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Review article

Visualization and analysis of knowledge domains for recent developments in coal mechanical properties studies

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A R T I C L E I N F O

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A B S T R A C T

To better understand the research progress and trends in the mechanical properties of coal, and to promote theoretical research on the prevention and control of dynamic disasters, we employed the bibliometric method to analyze the research progress in this field. A total of 3450 documents from the Web of Science (WOS) core database were reviewed and analyzed. Our analysis focused on the annual distribution of literature, the distribution by country/region, organization, and author, as well as the distribution of significant source journals. We also identified research hotspots and frontiers. The results indicate a significant increase in the number of research papers on the mechanical properties of coal. China, America, Australia, India, Spain, Poland, England, Japan, South Korea, and Turkey were found to be the most active countries in this research area. The research results from China, America, and Australia were found to be the most influential, and C&BM, FUEL, INT J ROCK MECH MIN, INT J COAL GEOL, RM&RE, C&CR, and JCP were identified as the primary sources of research publications on the mechanical properties of coal. The basic theory and research system of coal mechanical properties investigation have been established, and there are numerous future research directions and areas to explore. Some current hotspots include the development of coal mechanical property models, permeability models related to mechanical properties, establishment and prediction of coal strength-temperature relationships, investigation of the proportioning scheme of granite and coal bottom ash in concrete mixes, and research on the improvement effect of fly ash on concrete manufacturing properties.

1. Introduction

Accurate assessment of the mechanical properties of coal is crucial for mining design, as it ensures progress and safety in deep coal mining [1,2]. Coal, being a solid material, possesses a well-developed pore system. The properties of these pores, such as size, connectivity, development degree, mineral matter, and coal matrix, greatly influence the mechanical properties of coal [1–7]. Research

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methods involve conducting laboratory tests, numerical simulations, and field studies to investigate coal's mechanical properties. These methods are similar to those used for studying the mechanical properties of other types of rocks. In this regard, the influence of pore structure, pore pressure-induced stress, and the effects of adsorbed gases on coal properties have attracted many scholars worldwide [8–11]. Coal is a typical defect-containing rock-like material, and its mechanical properties are very different from those of sandstone, mud, and shale. During the loading process, the tips of microfractures in coal are highly susceptible to stress concentration, leading to the expansion and destruction of main fractures [12,13]. To enhance coal mining performance, coal bed methane recovery, and mine safety, it is essential to thoroughly evaluate the mechanical properties of coal.

Earlier studies on coal mechanical properties focused on obtaining coal mechanical parameters and were limited to test methods and related services [14,15]. Recently, with the enrichment of technical test methods and related theories, the influence of factors such as adsorbed gas (such as methane and CO_2), mechanical pathways, surrounding pressure, temperature, various loading rates, anisotropies, and fluid intrusion on the mechanical characteristics of coal has been investigated [16–26]. An accurate assessment of these factors' effect on coal's mechanical parameters is essentially based on the direct or indirect loading of coal at different strain rates. These tests include creep loading in a very low strain rate range to obtain the plastic properties of coal, uniaxial and triaxial tests of coal (gas-bearing coal) at low strain rates to assess its quasi-static mechanical properties, low-velocity hammer impact loading and high strain rate impact loading tests to understand the dynamic mechanical characteristics of coal and its feedback, as shown in Fig. 1. Other tests, such as Brazilian splitting and bending tests, are also conducted. Existing studies show that coal strength is usually related to coal length-to-diameter ratio, coal type (raw vs. synthetic coal), the gas content of coal, and coal water content. For example, Van der Merwe [27] concluded that the coal strength has a linear correlation with the diameter-to-length ratio, decreasing exponentially with the size of test specimens. Meng et al. analyzed the deformation and strength and coal by triaxial compression tests, and experimental results showed that the difference in strength between the two is due to the size of the forming pressure and the influence of different binders [28].

The characteristics of coal are influenced by several factors, of which adsorbed gas and loading type are considered key factors. Results from uniaxial and triaxial tests on gas-bearing coals with different peritectural and pore pressures have demonstrated that adsorbed and free gases play a crucial role in influencing the deformation damage of gas-bearing coals, thereby impacting the relevant mechanical parameters and intrinsic relationships of the coals [20,21,29–36]. Larsen and Ranjith conducted several tests and analyzed the impact of CO_2 on the coal characteristics, and found that the strength and modulus of elasticity of CO_2 adsorbed by coal decreased significantly, with the difference originating from the pressure and the adsorbed CO_2 [37–40]. Using numerical simulation, Chen et al. analyzed the spatiotemporal changes in triaxial stress during coal mining within a protected layer. The study also considered the mechanical loading/unloading path an essential stress distribution factor. They then applied this law to laboratory experiments to investigate the evolution of coal body damage and permeability during the protected layer mining process [41]. With the widespread application of industrial CT, mechanical-permeability coupled property test characteristics, and mechanical simulation, the study of coal mechanical properties have entered the microscopic, multi-factor coupling, and numerical stages [1–3,12,41–57]. The fine-scale evolution mechanism of coal rupture, the analysis of coal mechanical behavior, the synergistic evolution mechanism of permeability behavior, and numerical mechanical experiments have attracted tremendous attention for investigating the mechanical features of coal subjected to high stresses.

The literature survey reveals that the majority of studies conducted on coal have primarily concentrated on a specific aspect, leaving a dearth of research on the present-day processes and trends in coal mechanical properties from a bibliometric standpoint. This paper aims to fill a gap in the field by employing quantitative and statistical methods to assess the published article. The objective of this approach is to investigate the present state of development, trending research topics, and emerging trends in a specific field. It is worth noting that this method has been widely applied in diverse applications [42]. For instance, Shao et al. visualized the coal pore space based on a bibliometric approach and concluded that molecular simulation, methane reservoir, and methane adsorption are the

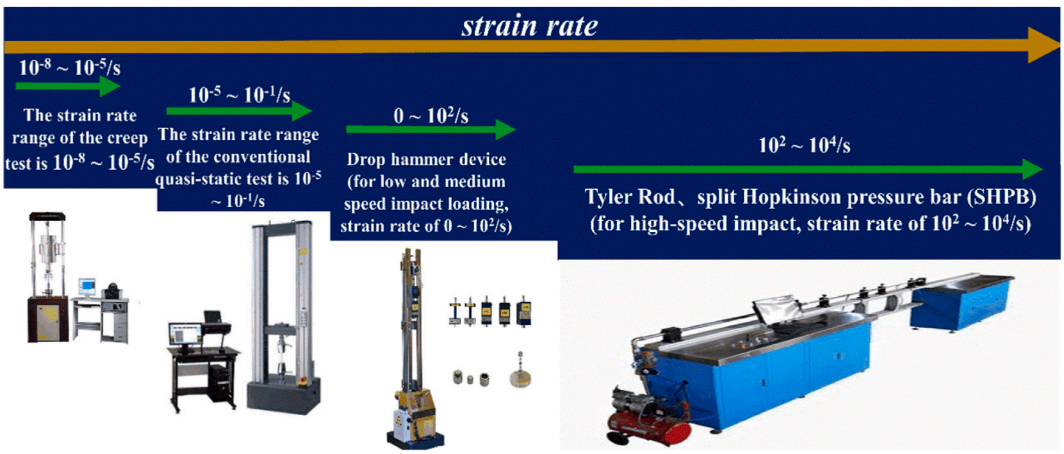

Fig. 1. Different experiment and their strain rate ranges.

frontier of research in this field [42]. Shi et al. assessed the current state of research in rock excavation using a bibliometric approach and identified rock damage constitutive models, excavation damage zones, numerical simulations, and rock prediction techniques as important research directions [58]. To comprehensively understand the research achievements and directions of coal mechanical properties, CiteSpace and Vosviewer methods were applied to analyze the article and identify research hotspots. This analysis summarized the critical issues in international coal mechanical properties research. Our study provides valuable references for those working at the forefront of this field, as it identifies scientific issues and suggests potential research directions.

2. Data and method

2.1. Database

The Web of Science (WOS) core collection was selected as the primary data source for this study. We used the search keyword 'Coal Mechanical Properties' and set the cut-off time as December 2022. Each record includes the author, institution, abstract, keywords, year of publication, date (volume), and references. To ensure the effectiveness and representativeness of the literature, we selected the 'article' literature type and excluded irrelevant literature and conference papers. The 3450 document records cover 9 types of documents, primarily articles (75 %), proceedings papers (20 %), and reviews (5 %) (see Table 1). It is important to note that some documents can be categorized into multiple types, resulting in the total number of document types used for counting exceeding the number of retrieved documents. Throughout the study, we focused on the top three ranked items: articles, proceedings, and reviews. As a result, 3450 articles were imported into CiteSpace and Vosviewer for visualization and analysis.

2.2. Tools and methods

CiteSpace Knowledge Graph, developed by Professor Chen CM of Drexel University, has recently been utilized in China and is a feature-rich software. It employs various visual techniques, such as keyword co-occurrence, organizational distribution, author collaboration, and document integration, to visualize and analyze subject boundaries and the status of knowledge associations.

VOSviewer (Visualization by Similarity) was developed by Dr. Neiss Jan Van Eck and Ludo Waltman of Leiden University Technology Center (CWTS) and is a tool that maps and builds scientific landscapes using reference data from different sources, including WOS, Scopus, and Dimension. VOSviewer employs a unified network mapping and clustering approach to measure networks scientifically. It supports different types of networks, such as co-author networks, co-citation networks, bibliographic map coupling, and citation network analysis.

3. Results and discussion

3.1. Trend analysis of annual publications

The number of relevant papers in the field of research on the mechanical properties of coal was 3450 (1997–2022), and the number of published papers and the three stages of development is shown in Fig. 2.

Initial Stage (1997–2010): Between 1990 and 2010, the annual literature output in the field of coal research was relatively low, peaking at only 68 works (see Fig. 3 (a, b)). During this time, scholars focused on the thermodynamic laws of coal combustion and pollution prevention and control, as coal was the primary fuel source. For instance, Fu et al. studied the combustion kinetic parameters of coke and the relationship between coal properties [14], while Sahan proposed a low-cost coal cleaning method through various experiments [59]. In 2010, Shahriar studied coal characteristics. This article considerably developed the investigations on the mechanical characteristics of rocks [29,60,61].

Stable Growth Stage (2011–2017): From 46 in 2011 to 193 in 2017, the literature output on coal characteristics displayed steady growth, indicating a deeper exploration stage. During this stage, the researchers investigated the relationship between the mechanical properties of coal and its local structure, chemical composition, and some external environmental changes, such as temperature changes, fluid filling, and gas adsorption properties, to improve the efficiency of coal processing and exploitation of the model [10,

Table 1
Types of retrieved documents in emergency evacuation studies.

Rank	Type of document	Documents	Proportion
1	Article	2582	0.74841
2	Proceedings paper	680	0.19710
3	Review	188	0.05445
4	Editorial material	17	0.00492
5	Correction	12	0.00348
6	Letter	3	0.00087
7	Meeting abstract	2	0.00058
8	Retracted publication	2	0.00058
9	News item	2	0.00058
Total	–	3488	>1

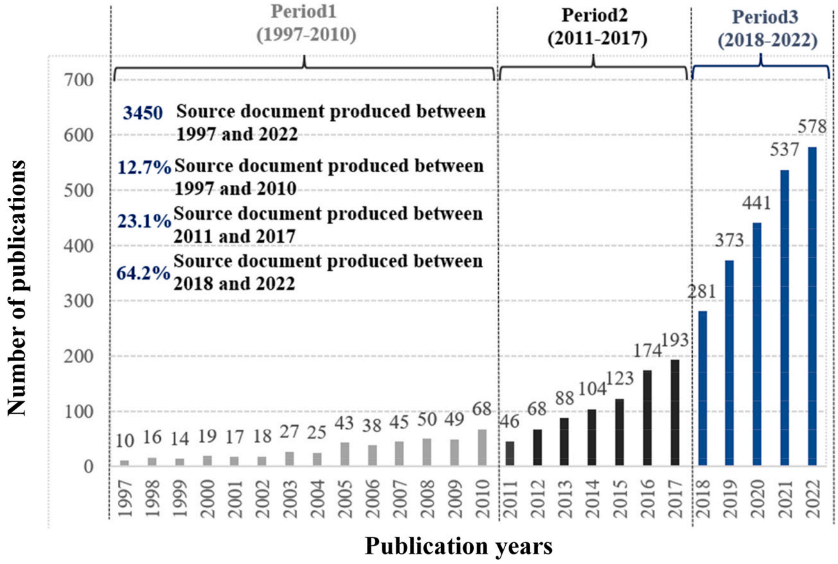

Fig. 2. Publication growth trends around the world.

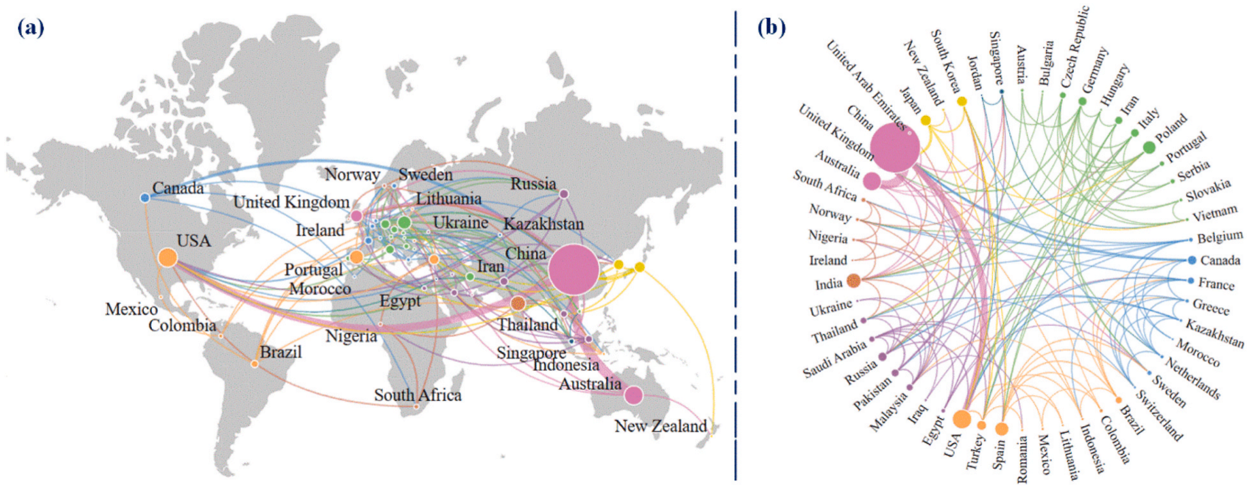

Fig. 3. Distribution of global publishing countries.

62–65]. In addition, efforts have been made to study the geo-mechanical properties of coal seams during CO_2 adsorption at underground stress conditions to enable the safe implementation of CO_2-enhanced coalbed methane (CO2-ECBM) recovery [10], and possible CO_2 storage aspects [11].

Rapid Development Stage (2018–2022): From 2018 to 2022, the annual literature output on coal characteristics increased significantly, marking a new stage of development. At this stage, the researchers focused on an in-depth study of various parameters and test conditions affecting the coal characteristics, including combined rock masses, acidic and alkaline fluids, load types, microwaves, repetitive fracturing, fracture distribution, etc. [7,13,23,25,26,28,38,44,52,66–84]. Moreover, with recent technological advances, researchers have used atomic force microscope (AFM), acoustic emission (AE), scanning electron microscopy (SEM), nanoindentation, three-dimensional computed tomography scanning (3D CT) modeling, and other tools to investigate the mechanical properties of coal, addressing challenges posed by the inaccessibility of direct observations [62,69,71,76,85,86]. Building on this foundation, research focused on computer simulations of the interaction between coal and related fluids (e.g., supercritical CO_2, water, gas) and further investigated the intrinsic model and damage mechanisms [12,86].

3.2. Leading countries and bilateral cooperation

Comprehending the spatial distribution depicted in academic papers pertaining to their respective research areas is a valuable asset for researchers as it enables them to discern important research trends within the field promptly. This understanding aids in absorbing research outcomes and fosters the development of scientific collaboration [87].

Table 2 shows that China, the United States, and Australia have the highest number of published articles in the field of study. Among the top ten countries, Australia, the United States, and Spain had the highest ACI index, implying a relatively high level of research in these countries. Although Chinese scholars ranked first in the world regarding the number of published papers, their ACI index was only 15.21, placing them in the ninth position. This indicates a need for improvement in the research recognition of Chinese scholars.

Furthermore, Table 2 displays the link strength data calculated by the VOS viewer. In Fig. 3(a, b), we can see a knowledge map of the co-authorship network in each country. Each node on the map represents a country, and the connections between nodes reflect the cooperation level. The strength of the connection reflects the robustness of the cooperation. Upon analyzing the data and map, we can conclude that China, Australia, and the USA have the highest total link strength and number. Countries with abundant indigenous coal resources are relatively more advanced in the research conducted in this area since coal is a consumer product.

3.3. Main organizations and institutes

Among the organizations listed in Table 3, China has the largest number of affiliated organizations with eight, while Australia and Spain each have one. Shandong University of Science and Technology ranks second with 165 publications, with a research focus primarily on sensitivity analysis of parameters of mechanical models, while Chinese Acad Sci ranks with 117 publications.

However, regarding ACI (Article Citation Impact), Consejo Superior de Investigaciones Científicas (CSIC) and Monash University are the top two, with scores of 27.1 and 23.1, respectively. This indicates that they strongly influence the academic community and possess first-class academic credibility.

The mapped knowledge domains organized by co-authoring are depicted in Figs. 4 and 5. It is observed that the China University of Mining and Technology and Shandong University of Science and Technology are identified as two of the most closely cooperative research institutions.

3.4. Main source journals and co-citation analysis

The top ten publications in the field of study are presented in Table 4. The data included journal titles, countries, overall connectivity, Citation Index, and impact factor.

The co-citation of journals can be used to map the knowledge domain of co-cited journals. In this method, a connecting line between two journals indicates that they have been cited in the same publication, and the line thickness represents the co-citation intensity of the two journals. VOSviewer was used to map the distribution of source journals in the coal mechanical properties, and Fig. 6 shows the leading journal mapping network.

The network comprises four main clusters represented by different colors. Each color represents a cluster of journals. The journal with the largest node in the yellow cluster is Construction and Building Materials, followed by Cement and Concrete Research, and Cement & Concrete Composites. The overall research direction of this cluster is material structure mechanics.

The blue cluster, which mainly focuses on the safety and development of energy resources, is closer to the green cluster in terms of research direction. The most prominent journal in the blue cluster is Fuel. In contrast, the red cluster is a series of research on coal carbon materials, such as coal bed methane mining, coal mine geological disasters, and geological energy storage. It should be indicated that red and blue clusters focus on safety management and accident prevention research.

As mentioned above, the classification of the clusters suggests that these publications are of considerable interest to researchers engaged in coal characteristics research and seek to communicate their findings.

3.5. Co-citation analysis of core literature

Total citation count statistically ranks retrieved documents. Table 5 shows the ten most cited articles in this field and the most popular studies investigating coal characteristics.

Table 2
Top 10 countries with the most research on mechanical properties of coal.

Rank	Country	Documents	Percentage	Citations	ACI	Total link strength
1	China	1996	57.85 %	30360	15.21	499
2	American	283	8.31 %	7955	28.11	219
3	Australia	273	7.91 %	8956	32.81	242
4	India	169	4.90 %	2893	17.12	44
5	Spain	152	4.40 %	3527	23.20	50
6	Poland	139	4.03 %	1740	12.52	31
7	England	113	3.28 %	1872	16.57	120
8	Japan	96	2.78 %	1756	18.29	57
9	South Korea	88	2.55 %	1700	19.32	37
10	Turkey	75	2.17 %	1481	19.75	38

Table 3
Top 10 organizations with the most publications in mechanical properties of coal studies.

NO.	Organization	Country	Publications	ACI	Correspondence clustering	total link strength
1	China University of Mining & Technology	China	521	18.1	#5 dual poroelasticity	244
2	Shandong University of Science and Technology		165	18.4	#1 sensitivity analysis	76
3	Chinese Acad Sci		117	22.3	#0 ceramic membrane	74
4	Chongqing University		115	17.4	#2 permeability	57
5	Anhui University Science and Technology		109	5.0	#10 bearing mechanism	57
6	Henan Polytech University		111	10.9	#8 filler	57
7	Xian University Science and Technology		85	9.84	#11 microscopic characteristics	39
8	China University of Mining & Technology Beijing		80	12.1	#1 sensitivity analysis	41
9	Monash University	Australia	72	23.1	#4 lignite	43
10	Consejo Superior de Investigaciones Científicas (CSIC)	Spain	66	27.1	#9 biomass fly ash	2

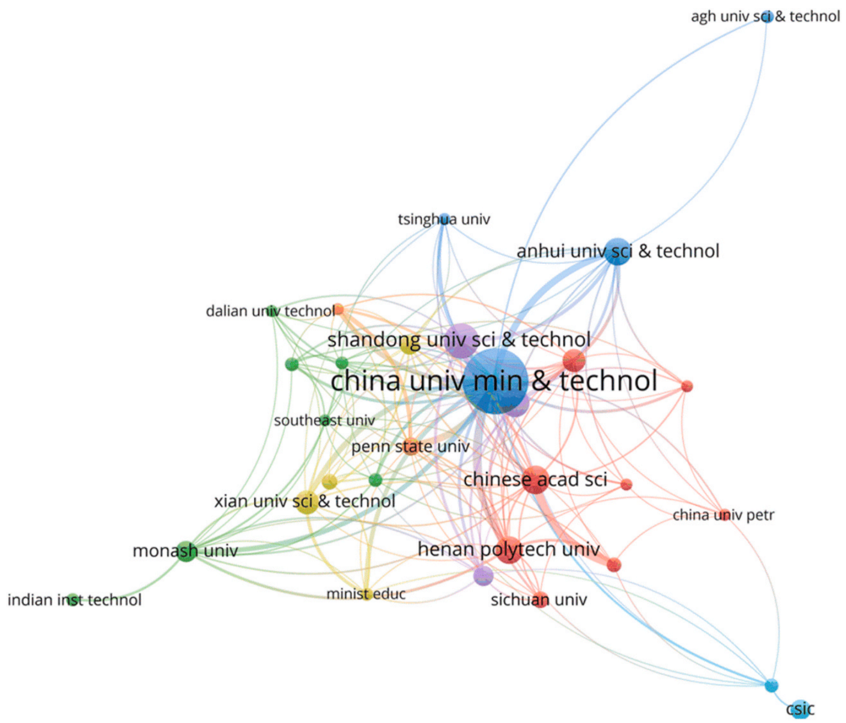

Fig. 4. Diagram of the cooperative network of main research institutions for the field of study.

Table 5 reveals that Chinese scholars are the dominant contributors to the literature, and the most cited paper is "Fly ash-based geopolymers: clean production, properties and applications" by Zhang et al. [90]. This article provides a comprehensive review of the scientific advancements in the preparation, properties, and applications of fly ash-based geopolymers, and proposes that these materials can exhibit more functional and unique properties. Another highly cited paper, "A case study on large deformation failure mechanism of deep soft rock roadway in Xin'an coal mine, China" by Yang et al. [89], investigates the failure mechanism and stability control of deep soft rock roadway. The research and test results indicate that the surrounding rock is highly fragile and susceptible to water erosion. Furthermore, numerical simulations and field tests demonstrate the efficacy of the new support scheme.

Much of the frequently cited literature pertains to emerging and high-profile industries, such as computing, materials science, hybrid technology experimentation, and numerical simulation. The primary objective of this research is to tackle complex issues in coal production. This literature will be crucial in shaping energy research and development trajectory.

3.6. *Core author analysis*

The range of author restrictions was set to include at least one article, resulting in a threshold of 2890 authors with relatively fewer collaborative clusters within the author group. To provide more convincing evidence, the adjusted author collaboration network is presented in Fig. 7, where the number of articles published by each scholar was increased to correct the threshold value. The node size in the fig represents the number of publications, while linkages between nodes indicate collaboration between authors. The total link strength reflects the degree of collaboration between authors (see Fig. 8).

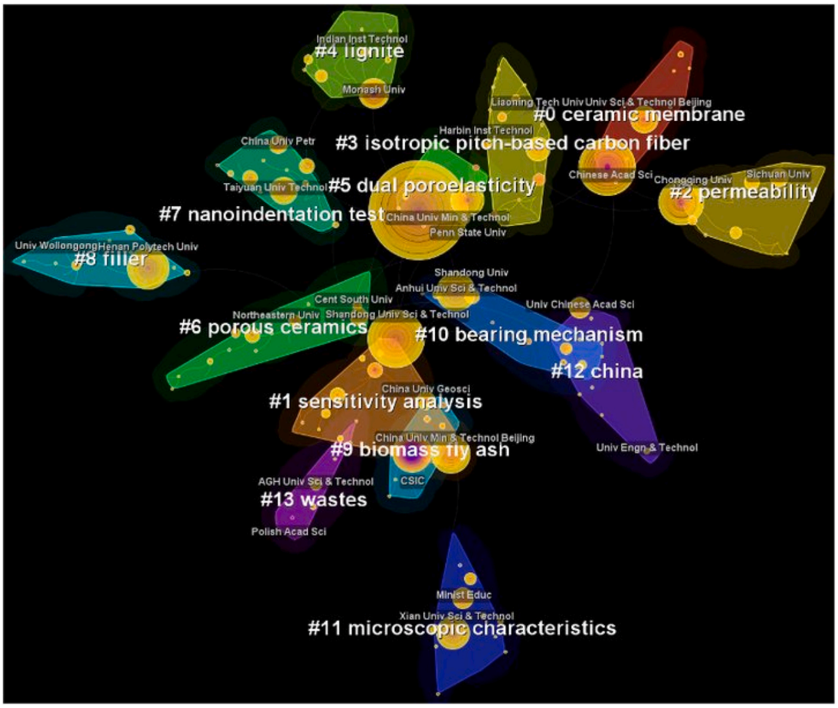

Fig. 5. Schematic diagram of the network of research institutions and keyword division of coal mechanical properties research.

Table 4
Top 10 Main source journals with the most publications in mechanical properties of coal studies.

NO.	Journal Title	Country	Total link Strength ($\times 10^3$)	Citations	Citations Index	Impact factor
1	**Construction and Building Materials**	England	223.7	7025	SCIE	10.6
2	**Fuel**	England	173.4	5289	SCI	11.2
3	**International Journal of Rock Mechanics and Mining Sciences**	England	155.8	5416	SCI	11.0
4	**International Journal of Coal Geology**	Netherlands	112.8	3328	SCI	12.7
5	**Rock Mechanics And Rock Engineering**	Austria	98.9	2994	SCI	10.9
6	**Cement and Concrete Research**	England	94.2	2866	SCI	19.3
7	**Journal of Cleaner Production**	USA	78.1	1889	SCIE	15.8
8	**Energy & Fuels**	USA	59.4	1619	SCIE	6.3
9	**Cement & Concrete Composites**	England	57.9	1424	SCIE	13.3
10	**Journal of Natural Gas Science and Engineering**	England	55.8	1392	SCIE	7.8

Table 6 details the top 20 authors with the highest number of publications. Of these authors, P. G. Ranjith (ACI: 44.34) and M. S. A. Perera (ACI: 41.50) from Australia have the highest ACI scores, followed by Dan Ma (ACI: 36.13) from China and Derek Elsworth (ACI: 35.89) from the United States. Other notable authors include Wang Enyuan and Gao Mingzhong from China, and Stefan Iglauer from Australia. These findings suggest that scholars from these countries have received significant attention in this field.

Authors from different countries have formed a relatively complete cooperative system, with Chinese institutions and authors being the primary contributors to research. Notably, Chinese scholars have published a substantial number of papers in this field, indicating a strong industry research impact. Furthermore, the number of links among authors highlights their collaborative activities, indicating that most scholars can benefit from collaborations with productive scholars to strengthen their research output.

3.7. Hot spot and frontier of coal mechanical properties

3.7.1. Research hot spot

Analyzing the distribution and evolution of research topics can offer valuable insights into how research priorities, analytical perspectives, and research methods have changed over time. Furthermore, keywords, which express research topics in a complex manner, can indicate the internal connections between disciplinary knowledge bodies to a certain extent [42,93,95–100].

To obtain a knowledge graph of keyword co-occurrence, the occurrence frequency of keywords related to coal mechanical properties research is filtered twice and above, resulting in a final set of 306 keywords. These keywords are clustered and analyzed using

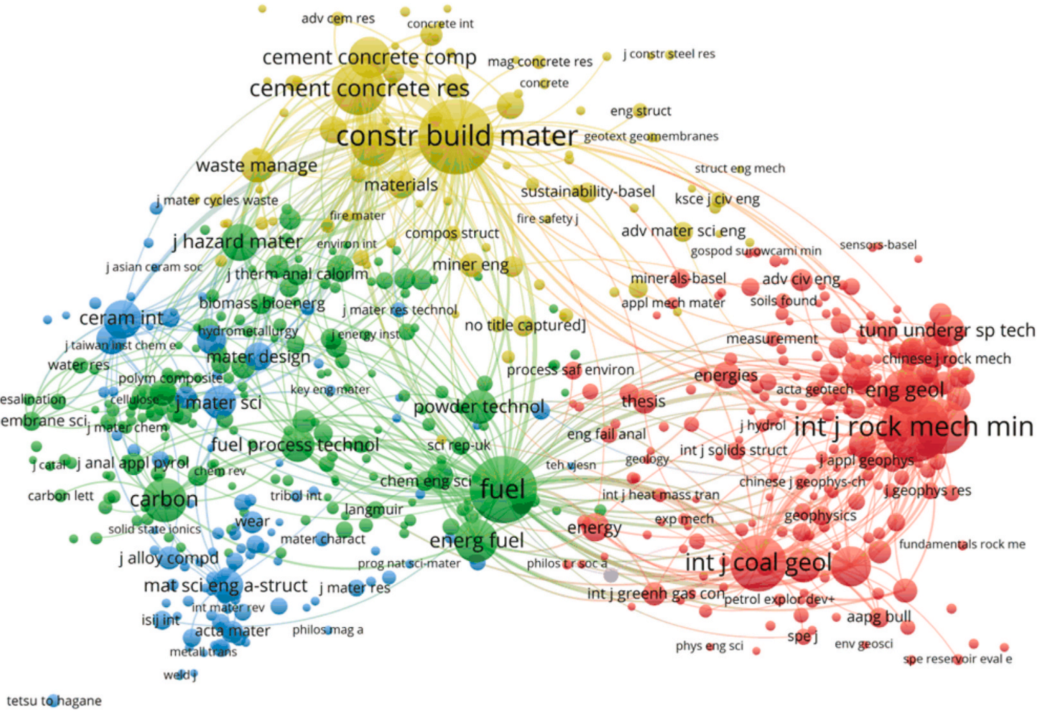

Fig. 6. Co-citation knowledge spectrum of major journals.

Table 5
Top ten literature with the most citations in coal mechanical properties studies.

Rank	Title	Authors	Journal	C	Y	IN	CN
1	"Mechanical properties and damage constitutive model of coal in coal-rock combined body"	Liu et al. [63]	International Journal of Rock Mechanics and Mining Sciences	149	2018	2	1
2	"Nanoscale pore structure and mechanical property analysis of coal: an insight combining AFM and SEM images"	Li et al. [74]	Fuel	150	2019	3	2
3	"Recent developments in drying and dewatering for low rank coals"	Rao et al. [88]	Progress in Energy and Combustion Science	182	2015	2	1
4	"A case study on large deformation failure mechanism of deep soft rock roadway in Xin'an coal mine, China"	Yang et al. [89]	Engineering Geology	239	2017	1	1
5	"Fly ash-based geopolymer: clean production, properties and applications"	Zhang et al. [90]	Journal of Cleaner Production	436	2016	4	3
6	"Experimental study on anisotropic strength and deformation behavior of a coal measure shale under room dried and water saturated conditions"	Cheng et al. [91]	Shock and Vibration	171	2015	4	2
7	Experimental investigation of thermal effects on dynamic behavior of granite"	Fan et al. [18]	Applied Thermal Engineering	190	2017	3	1
8	"Development of Cu-based oxygen carriers for Chemical-Looping with Oxygen Uncoupling (CLOU) process"	Pilar Gayán et al. [92]	Fuel	171	2012	1	1
9	"Energy recycling from sewage sludge by producing solid biofuel with hydrothermal carbonization"	Zhao et al. [93]	Energy Conversion and Management	164	2014	2	2
10	"Variations of hydraulic properties of granular sandstones during water inrush: effect of small particle migration"	Ma et al. [94]	Engineering Geology	159	2016	4	2

[a]Y = Year; C = Citations; IN = Institute Number; CN = Country Number.

VOSviewer visualization technology. The knowledge graph that is produced displays various nodes that represent different keywords. The VOSviewer visual representation highlights the frequency of each keyword by the node size, while the connections between nodes indicate the strength of the relationship between keywords.

Cluster 1 (in red): The red cluster in the keyword co-occurrence knowledge graph is characterized by two prominent keywords, "behavior" and "strength". These keywords are linked to 550 and 440 nodes, respectively. The red cluster focuses primarily on carbon's strength and creep behavior and serves as a keyword for articles on testing carbon properties. For instance, Chen et al. analyzed the deformation and damage mechanism in coal-rock assemblages under uniaxial compression [101], while Zhao et al. suggested that the failure mechanism in coal is a function of strain rate and microstructure [102]. Additionally, the high-frequency keywords in cluster 1

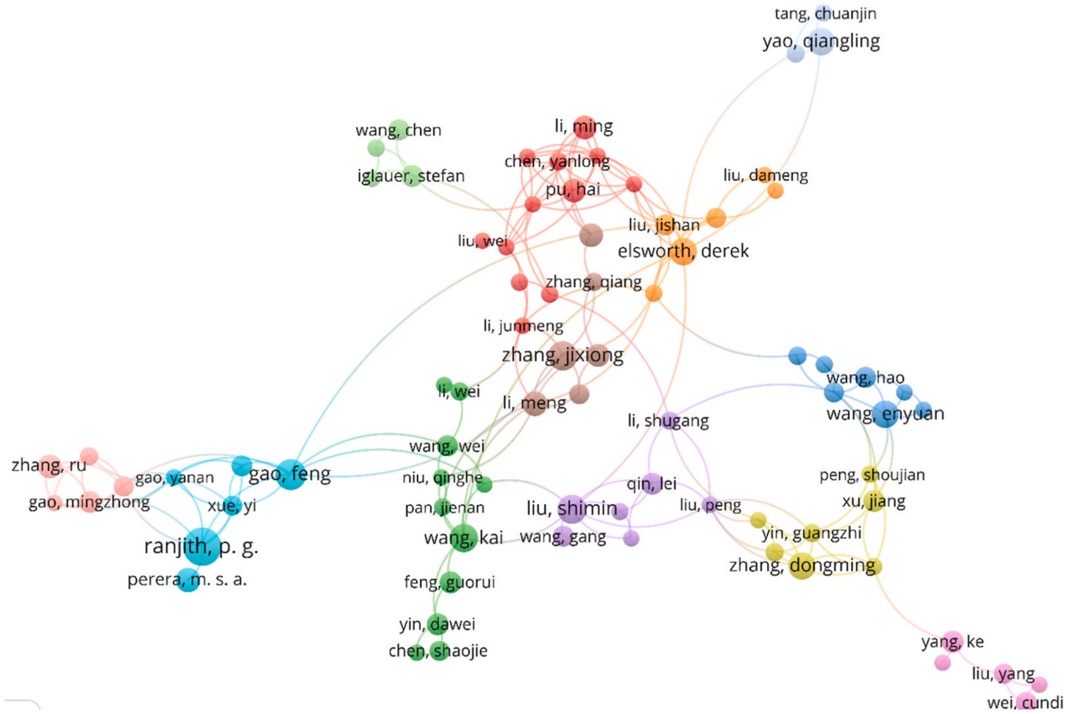

Fig. 7. Knowledge domain map for the co-authorship network in coal mechanical properties studies.

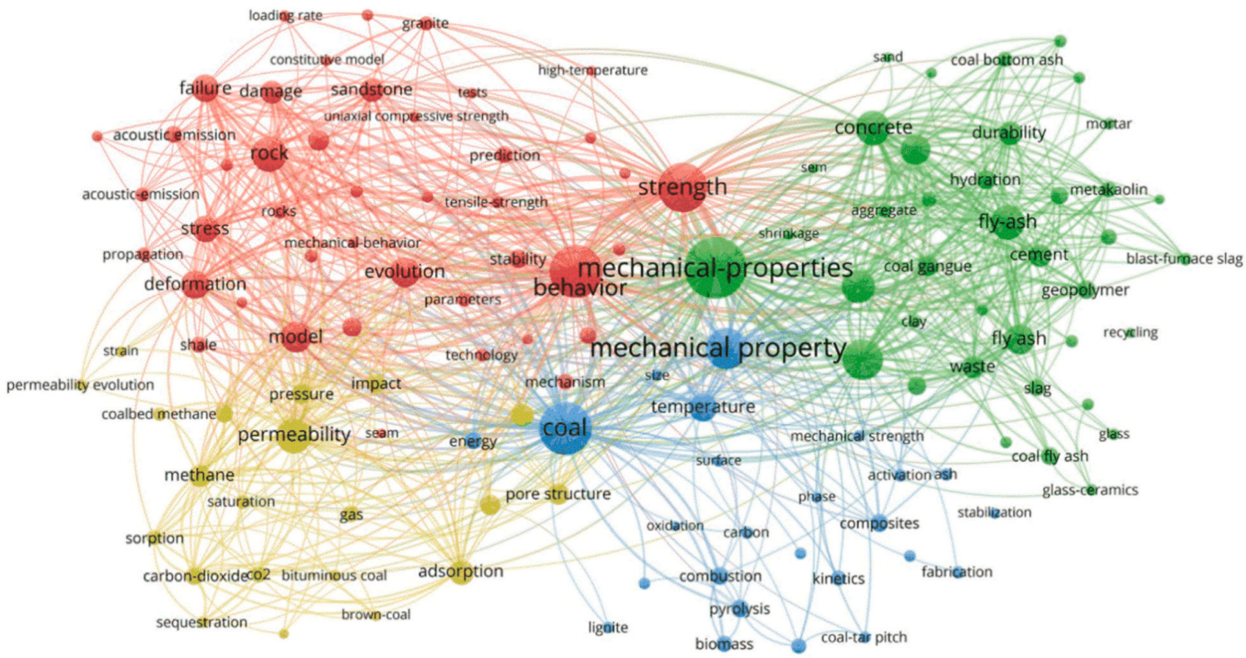

Fig. 8. Knowledge domain map of the keyword co-occurrence network in studying coal mechanical properties.

include "deformation", "prediction", "model", "destruction", and "strain", indicating that the development of coal's mechanical property model and the expansion of relevant mechanical parameters for prediction are also areas of interest for field studies. For example, Liu et al. studied the mechanical characteristics and damaged model of coal in coal-rock assemblages [67]. Pereira et al. evaluated the combined effect of free and adsorbed CO_2 on carbon strength based on the Mohr-Coulomb damage criterion and conducted numerical simulations to verify the model's reliability [8,80].

Table 6
Top 20 Main source Authors with the most publications in mechanical properties of coal studies.

Rank	Author	Organization	Total link strength	Country	Quantities	ACI
1	P. G. Ranjith	Monash University	27	Australia	35	44.34
2	Gao, Feng	School of Resource and Safety Engineering, Central South University	29	China	24	27.50
3	Liu, Shimin	The Pennsylvania State University	15	USA	22	20.45
4	Zhang, Jixiong	China University of Mining & Technology	32	China	22	14.18
5	Wang, Kai	Tsinghua University	14	China	21	17.48
6	Derek Elsworth	The Pennsylvania State University	23	USA	19	35.89
7	Wang, Enyuan	China University of Mining & Technology	12	China	19	31.05
8	Yao, Qiangling	China University of Mining & Technology	19	China	19	16.16
9	Zhang, Dongming	Chongqing University	17	China	19	10.21
10	M. S. A. Perera	University of Melbourne	14	Australia	16	41.50
11	Li, meng	Xi'an Jiaotong–Liverpool University	25	China	16	13.31
12	Ma, Dan	School of Civil Engineering and Architecture, Henan University	7	China	15	36.13
13	Zhang, Ru	University of Mining and Technology (Beijing)	28	China	15	25.73
14	Pu, Hai	China University of Mining & Technology	30	China	15	13.47
15	Li, Ming	College of Civil and Transportation Engineering Hohai University	15	China	15	6.93
16	Sun, Qiang	College of Geology and Environment, Xi'an University of Science and Technology	13	China	14	9.71
17	Gao, Mingzhong	College of Water Resource & Hydropower, Sichuan University	32	China	13	33.23
18	Stefan Iglauer	Edith Cowan University	19	Australia	13	25.62
19	Zhou, Lanzhang	University of Science and Technology of China	28	China	13	23.38
20	R Menendez	University of Oviedo	19	Spain	13	21.77

Cluster 2 (in green): The green cluster is primarily composed of the keywords "mechanical properties," "concrete," and "fly ash," with "mechanical properties" being the most frequently appearing keyword. Fly ash, which is the main solid waste produced from conventional coal-fired thermal power plants, is composed of fine ash that is trapped in flue gas after coal combustion. Fine ash is commonly utilized in the production of concrete, where it plays a crucial role in the following aspects: (1) Concrete workability can be achieved by incorporating an adequate proportion of fly ash. This approach enhances concrete's fluidity, cohesion, and water retention, facilitating pumping, pouring, and reducing slump loss. (2) reducing the heat of hydration - fly ash has low hydration heat and can effectively decrease the exothermic heat of concrete, which is particularly beneficial for large-scale concrete projects, and greatly reduces the occurrence of temperature cracks. (3) improving the durability of concrete - fly ash can increase the compactness of concrete, improve the interfacial structure, and reduce the amount of calcium hydroxide susceptible to corrosion by secondary reaction, thus enhancing the impermeability of concrete and resistance to sulfate corrosion. Fly ash can also be beneficial in reducing the risk of alkali-silica reaction, which can lead to the cracking and weakening of concrete. Fly ash has a large specific surface area and

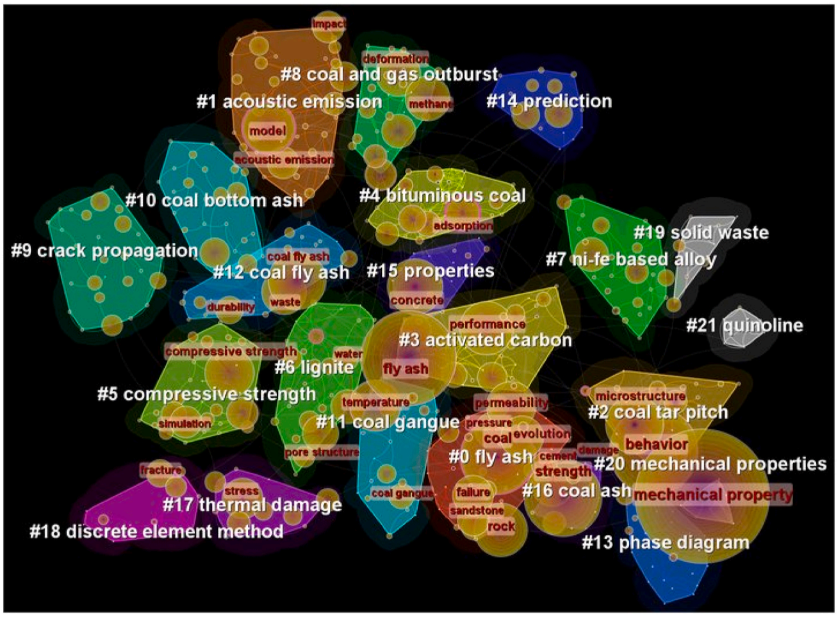

Fig. 9. Coal mechanical properties research cluster.

strong adsorption capacity that can adsorb and react with alkali in cement to reduce the alkali content, thereby reducing the potential for alkali-silica reaction. (4) reducing the cost - adding fly ash can reduce the amount of cement needed for the same strength of concrete by about 10 % [103–107].

Cluster 3 (in yellow): The most frequent keyword in cluster 3 is "permeability," followed by "adsorption" and "methane." This cluster highlights conventional experimental tests and tests for the study of coal mechanical properties, including the study of gas adsorption in coal bodies [33,35,108,109], pore structure [2,12,46,47,109], and assessment and testing of coal body permeability [48–51,110]. Other keywords in the cluster also indicate the presence of bituminous coal and lignite, emphasizing that coal rank is a crucial consideration in addition to the conventional test objectives mentioned above [52–55,75]. Cluster 4 (in blue): The largest node in cluster 4 represents the keyword "Coal," connecting 434 keywords, followed by "Temperature," connecting 164 keywords. The research focus indicated by the keywords in cluster 4 is the mechanism and law of coal spontaneous combustion, which poses a great threat to coal production, storage, and transportation. Many researchers have studied the behavior of the spontaneous combustion of coal and its underlying mechanism. For example, Ren et al. explored spontaneous combustion and critical parameters of pulverized coal at high temperatures. They found that the central point temperature curve of pulverized coal shows an upward trend at the beginning of the reaction, while the increase of pulverized coal volume is detrimental to heat transfer and oxygen permeation diffusion, which will lead to hysteresis of the coal temperature curve [56].

3.7.2. Research frontier identification

The distribution of co-occurring keywords was analyzed using CiteSpace to generate a keyword clustering map and a timeline view of the study on coal mechanical properties, presented in Figs. 9 and 10, respectively. Cluster analysis is an effective approach to identify potential semantic themes in text data and can aid in detecting and discovering knowledge research patterns [111]. This paper discusses a data processing method that employs three computational techniques: Log Likelihood Ratio (LLR), Word Frequency-Inverse Document Frequency (TF-IDF), and Mutual Information (MI). These techniques are used to transform unstructured text into structured data objects. The resulting structured data can be utilized to detect and discover research patterns and knowledge [112,113].

Fig. 9 displays the 21 clusters that were obtained, with the five key clusters having the highest centrality, i.e., containing the most keywords, identified as "mechanical properties", "acoustic emission", "fly ash", "coal and gas outburst", and "compressive strength". The clusters "fly ash", "coal and gas outburst", and "compressive strength" indicate the continued significance of measuring coal strength in the process of preventing and controlling coal and gas outbursts in the field of mechanical properties research. Meanwhile, acoustic emission technology has been widely employed in testing the mechanical properties of coal in stress-strain testing [114], damage estimation [115], energy dissipation calculation [1], and mechanical model determination [116], serving as a powerful auxiliary tool in problem-solving.

Additionally, we utilized CiteSpace software to perform a Timeline view analysis, which allowed us to gain valuable insights into the historical development of research hotspots. Prior to conducting the analysis, we made necessary keyword edits to ensure accurate results (refer to Fig. 10 for details). This analysis sheds light on the relationship between clustering and the evolution of keywords over time. It offers valuable insights into how search priorities shift over time. The horizontal axis in the keyword sequence diagram represents time, while the vertical axis represents the clustering of different keywords. Each node denotes a unique keyword, with the line between the nodes representing their co-occurrence relationship and the thickness indicating the co-occurrence strength. The connection thickness between two nodes can serve as a quantitative measure of their relationship. The size of a node corresponds to the number of times a keyword appears in a given year, while the color of a node represents the frequency of occurrence of that keyword.

Fig. 10 shows ten timeline lines identified after 25 years of development in this field, each representing topics studied during different periods. Given that the study of coal mechanical properties involves multiple interconnected systems, and each system is closely interlinked, numerous connections were observed between the ten timeline lines, indicating the interdisciplinary nature of the research hotspots. The red line on the timeline reveals that four thematic directions, including permeability model evaluation, coal mechanics modeling, coal fly ash for concrete property improvement, and energy dissipation law research, have emerged as the frontiers of research in this field.

Table 7 was generated through the Burst Detection function in CiteSpace software, and it lists the 25 keywords that experienced a surge in intensity during the development of this research area, along with their start date, end date, and intensity. As shown in Table 7, research hotspots in the study of the coal characteristics are constantly changing from year to year, with different years of keyword outbreaks. Investigating coal characteristics remains a hot topic in materials science, with a significant amount of literature published. Recently, the keywords "High temperature", "Fracture toughness", "Pressure", "CO_2", and "Tensile strength" have frequently appeared in research papers. The test methods and environment are also areas of focus in the study of coal mechanical properties, indicating an essential correlation between coal mechanical properties and external factors such as temperature, gas involvement, and pressure [2,8,10,12,18,31,80,109,117,118]. Among the keywords listed, "Coal tar pitch" experienced the longest mutation period, and a substantial amount of literature during this period focused on the impact of coal tar leakage on the mechanical properties of asphalt concrete pavement, leading to research on coal asphalt rheology and charring related to the coal characteristics [119–122].

Currently, the keywords "coal bottom ash", "durability", "granite", "reservoir", and "aggregate" are in mutation, representing the current research hotspots. The terms "coal bottom ash", "granite", and "durability" are interrelated, and the corresponding research areas include the feasibility assessment of granite powder and coal bottom ash in different strength concrete mixes. "Reservoir" and "aggregate" are also interrelated, with research areas including producing high-performance, lightweight aggregates using industrial waste technology, manufacturing lightweight aggregate concrete with structural strength classes, and studying their freshness, hardness, and durability.

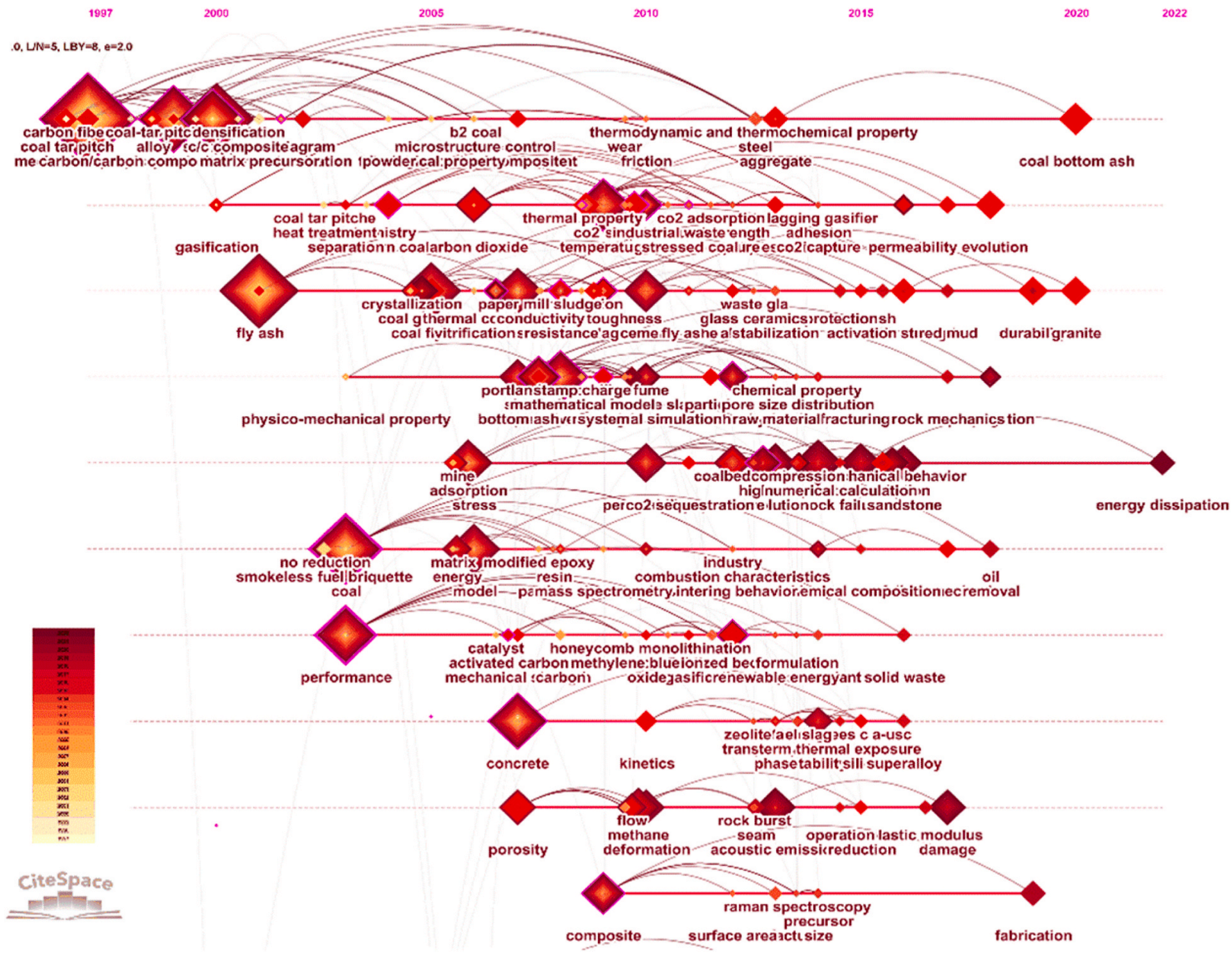

Fig. 10. Keywords timeline view of the coal mechanical properties study.

3.8. *Implications*

In this study, the permeability model assessment and coal mechanical modeling have emerged as key areas of research in the field of coal mechanical properties. Accurately constructing and evaluating the permeability model of coal seams is crucial for various aspects such as coalbed methane resource evaluation, coalbed methane production capacity assessment, coalbed water management, and optimization of coalbed methane mining technology. These efforts can significantly enhance the development and utilization efficiency of coalbed methane resources and improve economic benefits. Researchers have increasingly focused on incorporating temperature effects into the study of low permeability coal beds. Some scholars and experts have explored techniques such as microwave heating, high-temperature water vapor heating, and enhanced coalbed methane mining (ECBM) with electric heating [123,124]. Another promising approach is in-situ heat injection mining, which offers a new perspective on the extraction of coal and gas from deep coal seams [125]. However, as mining depth increases, deep coal reservoirs experience higher temperatures and reservoir pressures. It is currently believed that determining coal permeability solely based on effective stress is insufficient. The transport of coalbed methane is also influenced by reservoir pressure and temperature, as well as the Klinkenberg slip effect on the permeability of coal reservoirs with low permeability and low pore pressure. Nevertheless, the coupling law of coal seam permeability under heat flow solid and the specific impact of the sliding effect on permeability in the in-situ state of deep coal bodies are yet to be fully understood. In addition, there are still some shortcomings in this technology that need to be addressed from an academic perspective. These include energy consumption, cost, environmental impact, reservoir suitability, and mining cycle time, which are key issues that require attention.

Besides, the failure of coal bodies is believed to be primarily caused by energy-driven instability. With the increasing intensity of mining worldwide and the complexity of mining conditions, it becomes necessary to conduct further research to explore and explain the characteristics of coal and rock instability and failure. This includes understanding the formation mechanism and distribution of cracks, as well as studying various mining activities that have led to complex research areas. These areas include stress release between coal seam groups, crack expansion, changes in the state of coal seam gas occurrence, alterations in the pore and crack structures of coal

Table 7
The burst word data for coal mechanical properties study keywords.

Keyword	Years	Strength	Begin	End	1997-2022
mechanical property	1997	11.78	1997	2002	
coal tar pitch	1997	9.49	1997	2014	
microstructure	1999	6.47	1999	2001	
fly ash	2001	7.14	2001	2004	
brown coal	2004	8.57	2004	2017	
crystallization	2005	6.72	2005	2012	
coal fly ash	2005	9.54	2007	2013	
porosity	2007	7.08	2007	2017	
system	2009	7.2	2009	2016	
kinetics	2010	10.32	2010	2017	
sorption	2010	6.5	2010	2019	
combustion	2012	8.6	2012	2018	
sequestration	2013	6.42	2013	2016	
high temperature	2014	7.84	2016	2018	
fracture toughness	2009	6.87	2016	2019	
pressure	2012	6.89	2017	2018	
shale	2018	12.08	2018	2020	
tenslie strength	2016	9.28	2018	2020	
CO_2	2009	7.82	2018	2019	
coal mine	2016	7.53	2019	2020	
coal bottom ash	2020	10.03	2020	2022	
durability	2019	9.63	2020	2022	
granite	2020	7.84	2020	2022	
reservoir	2015	7.18	2020	2022	
aggregate	2013	6.88	2020	2022	

and rock masses, and modifications in gas migration pathways within coal seam groups. When developing a coal mechanics model, it is important to consider coal quality characteristics such as carbon content, ash content, sulfur content, as well as physical characteristics like porosity, pore size distribution, and component composition. Additionally, geological structure, including bedding planes, joint planes, and fault planes of coal seams, should be taken into account. Moreover, stress conditions, temperature, humidity, and loading conditions are key factors that need to be considered. Recent research on coal mechanics models has started to incorporate the coupling effects of various physical factors, such as coal-rock-water coupling and thermal-mechanical coupling, to accurately describe complex scenarios in practical engineering [8,10,18,32,117,118,126,127]. With the continuous advancement of computer technology and numerical methods, the accuracy and refinement of coal mechanics models have significantly improved. Future development in this field will focus on addressing issues such as multi-physical field coupling, large deformation, and dynamic response, in order to enhance the theoretical foundation of model establishment and the acquisition of experimental data. This will better cater to the needs of engineering applications. By comprehensively utilizing the aforementioned technical conditions, a more accurate and reliable coal mechanics model can be established. Such a model will contribute to the understanding and prediction of the mechanical behavior of coal seams, and provide a scientific basis for coal mine safety and excavation engineering.

4. Conclusion

This paper reviews the literature on the mechanical properties of coal, utilizing information visualization techniques to gain knowledge of the literature and domain maps of major WOS databases. The following properties of coal mechanical properties research have been observed thus far.

1. The number of published articles investigating the mechanical properties of coal has significantly increased over the past 25 years. These publications can be categorized into three stages: the initial stage (1997–2010), the stable growth stage (2011–2017), and the rapid development stage (2018–2022). Since 2018, the pace of development has accelerated, and coal mechanical properties

research has entered a period of rapid growth. In this context, a comprehensive cooperation system has been established globally, in which Chinese researchers have a prominent role.

2. Studying the mechanical properties of coal is essential for preventing and controlling spontaneous coal combustion, gas protrusion, and other dynamic disasters. Coal strength and creep behavior and mechanical property testing, fly ash improvement of concrete properties, coal permeability assessment, and mechanical properties of gas-bearing coal represent the knowledge base and research directions in the field of coal mechanical property research. The acoustic emission technique is crucial among these four research directions. The most cited journals are "Construction and Building Materials," "Fuel," and "International Journal of Rock Mechanics and Mining Sciences," which publish the most articles on coal mechanical properties.
3. Studying coal mechanical properties has formed a theoretical framework and extended several research directions and knowledge areas. Current research hot spots include establishing and predicting the coal mechanical properties model, permeability model, coal strength-temperature relationship, research on the proportioning scheme of granite and coal bottom ash in concrete mixes, and research on the improvement effect of fly ash on concrete manufacturing properties.
4. In future research on coal mechanics, it is imperative to utilize modern computer technology and multidimensional numerical simulation methods to address various challenges such as multi-physical field coupling, large deformation, and dynamic response. This approach holds immense importance for the advancement of coal mechanics and can also serve as a scientific foundation for ensuring coal mine safety and improving excavation engineering.

Data availability

The data that has been used is confidential.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Chen Wang: Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xiaomeng Xu:** Investigation, Funding acquisition, Formal analysis, Data curation. **Yihuai Zhang:** Writing – review & editing, Visualization, Validation, Methodology. **Muhammad Arif:** Writing – review & editing, Data curation, Conceptualization. **Siyuan Zhang:** Writing – review & editing, Funding acquisition, Conceptualization. **Meijuan Lan:** Writing – review & editing, Conceptualization. **Binshan Yu:** Writing – review & editing, Validation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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