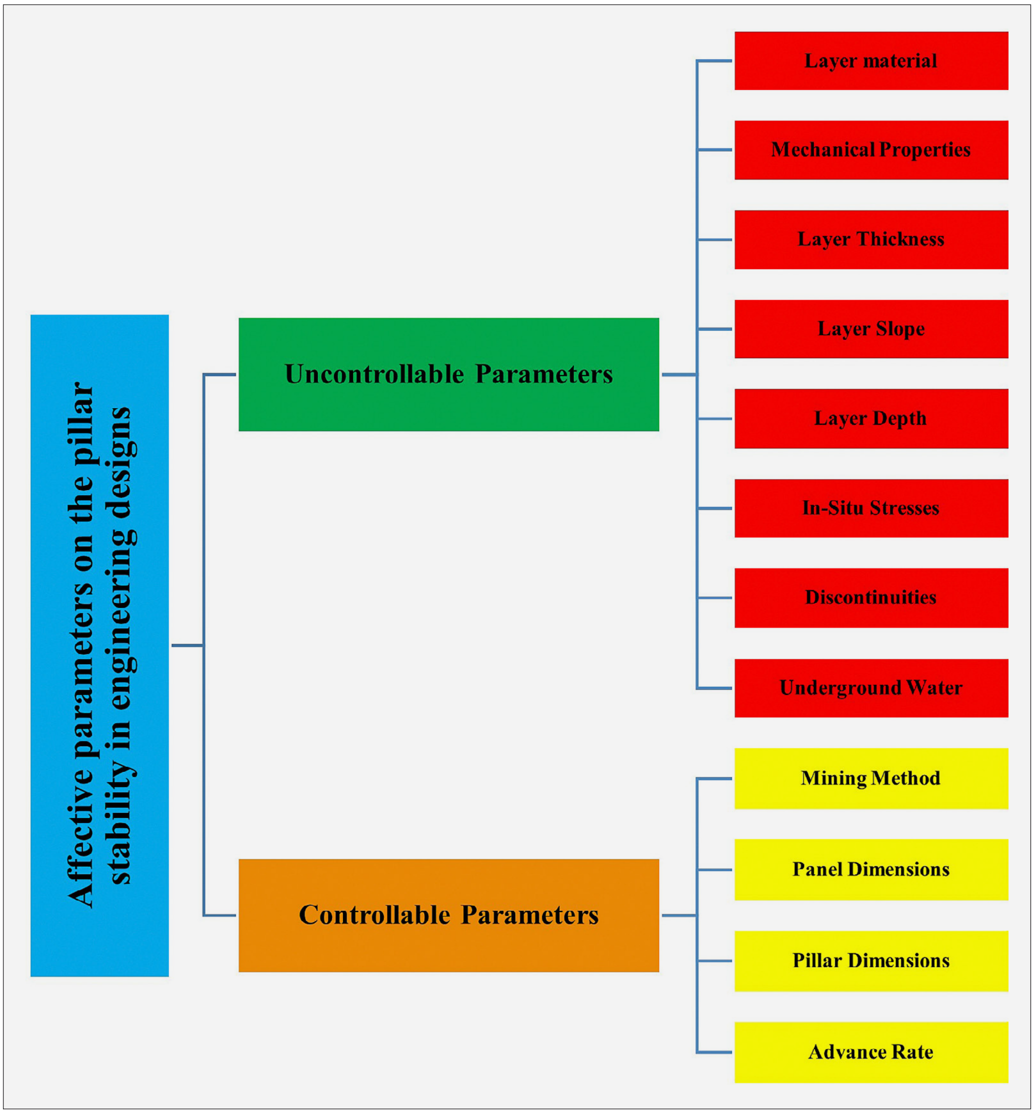


Figure 2: Parameters affective pillar stability in engineering designs

trollable parameters include parameters related to engineering designs, opening dimensions, advance rate, type of underground mining method, and other items. Uncontrollable parameters generally include geological factors such as layer depth, layer thickness, rocks type, thickness and number of key Strata, and layer slope **(Ataei, 2015).** Important parameters on pillar design are classified in **Figure 2.** The purpose of this study is to introduce the parameters that have rarely been considered in coal pillars design, at the same time they can play an essential and influential role in engineering designs. This research critically investigates the affecting factors on the stability of pillars, especially coal pillars, and examines shortcomings and challenges in this field.

2. Most affecting parameters in mine pillar design

Numerous researchers have studied the stability of mine pillars and the affecting parameters in underground mining. Following, the affecting parameters on the stability of mine pillars, especially coal pillars are analyzed.

2.1. Pillar bearing capacity

One of the main factors in the pillar design is the pillar's strength and bearing capacity. The pillar's strength is defined as the maximum amount of applied load per unit area of the pillar before reaching failure. Pillar bearing capacity determines the economy and safety of underground mining operations. Therefore, calculating and estimating pillar strength is a primary step in mine pillars design. Numerous factors affect a pillar's strength that can be divided into controlled parameters, including the pillar's final dimensions, pillar relative dimensions and pillar geometric shape, width to height ratio, time (duration of applying load on the pillar), and uncontrollable parameters, including jointing, in-situ stresses, the ratio of horizontal to vertical stresses, connection conditions between roof and floor, surrounding rocks type, creep, strata stiffness, thickness and number of key strata, seam slope, and other items **(Chugh et al., 1990; Kostecki and Spearing, 2015; Wang et al., 2015; Yang et al., 2015; Ataei, 2015).**

2.2. Pillar dimensions

Experiments have shown that a specimen's strength will decrease with increased dimensions. The strength differences between small laboratory and large in-situ specimens are justified by the differences in dimensions and sizes. According to coal laboratory and field research, the strength of a coal pillar diminishes exponentially with increasing dimension; so, the strength of a coal pillar has a finite value. As a result, Bieniawski introduced the idea of critical size for the first time in 1968 in order to design mine pillars in rock masses. The specimen strength won't change if the specimen's dimensions are increased above the critical size. The strength of massive pillars can be easily determined by applying the idea of critical size. To define a criteria between the size and strength of laboratory specimens and in-situ specimens, numerous researchers have put forth various essential measurements and connections **(Holland and Gaddy, 1957; Holland, 1964; Ataei, 2015; Saki, 2016; Zhang and Ni, 2018).**

2.3. Joints and Faults

Pillar's failure type depends on the joint pattern and their frequency and arrangement. Cross-joint systems can reduce the pillar's strength, while the pillar's stability can't be ensured without external support systems such as rock-bolt or wire-mesh. One of the main factors that reduce the pillar's strength by increasing pillar dimensions is increasing the presence of joints and discontinuities in the pillar's structure. By affecting shear stress on discontinuities plates, jointed rock mass strength will reduce, and as a result, shear failure occurs within the pillar. Following the stress concentration increases in vertices of cracks and joints in the pillar, all cracks expand and will reduce the pillar's tensile strength. Consequently, causing tensile failure in the pillar. According to York et al. In 2000, which led to the presentation of relationships to express the discontinuities effect on coal pillars strength, three parameters of joint density, joint direction, and joint surface strength have the most significant impact on the variation of coal pillar strength **(Holland, 1973; Ataei, 2015).**

Another discontinuity that will weaken the pillar is a fault; in order overcome stability concerns, more minerals must be left as pillars in that location, which will slow down the rate of mineral extraction and recovery. The probability of instability in the pillar will rise in situations where the fault plane angle is smaller and the axis of the main pillar is not parallel to the fault line. In these situations, pillar strength can be increased by increasing the pillar's width and width to height ratio; as a result, the pillar's shape will change **(Bieniawski, 1968; Ataei, 2015).**

2.4. Geometry of a mineral deposit

The position of the pillar in relation to the dimension of the mineral is crucial to pillar design. It is best to place pillars alongside the mineral to prevent the development of sharp edges. The applied loads value on the pillar and its strength are affected by the pillar's position with respect to slope and deposit length. For practical reasons, it is advised that the surfaces of pillars be parallel to the workspace's floor and roof **(Holland, 1973; Winton, 1999; York et al., 2000; Ataei, 2015).**

2.5. Rock type

Materials and rock types also affect the pillar's strength. Pillars can carry more loads when the surrounding rocks are stronger and vice versa. This means the probability of instability will increase when surrounding rock types are weaker, forcing pillar to bear more loads **(da Silva et al., 2013; Kaiser et al., 2011; Martin and Maybee, 2000; Winton, 1999).**

2.6. Key strata

Key strata are rock layers that controls the movement of the majority or all of the upper layers. Key strata bear upper layers' weight and play an essential role in the stability of underground structures. Jointed rock mass has

Table 1: Literature on effective parameters in pillar design over the past decade

Researcher	Year	Examined parameters	Study Method	Ref.
Kumar et al.	2019	Geology	Numerical	(Kumar et al., 2019)
Yao et al	2019	Geology	Experimental	(Yao et al., 2019)
Jeremic	2020	Geology	Experimental and Analytical	(Jeremic, 2020)
Sharma et al.	2021	Geology	Optimization	(Agrawal, et al., 2021)
Walton and Sinha	2021	Geology	Experimental and Analytical	(Walton and Sinha, 2021)
Yu et al.	2022	Geology	Experimental	(Yu et al., 2022)
Prassetyo et al.	2019	Engineering and Time	Experimental and laboratory	(Prassetyo et al., 2019)
Poulsen	2010	Engineering and Geology	Analytical	(Poulsen, 2010)
Kaiser et al.	2011	Engineering and Geology	Experimental and Numerical	(Kaiser et al., 2011)
Wattimena et al.	2013	Engineering and Geology	Experimental	(Wattimena et al., 2013)
Zhou et al.	2015	Engineering and Geology	Fuzzy	(Zhou et al., 2015)
Li et al.	2015	Engineering and Geology	Numerical	(Li et al., 2015)
Meng et al.	2016	Engineering and Geology	Experimental and Numerical	(Meng et al., 2016)
Reed et al.	2017	Engineering and Geology	Experimental	(Reed et al., 2017)
Mark and Agioutantis	2019	Engineering and Geology	Experimental	(Mark and Agioutantis, 2019)
Singh et al.	2011	Engineering	Experimental	(Singh et al., 2011)
Ghasemi and Shahriar	2012	Engineering	Analytical	(Ghasemi and Shahriar, 2012)
Verma et al.	2014	Engineering	Review, Analytical and Numerical	(Verma et al., 2014)
Shaojie et al.	2016	Engineering	Experimental and Analytical	(Shaojie et al., 2016)
Wang et al.	2020	Engineering	Experimental and Analytical	(Wang et al., 2020)
Deng et al.	2021	Engineering	Analytical and Numerical	(Deng, 2021)
Kumar et al.	2021	Engineering	Optimization	(Kumar et al., 2021)
Wang et al.	2020	Engineering	Analytical	(Wang et al., 2020)
Zhang et al.	2018	Engineering and mining	Numerical	(Zhang et al., 2018)
Zhang et al.	2017	Mining	Numerical	(Zhang et al., 2017)
Wang et al.	2017	Mining	Numerical	(Wang et al., 2017)
Wang et al.	2011	Mining	Numerical	(Wang et al., 2011)
Xia et al.	2021	Mining	Numerical	(Xia et al., 2021)
Duan et al.	2021	Mining	Experimental	(Duan et al., 2021)
Ardehjani et al.	2024	Mining	numerical	(Ansari et al., 2024)
Peng	2015	Engineering, Geology and mining	Review paper	(Peng, 2015)
Zulfahmi et al.	2023	Engineering, Geology and mining	Numerical	(Zulfahmi et al., 2023)

almost a negligible value of tensile strength. This indicates that rock mass failure begins with tensile failure (Qian et al., 2003). One or more key strata may affect the roof layers' displacement in an underground mine, the extent of this effect depends on the key strata thickness, rock's material and strength, number of key strata, and their distance from the immediate roof above the Gob. When the thickness of the key strata is less, the amount of roof displacement depends on the key strata strength and other surrounding layers. If layers mechanical properties are weak, more load is applied to pillars and subsequently instability risk in pillars will increase **(Bieniawski, 1986; Ju and Xu, 2013; Li et al., 2018; Kuang et al., 2019).**

2.7. Confining pressure

Based on all failure criteria, specimen strength will increase following an increase in confining pressure. Also, applying confining pressure causes changes in some rock mechanical properties, such as the Poisson's ration and Young module. It is possible to define a central (inner) and outer part for every pillar. The outer part must have the necessary conditions to apply appropriate confining pressure on the inner part to prevent possible deformations. The value of this confining pressure applied to the pillars inner part can be calculated using theories presented in the literature **(Ardehjani et al., 2020; Ataei, 2015).**

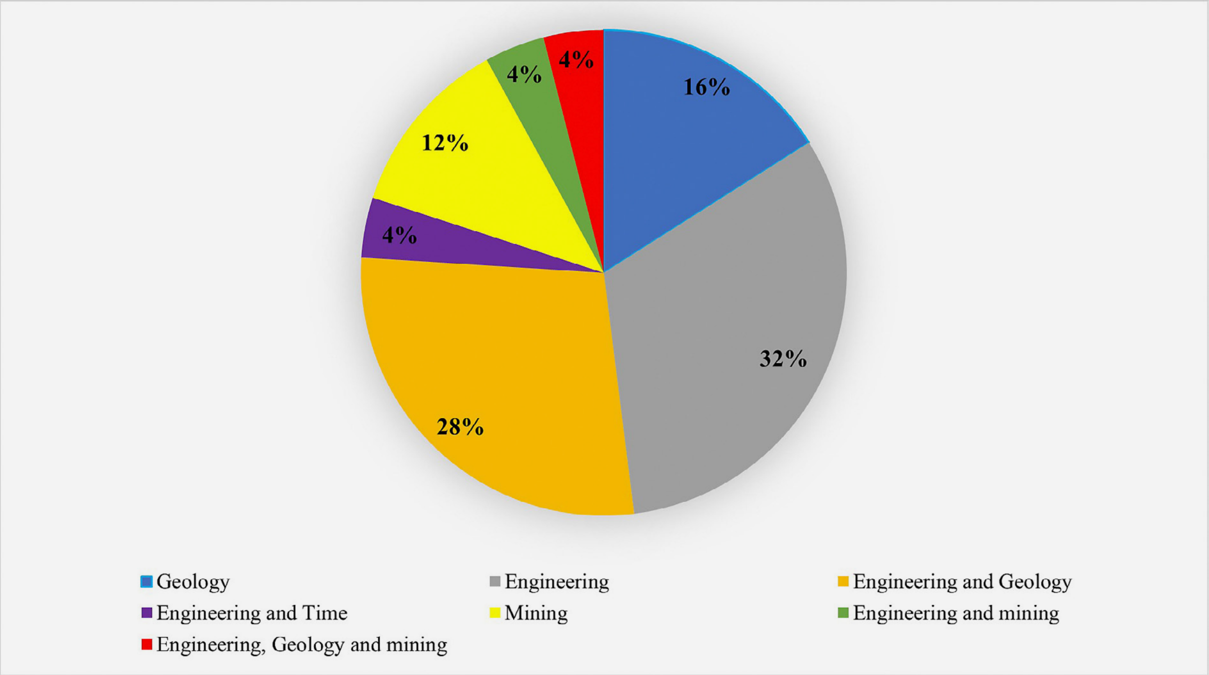


Figure 3: The percentage of examined parameters in pillar design over the past decade

2.8. Inclined layers

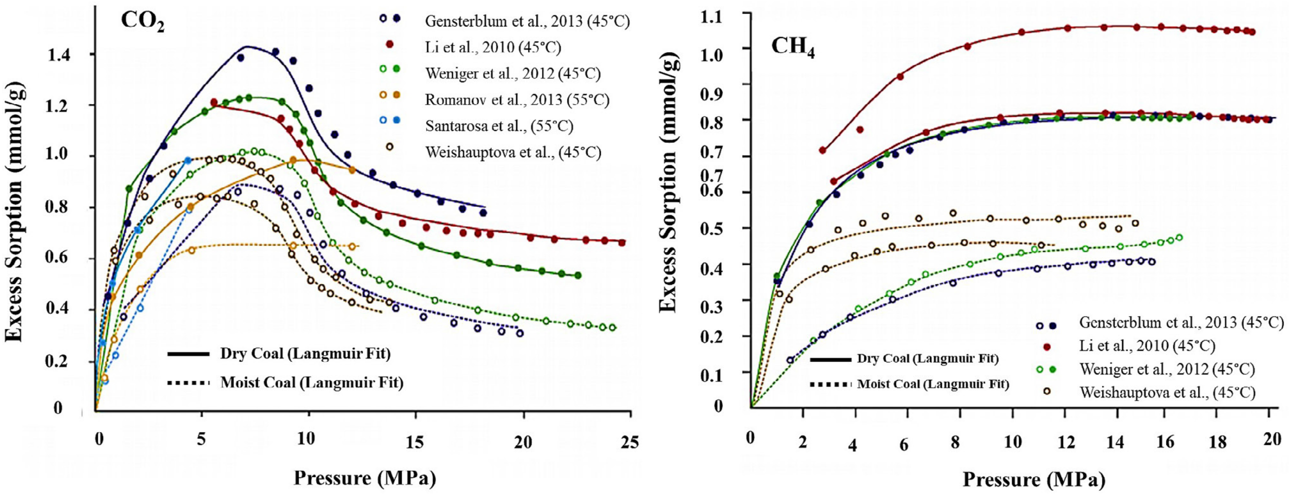
In inclined layers, increasing the layer's slope increased applied shear stress on pillars. As a result, the probability of pillar shear failure is increased. It should be noted that, with increasing the layer's slope, the amount of roof vertical displacement will decrease, and pillars will experience more overburden load. Thus, for inclined pillar design one shall consider larger dimensions for pillars to bear overburden loads **(Ataei, 2015; Ardehjani et al., 2020; Ardehjani et al., 2021).**

By examining the trend of studies on mine pillars stability in recent years, it is clear majority of methods and studies **(Mark and Agioutantis, 2019)** are concentrated on parameters such as geological conditions and parameters **(Kumar et al., 2019)**, engineering designs **(Shaojie et al., 2016; Wang et al., 2020)**, the impact of mining process on the mine opening, and pillars stability **(Zhang et al., 2017; Xia et al., 2021)**, the impact of time on the pillars deformation and bearing capacity **(Prassetyo et al., 2019; Wang and Cai, 2021)**, pillar's rocks material and type **(Choudhary et al., 2021; Walton and Sinha, 2021)**, and other parameters that are explained before in more detail. A list of research studies on effective parameters for pillar design, and researchers with the most citations in this field over the last decade, are listed in **Table 1**. In this table, parameters are classified and examined in several main groups: geology, engineering, geology and engineering, and mining. Geology parameters include things such layer's slope, confining pressure, important strata, rock type, joints and faults, and the geometry of a mineral deposit. mining parameters are including, the type of mining methods. Engineering parameters are including panel dimension, pillar dimension, advanced rate etc. It is evident from the literature that geological and engineering parameters are influential on stable and optimal pillar design. The percentage of studied parameters for pillar design over the past decade is shown in **Figure 3**.

According to **Figure 3**, most of the research studies were conducted to investigate the effects of engineering, engineering and geology, and geology parameters, respectively. These parameters have the most significant impact on each other in designing underground spaces; subsequently, to perform a safe, stable, and economical design, these parameters impact on each other shall also be examined. To construct an underground space, Earth provides construction raw materials for engineers; thus, these raw materials cannot be changed. To deal with these conditions, engineering designs must be made in such a way as to meet the geological conditions of the area, including rocks type, joints and cracks, groundwater, and other items. Therefore, most of the research has been carried out to investigate the effect of engineering and engineering and geology parameters on the stability of pillars and underground spaces.

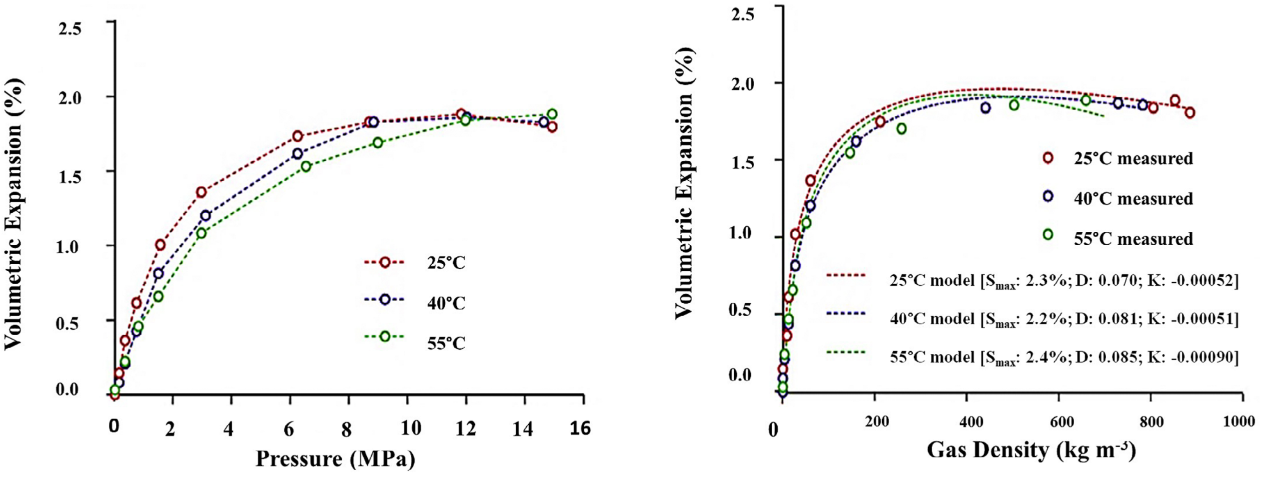
3. Coal pillars design

In underground coal mines, to ensure the stability of excavated spaces during mining operations, pillars are designed from coal or surrounding rocks. Coal pillars design is exactly the same as other mine pillars; also, the parameters mentioned in **Figure 2** are considered in their design. In addition to mentioned parameters for coal pillar design, for the first time in 2017, Do et al.



(a) (b)

Figure 4: The maximum volume of gas adsorbed by wet and dry coal specimens at different pressures for CO_2 and CH_4, respectively in Figures (a), and (b) (**Mukherjee & Misra, 2018**)



(a) (b)

Figure 5: Coal volumetric swelling in exchange for increased CO_2 adsorption as a function of a) pressure and b) density at different temperatures (**Day et al., 2008**).

studied the effect of CO_2[1] adsorption on coal pillars and walls stability in abandoned coal mines. This study aimed to evaluate the feasibility of CO_2 sequestration in abandoned coal mines. According to this study, following CO_2 adsorption, coal pillars wall become unstable, and the possibility of roof collapse and ground subsidence increases. They revealed that CO_2 adsorption reduces mechanical properties, including coal's strength and modulus of elasticity; as a result, the probability of instability in coal pillars increases **(Du et al., 2017).**

This study raises questions as to whether gas type affects the values of mechanical properties? Will only gas adsorption cause these variations? Do gas emissions also result in changes in coal mechanical properties? Answering these questions requires investigating coal behavior after various gases adsorption and emission; therefore, literature of research on coal behavior during different gases adsorption and emission is examined.

4. Analysis of gas emission and adsorption impact on coal structure

Based on studies, following gas adsorption and emission coal swells and shrinks, respectively. According to research, this deformation due to gas adsorption and emission exposes coal to changes in mechanical properties; adsorption of higher sorption gases such as CO_2 and CH_4[2] dramatically reduces coal strength and its modulus of elasticity. Major studies on the effect of gas adsorption and emission on coal mechanical properties were carried out in CO_2 sequestration in coal or enhanced coal bed methane (ECBM) technique by injecting fluids such

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[1] Carbon Diacid

[2] Methane

as CO_2, N_2, and brine. Therefore, most research and studies in this field have been carried out on ECBM and CO_2 sequestration. This research generally concentrates on the processes and principal parameters affecting CH_4 recovery and CO_2 sequestration discussed below.

Global desire for the CO_2-ECBM technology has revealed that coal swelling following CO_2 adsorption markedly reduces coal permeability. A recent study by Liu et al. In 2017 concluded that in CO_2-ECBM process, the rate of coal swelling following CO_2 adsorption is significantly higher than the amount of shrinkage due to CH_4 emissions s **(Fokker and Van Der Meer, 2003; Fujioka et al., 2010; Liu et al., 2017).** To avoid the reduction of coal permeability following CO_2 adsorption, N2 gas injection during CO_2 injection has been proposed and implemented. N2 injection reduces the stress near the injection well; it also helps to improve permeability reduction associated with CO_2 injection. Nevertheless, some researchers believe this method is not practical because the whole process is time-consuming **(Fujioka et al., 2010; Pan and Connell, 2012).**

To better understand the impact of gas adsorption and desorption on coal mechanical properties, initially one needs to become familiar with adsorption and desorption processes. Adsorption is a physical and chemical process described as the adhesion of particles from one phase to the surface of another phase. The reverse of this process is known as desorption (emission). Adsorption is based on adsorption forces and energies, classified into physical and chemical adsorption **(Ruthven, 1984).**

As mentioned earlier due to gas adsorption and emission coal swells and shrinkages, respectively. As a result of this swelling and shrinkage, coal volume will change, and coal will experience a volumetric strain (**Figure 4**). Volumetric strain is defined as volume changes with respect to the initial volume of a specimen **(Larsen, 2004; Pan and Connell, 2007)**. It should be noted that the penetration of CO_2 in the coal matrix at higher pressure causes structural changes and rearrangement; coal's response to gas penetration is to change its structure to a more stable structure and more resistant to further gas penetration s**(Karacan, 2003; Karacan, 2007; Kelemen and Kwiatek, 2009 ; Day et al., 2011; Liu et al., 2016).**

There are various methods to measure coal volume changes, including dilatometric, optical, and direct strain measurements at high pressures. Typical volumetric strain profiles for pressure and compression stress are illustrated, in **Figures 5a** and **b**, respectively. The coal swelling increases with increasing pressure; and then the curve reaches a plateau, which indicates the end of swelling **(Day et al., 2008).**

Experimental data cleared that the highest swelling in coal structure following gas adsorption is for CO_2, then CH_4 adsorption, respectively. At the same time N_2 absorption causes the least amount of swelling in coal structure, actually it is close to zero (**Figure 6**) **(George and Barakat, 2001)**. After noble gases adsorption, such as helium in coal structure, swelling won't occur **(Day et al., 2008)**. The CO_2 / CH_4 swelling ratio is significantly high, and this rate has been reported to being higher at low pressures (<1 MPa). This ratio converges at 2:1 at higher pressures (12-15 MPa). Day et al. in 2012 reported that, gas injection with a combination of 20% CO_2 and 80% CH_4 causes additional swelling of about 50% compared to the injection of pure CH_4 in the coal specimen **(Day et al., 2012).** Swelling depends more on the injection pressure and composition of injected gas than on applied pressure on the specimen.

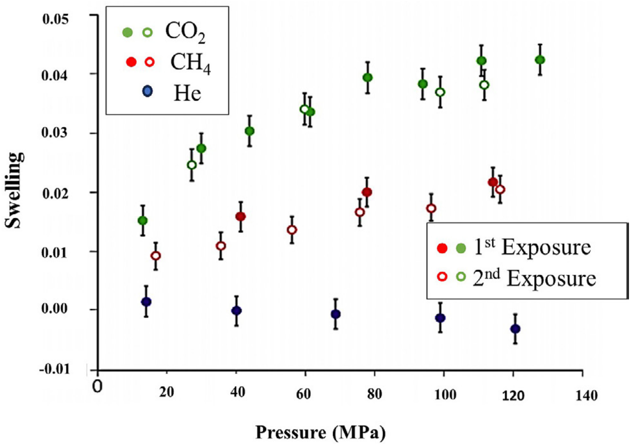

Figure 6: The Coal volumetric swelling under the influence of CO_2, CH_4 and He with increasing gas pressure at 45 ° C **(George and Barakat, 2001)**

5. Affecting parameter on coal deformation following gas absorption and emission

The capacity and amount of gas adsorption and emission by coal depend on several parameters. Based on researchers' studies, it is possible to classify these parameters into two groups, intrinsic and non-intrinsic parameters. Intrinsic parameters depend on coal intrinsic properties which are uncontrollable, while non-intrinsic parameters depend on external factors and thus are controllable. These two groups of parameters are classified in **Figure 7**. These parameters are examined based on previous studies as follows. Because these parameters impact each other, all of them are discussed together, so they have not been examined separately.

The temperature has an opposite effect on coal swelling due to gas absorption **(Day et al., 2008)**. Temperature increase will reduce the volume of adsorbed gas by coal, and as a result, induced strain due to gas adsorption will reduce **(Day et al., 2010).**

Moisture reduces coal's inducted swelling following CO_2 and CH_4 adsorption, and the intensity of this reduction for CH_4 adsorption is more remarkable than CO_2 **(Day et al., 2011)**. Saying that, in general swelling due

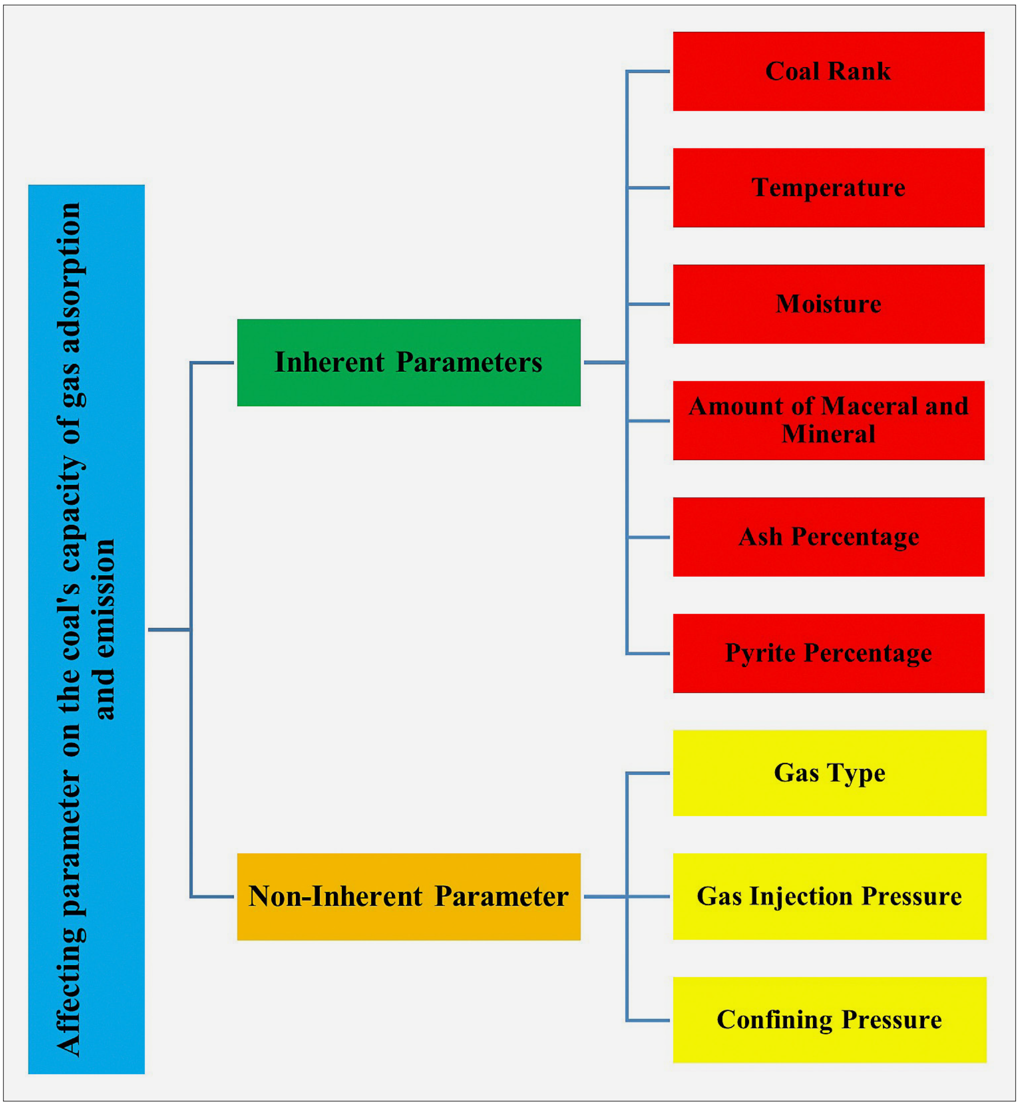

Figure 7: Affecting parameter on coal's capacity of gas adsorption and emission

to CO2 and CH_4 absorption in wet coals is less. However, the sum of induced swelling and strain following gas adsorption in moisture coal is more noticeable than in dry coal. Laboratory experiments revealed that, with coal rank decreasing, swelling due to gas absorption will increase **(Day et al., 2008)**. **Figure (8)** shows that the complete replacement of CH_4 by CO_2 creates double strain in sub-bituminous coal compared to bituminous coal **(Karacan, 2007; Durucan et al., 2009)**. This means that, increasing coal rank causes more minor changes in coal structure due to gas adsorption.

Walker et al. Reported in 1988 that under similar laboratory conditions, volumetric swelling due to CO_2 adsorption was lower than the volume of adsorbed CO_2 **(Walker et al., 1988)**. Cui et al. In 2007, experimentally determined volume swelling due to gas adsorption was linearly related to the volume of adsorbed gas **(Cui et al., 2007)**. Day et al. in 2008, reported at low pressures, the volume of gas adsorption is more significant than swelling, but in the range of medium pressures this volume becomes linear **(Day et al., 2008)**. Reasons for the non-linearity relationship between coal swellings following gas adsorption in different pressure ranges are not yet well understood. Adsorption causes structural saturation and may be attributed to the end of swelling. Coal with a High-absorption capacity necessarily isn't coal with high-swelling ability. The maximum adsorption capacity also isn't proportional to maximum swelling ability **(Day et al., 2010)**. Harpalani and Chen reported in 1995, that although adsorption is nonlinear, swelling is linearly related to gas injection pressure at low pressures **(Harpalani and Chen, 1995).**

The amount of minerals, ash, and pyrite have the same impact on gas value adsorption. If the amount of these impurities is more, the volume of gas adsorption will decrease; as a result amount of coal mechanical properties changes, and gas emission from the coal will decrease **(Laxminarayana and Crosdale, 1999; Laxminarayana and Crosdale, 2002; Weniger et al., 2010; Weniger et al., 2012).**

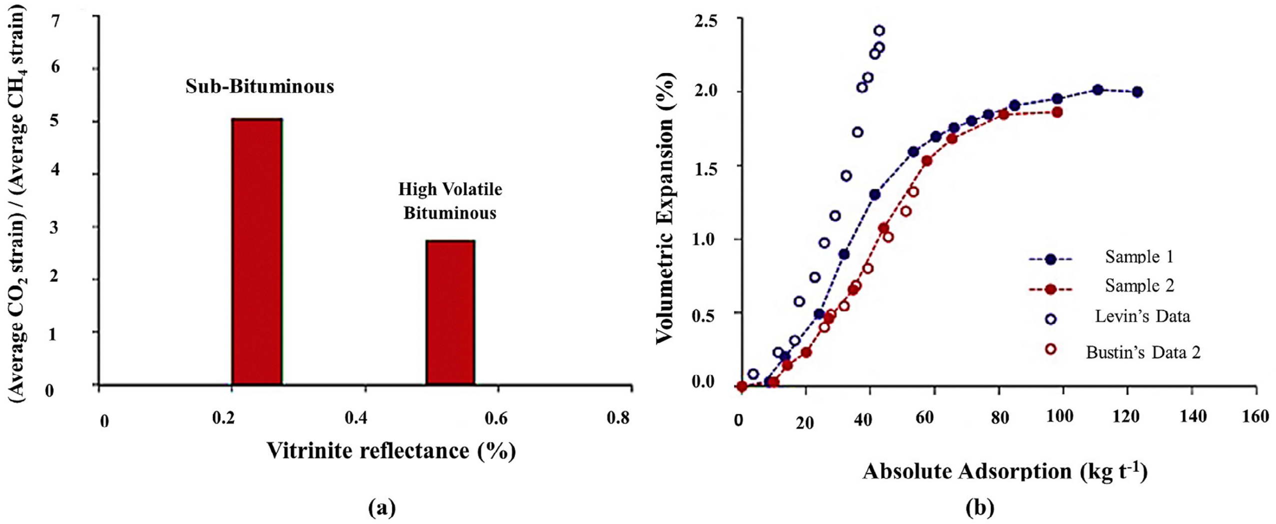

Figure 8: a) Average strain ratio of CO_2 / CH_4 in two coals with different ranks **(Robertson and Christiansen, 2005). b)** Indicates the relationship between volumetric swelling and absolute CO_2 adsorption in coal **(Day et al., 2008).**

Most previous studies have been carried out on CO_2 adsorption and sometimes CH_4 adsorption and its effect on coal structure. These studies have shed light on both CO_2 sequestration and ECBM methods. It should be noted that, studies on the impact of gas emissions especially CH_4 emissions, on coal structure and mechanical properties in minable layers and during mining operations have been rarely carried out, and major studies are on un-minable seams or abandoned mines. Considering that after gas adsorption and emission from coal specimens, its structure changes, and following this deformation, new joints and cracks are generated in its structure; The question arises, how much the gas adsorption and emission will alter coal's mechanical properties. To answer this question, we can refer to the literature and research background.

6. Investigating various gases adsorption and emission impact on coal mechanical properties

Most studies on gas adsorption and emission impact on coal mechanical properties are about the feasibility of CO_2 sequestration and ECBM method. Because these methods are mainly performed in un-minable layers or abandoned mines, most studies are conducted as triaxial test experiments. By simulating deep earth conditions and saturating specimens with different gases, mechanical properties change in depth conditions after gas adsorption can be investigated. In the following, several studies on gas adsorption impact on coal mechanical properties are discussed.

Based on studies, mining engineers believe coal mechanical properties depend on the value of gas in the coal seam. In 1957, Ettinger et al. investigated the impact of CO_2, CH_4, and He adsorption on coal specimens' compressive strength. They realized that, CO_2 and CH_4 adsorption impact on coal specimens' strength are more significant than He adsorption; this is only related to the inherent active surface of CO_2 and CH_4 molecules relative to He. Consequently, CO_2, CH_4, and He absorption impact on coal mechanical properties is as $CO_2 > CH_4 >$ He. If, after the failure of gas saturated specimen, crushing particle dimensions are smaller, it means gas absorption has more significant impact on the specimen's compressive strength **(Ettinger et al., 1957).**

As a result of fractures and joints expanding and generation new discontinuities in the coal structure, CO_2 absorption by coal will weaken the coal seam mechanical properties. Also, The mechanical properties of coal seams will decrease as a result of an increase in methane emissions **(Aziz and Ming-Li, 1999; Du et al., 2017)**.

Ates and Barron in, 1988, studied CO_2 saturated adsorption impact on coal specimen strength at a pressure of 3.45 MPa. Also found, coal specimen strength had reduced by about 14% (**Ates and Barron, 1988**). In 2006, Ranjith and Vieté investigated the effect of CO_2 saturated adsorption on the mechanical properties of brown coal. According to this study, CO_2 saturation will reduce uniaxial compressive strength (UCS) by 13% and deformation modulus (E) by 26% in brown coal **(Viete and Ranjith, 2006).**

Ranjith and Perera, in 2012 used experimental tests to measure lignite and bituminous coal specimen strength changes under CO_2 saturation at pressures of 1, 2, 3, and 16 MPa, to investigate the impact of coal cleats density and angle on coal strength reduction rate. Accordingly, coal specimen saturation with CO_2 under 3 MPa pressure will reduce coal strength. In this saturation pressure the reduction of bituminous coal's strength is 4.5 times more than lignite coal. Bituminous and lignite coal strength reductions are 43% and 9.6%, respectively. Coal compressive strength decreasing for CO_2 saturation pressures in the range of 1-3 MPa, has a linearly falling trend. As the saturation pressure increases with a steeper slope, coal strength decreases. It should be noted, that this diagram slope is higher for bituminous coal than lignite coal. In other words, increasing CO_2 saturation pressure will increases the impact of CO_2 adsorption on coal strength **(Ranjith and Perera, 2012).** Increasing CO_2 saturation pressure increases coal gas adsorption capacity. Coal CO_2 adsorption capacity is proportional to the coal swelling matrix. Saturation pressure increasing will increase the amount of swelling and redistribute coal structure, which will significantly reduce coal mechanical properties **(Bae and Bhatia, 2006; Ranjith and Perera, 2012)**. As shown in **Figure 9a**, following CO_2 saturation in the injection pressure range from 1 to 3 MPa, bituminous coal has a 20% greater reduction in UCS strength than lignite. **Figure 9b** shows the best fitting curve on the uniaxial compressive strength reduction graph, following CO_2 saturation.

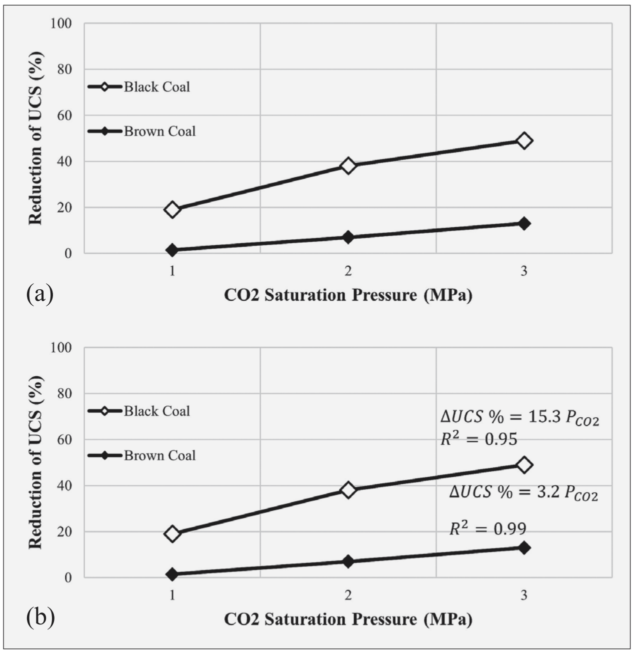

Figure 9: Comparison of uniaxial compressive strength reduction in bituminous and lignite coals **(Ranjith and Perera, 2012)**.

Perra et al. in 2013, saturated bituminous coal with CO_2 at 6 MPa injection pressure; then found that uniaxial compressive strength (UCS) and modulus of deformation (E) reduced by 53% and 36%, respectively. While increasing axial pressure to 8 MPa reduced UCS and E by 79% and 74%, respectively **(Perera et al., 2013).** Following CO_2 adsorption coal cohesion will decrease, and coal will fail in the direction of its Cleats. In addition to coal internal friction angle partly will reduce **(Liu et al., 2015)**.

The CO_2 flow rate in coal specimens, during applying axial pressure, initially decreases with increasing axial strain, while after specimen failure initially flow intensity increases sharply, then drops to a moderate level. This trend shows that by applying pressure, coal's joints and cracks are closed; in other words, the amount of permeability will decrease with increasing axial pressure. To determine the rate of coal strength change following CO_2 adsorption, the CO_2-saturated specimen stress-strain diagram is compared with a standard sample under identical loading conditions **(Viete and Ranjith, 2006)**. Thus, when a coal pillar is exposed to CO_2 adsorption, its strength decreases. Due to stresses induced by swelling, coal pillars will swell perpendicular to bedding; as a result, stress required to pillar failure will reduce **(Du et al., 2017).**

Based on studies, CO_2 adsorption reduces coal's strength under in-situ stress conditions. CO_2 is suspended in voids inside coal texture, dissolved in liquids in these voids, and adsorbed and trapped as surface adsorption inside coal. Coal CO_2 adsorption potential doesn't only depend on the adsorbent and absorbed chemical properties; several factors such as coal moisture content and coal surface rates to coal specimen's size are also involved in the acceleration of adsorption **(Viete and Ranjith, 2006).** In addition to mentioned factors such as axial and confining pressure, gas injection pressure, coal moisture content, cleats density, direction, and slope are also involved in reducing coal strength. When CO_2 enters in coal structure, it initially enters in cleats system and sits on cleats walls as a result coal strength is reduced **(Viete and Ranjith, 2007).** When, joint direction tends from 70 degrees to 20 degrees, bituminous coal strength following CO_2 adsorption by about 20%, will be reduced. Coal strength decreases at a slower rate as the slope of cleat's length decreases **(Ranjith and Perera, 2012).**

Based on the conducted research studies following gases adsorption and emission such as CO_2 and CH_4 in coal structure, coal mechanical properties generally will decrease. Most studies are carried out on two processes of CO_2 sequestration and methane gas recovery using ECBM. These two processes focus more on the impact of CO_2 adsorption or CO_2 substitution instead of CH_4. However, less research has studied methane emission's impact on coal pillars' stability. Gas emissions will reduce coal strength due to creating joints and cracks. Studies on gas adsorption and emission effects on coal mechanical properties are given in **Table 2**.

The percentage of conducted studies by separating process types about the effect of the gas substitution, adsorption, and emission on coal mechanical properties over the past two decades are shown in **Figure 10**. The percentage and number of conducted studies by separating gas type about the effect of gas substitution, adsorption, and emission on coal mechanical properties over the past two decades are shown in **Figure 11**. According to these two figures, and **Table 2**, most research has been conducted on CO_2 adsorption and its impact on coal mechanical properties. These investigations have been prepared to understand the carbon dioxide sequestration process in the coal seam. Based on **Table 2**, 22 articles have been published on gas adsorption, while only four

Table 2: Literature on changes in the mechanical properties of coal during gas adsorption and emission

Researcher	Year	Studied Process	Gas Type	Coal Tyap	Studied Mechanical Prop.	Ref.
Aziz and Ming-Li	1999	Adsorption	CO_2, CH_4 and CO_2/CH_4	South Island, New Zealand	Strength	(Aziz and Ming-Li, 1999)
George and Barakat	2001	Adsorption	CO_2, $CH_{4,}$ N_2 and He	Bituminous	Volumetric Strain	(George and Barakat, 2001)
Farhang Sereshki	2005	Adsorption	CO_2 and CH_4	Brown Coal	Length and width strain, Strength and Permeability	(Sereshki, 2005)
Viete and Ranjith	2006	Adsorption	CO_2	Bituminous	Modulus of Elasticity, Strength and Permeability	(Viete and Ranjith, 2006)
Majewska et al.	2010	Adsorption	CO_2 and CH_4	Bituminous	Volumetric Strain	(Majewska et al., 2010)
Ranjith et al.	2010	Adsorption	CO_2	Lignite	Strength	(Ranjith et al., 2010)
Perera et al.	2011	Review Paper	CO_2	Bituminous and Lignite	Mechanical Prop.	(Perera et al., 2011)
Ranjith and Perera	2012	Adsorption	CO_2	Coal	Strength	(Ranjith and Perera, 2012)
Masoudian et al.	2013	Adsorption and Substitute	CO_2 and CH_4	Coal	Mechanical structure change and permeability	(Masoudian et al., 2013)
An et al.	2013	Emission	Coal gas	Coal	Strength and Permeability	(An et al., 2013)
Wang et al.	2013	Emission	CO_2 and CH_4	Coal	Permeability	(Wang et al., 2013)
Wang et al.	2013	Adsorption	CO_2 and CH_4	Coal	Modulus of Elasticity, Strength and Permeability	(Wang et al., 2011)
Masoudian et al.	2014	Adsorption	CO_2	Coal	Strength and Modulus of Elasticity	(Masoudian et al., 2014)
Perera	2014	Adsorption	CO_2	Coal	Modulus of Elasticity, Strength and Permeability	(Perera, 2014)
Hol et al.	2014	Adsorption	CO_2, CH_4, N_2 and He	Coal	Modulus of Elasticity, Strength and Bulk Modulus	(Hol et al., 2014)
Bagga et al.	2015	Adsorption	CO_2	Coal	Strength	(Bagga et al., 2015)
Bin Fei et al.	2015	Adsorption	CO_2	Coal	Mechanical Prop	(Fei et al., 2015)
Masoudian	2016	Review Paper	CO_2	Bituminous and Lignite	Mechanical Prop.	(Masoudian, 2016)
Perera et al.	2016	Adsorption	CO_2 and$_{,}$ N_2	Lignite	Strength and Modulus of Elasticity	(Perera et al., 2016)
Ranathunga et al.	2016	Adsorption	CO_2	Coal, Sandston, mudstone	Strength and Modulus of Elasticity	(Ranathunga et al., 2016)
Wang et al.	2017	Adsorption	CO_2 and He	Bituminous	Strength and Modulus of Elasticity	(Wang et al., 2017)
Du et al.	2017	Adsorption	CO_2	Coal	Strength and Modulus of Elasticity	(Du et al., 2017)
Mukherjee and Misra	2018	Review Paper	CO_2 and CH_4	Bituminous	Mechanical Prop.	(Mukherjee and Misra, 2018)
Qin et al.	2018	Adsorption and Emission	CH4 and N_2	Coal	Mechanical Prop	(Qin et al., 2018)
Meng and Qiu	2018	Adsorption and Substitute	CO_2	Coal	Strength	(Meng and Qiu, 2018)
Lu et al.	2019	Adsorption and Emission	CH_4	Bituminous	Strength	(Lu et al., 2019)
Zhang	2019	Adsorption	CO_2	Bituminous	Strength	(Zhang et al., 2019)
Sampath et al.	2019	Saturated	Brine and CO_2	Coal	Mechanical Prop	(Sampath et al., 2019)
Su et al.	2020	Adsorption	CO_2	Coal	Strength	(Su et al., 2020)
Sampath et al.	2020	Review Paper	CO_2	South Island, New Zealand	Mechanical Prop.	(Sampath et al., 2020)
Liu et al.	2021	Adsorption	Liquid CO_2	Coal	Permeability	(Liu et al., 2021)
Zhang et al.	2024	Adsorption	CO_2, CH_4 and N_2	Bituminous	Mechanical Prop.	(Zhang et al., 2024)

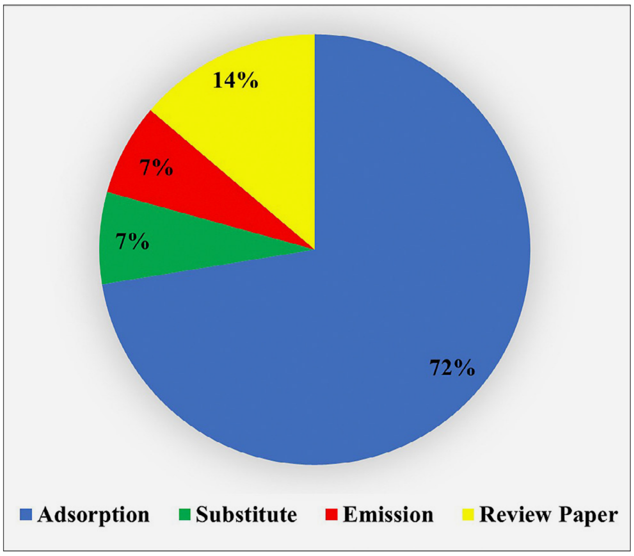

Figure 10: The percentage of conducted studies by separating the process on the impact of gas substitution, adsorption, and emission on coal mechanical properties over the past two decades

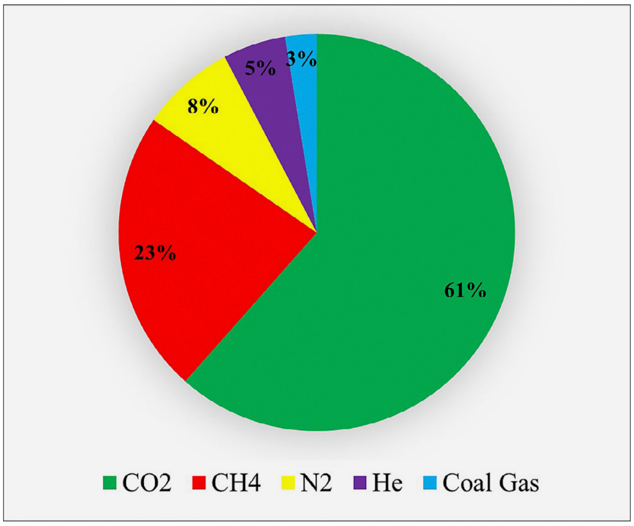

Figure 11: The percentage of conducted studies by separating the gas type on the impact of gas substitution, adsorption, and emission on coal mechanical properties over the past two decades

articles studied gas emission and gas substitute; also, four review papers have been conducted to study all processes. Furthermore, twenty-nine articles critically study CO_2 adsorption and emission impact on coal mechanical properties, and = nine research studies investigated the impact of CH_4 adsorption and emission on coal mechanical properties. Among all of this research, only one article focused on coal gas.

7. Discussion

Numerous scholars have looked at the impact of CO_2 adsorption on coal's mechanical properties, as shown by **Table 2** and **Figure 10**. Today, it is very typical that there are a lot of published studies in this topic due to the widespread practice of CO_2 sequestering in unmineable or abandoned mines to store this greenhouse gas, handle environmental issues, and lower the danger of global warming. Gas is released from walls and coal pillars in abandoned coal mines after a period of time when CO_2 gets trapped. Previous discussions indicate that this event will contribute to a decrease in the strength of the coal pillar. As a result, examining the impact of the gas emission process is crucial, but owing to the volume of research, this has received less attention.

One strategy for the most efficient use of coal mines is the recovery and use of coal gas as fuel, given the importance of fossil fuels and the high cost of natural gas. There are various coal gas recovery techniques, sometimes known as coal bed methane recovery, or CBM techniques. The ECBM method is one of the most advanced techniques for draining coal gas from a seam. It involves injecting gas or liquid, such as brine or CO_2, to awaken and remove coal gas. Injecting CO_2 into the coal seam is the most popular ECBM technique. It is advised to operate in coal seams that cannot be mined. However, this method can be applied in minable layers where the coal seam has a considerable amount of gas, and gas drainage shall be performed before mining **(Kostenko et al., 2022; Lozynskyi et al., 2022; Najafi and Rafiee, 2019; Zapletal et al., 2018)**.

After CO_2 adsorption and release, the stability of the remaining pillars in abandoned mines will be crucial because pillar failure or instability after CO_2 adsorption will induce unanticipated ground subsidence. Only CO_2 and CH_4 adsorption has been the subject of research on the identification and application of this technique. It is important to note that the primary component of this coal gas recovery technique is the coal seams replacement of CO_2 for CH_4. According to some researchers, there is no need to investigate the effects of gas adsorption and replacement on the mechanical properties of coal because this process should be used in layers that are not suitable for mining. However, it has been observed in many cases that this method is used to drainage coal gas in minable layers, which will increase the outburst possibility in coal mines **(Masoudian et al., 2013).** Accordingly, the gas substitution process and its impact on coal mechanical properties shall be further investigated.

Changes in the mechanical properties of coal are linked to gas substitution, although this aspect has not gotten as much attention. The impact of CO_2 adsorption on the mechanical properties of coal has been the subject of all research; the impact of gas emissions and substitution on coal has received less attention. Field investigations are crucial because the majority of research has only looked at changes in the strength of coal specimens in laboratories.

The emission of coal gas from non-gas-drainage strata during mining operations weakens the surfaces formed for the opening of the mine panel, leading to unanticipated instability and a higher likelihood of an outburst. Coal seam strength is decreased by gas release, and as a result, the likelihood of an outburst in a mine will rise. Gas drainage from the coal seam causes additional joints and fissures to form in the coal mass structure in gasified strata. As a result, coal seam strength is reduced. To avoid instability in underground spaces, strength reduction should be taken into account while designing the pillars.

The impact of gas emissions on the mechanical properties of coal specimens has been the subject of relatively little research, and the impact of these emissions on the stability of underground spaces has not been examined at all. This raises the question of whether gas emissions have any impact on the stability of underground spaces.

Coal gas is released from the coal seam by opening a mining panel and installing coal pillars to stabilize removed areas because of the differential between air pressure and overburden pressure. Researchers claim that the emission of coal gas weakens the coal and walls and creates new fractures and fissures in the coal structure. The degree of coal strength reduction resulting from gas adsorption and emission must be studied, along with the factors that influence it. Design calculations should consider the magnitude of the reduction if it is significant.

An essential, useful, and creative first step in resolving the problem of unstable underground mines during mining is to look into how coal gas emissions affect the stability of underground areas during mining. The description of coal behavior during gas adsorption and emission provides the foundation for this. Furthermore, this criterion will be examined for the first time in the design of underground spaces. Because of this, it is advisable to do adequate study on the ways in which gas adsorption, substitution, and emission alter the mechanical properties of coal, with a focus on the effects of coal gas emissions on the stability of underground coal mine pillars.

8. Conclusions

While many elements and factors influence the construction of mine pillars, the most important ones that affect pillar stability are those related to engineering and geology. In addition to the above-mentioned factors, the type of gas, as well as its adsorption and emission, must be taken into account during the original engineering designs of coal pillars. Coal swells and shrinks during CO_2 and CH_4 adsorption and emission, respectively, according to numerous research findings. This distortion of the coal structure will lead to the development of additional cracks and joints. Coal mechanical properties are altered by the formation of new joints and cracks in the structure, which lowers the coal's strength and elastic modulus. The walls and pillars of underground coal mines will become unstable due to a decrease in the mechanical properties of coal. However, it should be noted that the magnitude of these coal mechanical properties changes depending on gas type, coal type, coal's joints and inherent cracks (cleats) patterns, layer depth, and other cases. Additionally, a more thorough analysis and measurement of the variations in the mechanical properties of coal in each coal location are required.

Because of the pressure differential between the air in the mine's roadways under overburden pressure and the coal texture, coal gas is discharged into mine panels throughout the mining process. Unpredictable weakening of the coal pillars and the formation of new joints and cracks are the main causes of coal gas emissions. Also, this can result in unanticipated collapses and explosions in underground coal mines. Therefore, for safe, appropriate, and cost-effective coal pillar dimensions and underground mine opening design, the calculation of coal mechanical properties after gas adsorption and emission following mining operation would be crucial.

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SAŽETAK

Ispitivanje utjecaja emisija plina iz ugljena na analizu stabilnosti stupova ugljena: kritički pregled literature

Nužna komponenta jamstva sigurnosti podzemnih rudnika ugljena jest stabilnost podzemnih prostorija. Stupovi ugljena ostavljaju se na mjestu u podzemnim rudnicima kako bi stabilizirali otkopane prostore gdje su iskapanja izazvala raspodjelu naprezanja na terenu. Dimenzije stupova konstruiraju se u skladu sa zahtijevanim sigurnosnim i ekonomskim ograničenjima. Različiti čimbenici utječu na sigurnu i isplativu konstrukciju stupova, posebno stupova pri eksploataciji ugljena. Ovoj temi nije posvećena dovoljna pozornost u literaturi. Svrha je ove studije podržati teoriju o utjecaju emisije metana na stabilnost stupova ugljena. Ispitani su i kategorizirani početni efektivni parametri konstruiranja stupa. Prvi put istražuje se utjecaj emisije plina iz ugljena na stabilnost krovine, stupova i bokova. U tu svrhu pregledana su prethodna istraživanja mehaničkoga ponašanja ugljena izloženoga različitim vrstama plinova. Pregled literature pokazuje da će se mehanička svojstva ugljena (posmična čvrstoća, modul elastičnosti i jednoosna tlačna čvrstoća) smanjiti kada je on izložen utjecaju plinova. Tekstura ugljena stvara pukotine i prsline kao rezultat adsorpcije i emisije plina, što smanjuje mehanička svojstva ugljena i uzrokuje nestabilnosti u podzemnim prostorijama. Zaključak pregleda literature sugerira da su emisije plinova iz ugljenih stupova i bokova najvjerojatnije uzrokovale nepredvidive nestabilnosti i gorske udare u nekim podzemnim rudnicima. Prema saznanjima i uvjerenjima autora nedostaju kritički pregledi literature o mehaničkim svojstvima ugljena tijekom emisije plinova pa ova studija daje doprinos u tome smjeru.

Ključne riječi:
mehanička svojstva ugljena, emisije metana, stabilnost stupova ugljena, adsorpcija i desorpcija plina, mehanika stijena

Authors contribution

Emad Ansari Ardehjani (Ph.D. Candidate): Compiler of all articles, author of the complete manuscript, and implementer of the research concept. **Mohammad Ataei** (Full Professor): Idea generator and commentator on the review section related to the effective parameters in the stability of coal pillar. **Farhang Sereshki** (Full Professor): Idea generator and supervisor on the drafting section related to the behavior of coal during gas absorption and emission. **Ali Mirzaghorbanali** (Senior Lecturer): Scientific editor and English language editor. **Naj Aziz** (Full Professor): Scientific editor and English language editor.