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Differences of Mechanical Parameters and Rockburst Tendency Indices between Coal and Non-Coal Rocks and Modified Rockburst Tendency Classification Criteria for Non-Coal Rocks

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Abstract: Rockbursts represent hazardous dynamic disasters for underground coal mines and other underground rock engineering projects. Some bursting liability indices are put forward and applied to identify the likelihood of rock burst occurrence. The classification criteria of the bursting liability indices are proved to be reasonable for coals, but they are still immature for non-coal rocks. Thus, it is uncertain that it is reasonable to use the classification criteria of coal for evaluating the bursting liability of non-coal rocks. Hence, in this study, a large amount of data, such as the basic mechanical parameters, i.e., Poisson's ratio μ, elastic modulus E, uniaxial compressive strength σ_c, and uniaxial tensile strength σ_t, and the bursting liability indices, i.e., elastic strain energy index W_{ET}, bursting energy index W_{cf}, dynamic fracture duration time DT, and brittleness index B, of different coals and non-coal rocks were collected in China. Then, the differences of mechanical parameters and rockburst tendency indices between coal and non-coal rocks were studied systematically, and apart from the Poisson's ratio μ, the other three basic mechanical parameters of coal and non-coal rocks have great differences in data distribution and concentration scope, which proved that the non-coal rocks cannot share the same index system and classification criteria of coals. In addition, the evaluation results of a single index for rock bursting liability of rocks were directly compared in pairs, and the inconsistency rate for coals is about 42–68%. It is necessary to build a comprehensive evaluation method to evaluate the bursting liability of rocks. At last, the modified rockburst tendency classification criteria for non-coal rocks were put forward. It is reasonable to use the classification criteria of the W_{ET} and W_{cf} to classify the bursting liability of non-coal rocks, while it is unreasonable to use that of the DT and σ_c. It has been concluded that the index B are more suitable for non-coal rocks, and a new index, named strength decrease rate (SDR), was proposed to determine the bursting liability, which is the ratio of uniaxial compressive strength σ_c to duration of dynamic fracture DT.

Keywords: rock burst; coal; non-coal rock; basic mechanical parameter; bursting liability index; classification criterion

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Citation: Du, K.; Sun, Y.; Yang, S.; Lv, S.; Wang, S. Differences of Mechanical Parameters and Rockburst Tendency Indices between Coal and Non-Coal Rocks and Modified Rockburst Tendency Classification Criteria for Non-Coal Rocks. *Appl. Sci.* **2021**, *11*, 2641. https://doi.org/10.3390/app11062641

Academic Editor: Guido Ventura

Received: 2 February 2021
Accepted: 8 March 2021
Published: 16 March 2021

1. Introduction

In recent years, a large amount of deep mineral resources has been mined in China [1,2]. With the increasing burial depth of the mineral resources, the geo-stress levels also increase [3], and a series of rockburst disasters have occurred, which are a serious threat to safe production in deep underground mines in China [4]. In fact, the rock burst is a complex rock failure process with two main influencing factors, which are the mechanical properties of rocks, and the geo-stress conditions and levels [5,6]. It is widely reported that Poisson's ratio μ, elastic modulus E, uniaxial compressive strength σ_c, and uniaxial tensile strength σ_t are the basic mechanical parameters of rocks [7,8]. The σ_c and σ_t jointly reflect the strength properties of rocks, and the ratio of the σ_c to σ_t is called as the brittleness index B of rocks [9–11]. The brittleness index B is often used to indicate a significant bursting liability index for non-coal rocks [12]. Poisson's ratio μ and elastic modulus E express the deformation capacity of rocks [13]. These basic mechanical parameters of rocks influence the occurrence of rockburst in underground engineering. Therefore, many bursting liability indices were put forward based on the lab tests of the basic mechanical parameters [14]. In conclusion, there are more than a dozen indices to evaluate the rock bursting liability of rocks [15]. Four indices, i.e., elastic strain energy index W_{ET}, bursting energy index W_{cf}, duration of dynamic fracture DT, uniaxial compressive strength σ_c, are the most used indices to evaluate the bursting liability of coals in China, as shown in Figure 1.

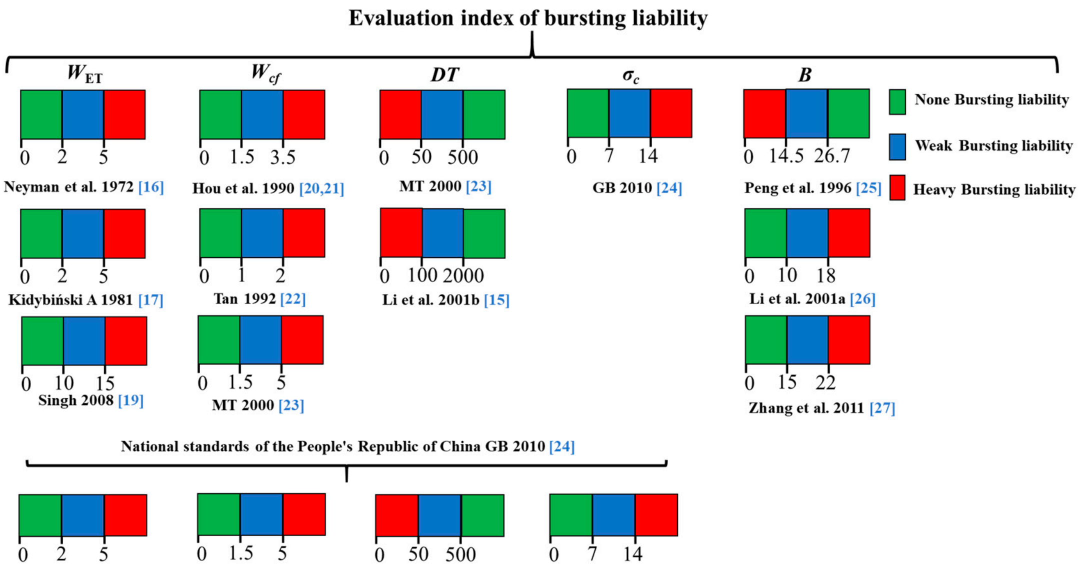

Figure 1. Main bursting liability indices and their classification standards.

The bursting liability classification criteria of coals are often divided into three bursting liability grades, i.e., heavy bursting liability, weak bursting liability, and no bursting liability. Neyman et al. firstly proposed the elastic strain energy storage index W_{ET} as a bursting liability evaluation index for coals in 1972 [16]. $W_{ET} > 5$, $2 < W_{ET} \leq 5$, and $0 < W_{ET} \leq 2$ are the classification criteria corresponding to heavy, weak, and no bursting liabilities of coals, which is proved to be reasonable for bursting liability prediction of coals by many testing data [17,18]. Sing [19] put forward a new classification criterion of W_{ET} for hard rocks in Canada, i.e., heavy bursting liability with $W_{ET} > 15$, weak bursting liability with $10 < W_{ET} \leq 15$, and no bursting liability with $0 < W_{ET} \leq 10$. In 1990, Hou et al. [20,21] wre the first to put forward the bursting energy index W_{cf} as another evaluation index of bursting liability, and defined that the values $W_{cf} > 3.5$, $1.5 < W_{cf} \leq 3.5$, and $0 < W_{cf} \leq 1.5$ are the classification criteria for heavy, weak, and no bursting liabilities, respectively. After the modified criterions of W_{cf} by Tan et al. [22] and MT [23], it is confirmed to be useful to predict the bursting liability of coals using the values of heavy bursting liability with $W_{cf} > 5$, weak bursting liability with $1.5 < W_{cf} \leq 5$, and no bursting liability with $0 < W_{cf} \leq 1.5$. In the Classification and Laboratory Test Method on Bursting Liability of Coal (MT/T 174-2000) [23], the fracture duration time DT in uniaxial compression tests was put forward, and $DT > 500$ ms, $50 < DT \leq 500$ ms, $0 < DT \leq 50$ ms were defined as the classification intervals for no, weak and heavy bursting liabilities of coals, respectively. Li.et al [15] defined $DT > 2000$ ms, $1000 < DT \leq 2000$ ms, $0 < DT \leq 1000$ ms as the classification criterions for no, weak, heavy bursting liabilities of non-coal rocks, respectively. In the Methods for Testing, Monitoring and Prevention of Rock Burst, Part 2: Classification and Laboratory Test Method on Bursting Liability of Coal (GB/T 25217.2-2010) [24] a new standard was put forward to evaluate the bursting liability of coals, which is the uniaxial compressive strength σ_c, and $\sigma_c > 14$ MPa, $7 < \sigma_c \leq 14$ MPa, and $0 < \sigma_c \leq 7$ MPa were the detailed classification criteria for no, weak and heavy bursting liabilities of coals. In 1996, Peng et al. [25] proposed the brittleness index B based on Griffith's strength theory to evaluate the bursting liabilities of non-coal rocks, and defined that the $B > 26.7$, $14.5 < B \leq 26.7$, and $0 < B \leq 14.5$ as the classification criterions for no, weak, and heavy bursting liabilities of non-coal rocks, respectively. In addition, the other two classification criterions were put forward by Li.et al [26] and Zhang et al. [27], which described "heavy bursting liability with $B \geq 18$, weak bursting liability with $10 \leq$ B < 18 and no bursting liability with $0 \leq B < 10$", and "heavy bursting liability with $B > 22$, weak bursting liability with $15 < B \leq 22$ and no bursting liability with $0 < B \leq 15$", respectively.

Nevertheless, rock burst disasters also frequently occur in deep underground non-coal mines and tunnels in China. Therefore, it is extremely vital to predict the bursting liability degree of deep non-coal rocks. The classification criterions of the bursting liability indices, i.e., W_{ET}, W_{cf}, DT, σ_c, have been proved to be reasonable for coals by many field data in China. Most bursting classification criteria used for hard rocks often refer to those of coals and were not put forward based on the special mechanical properties of non-coal rocks. The rationality of using the bursting liability criteria of coals to predict the bursting liability of non-coal rocks needs to be studied in depth. Hence, in this study, a large amount of data, including basic mechanical parameters and bursting liability indices of different coals and non-coal rocks have been collected in China, and reported in the previous literatures have been used. The distribution range and distribution proportion of the mechanical parameters and rockburst tendency indices of coals and non-coal rocks are analyzed, and the rationality of using the bursting tendency indices for non-coal rocks is discussed. Finally, a series of comparatively reasonable modified rockburst tendency indices and classification criteria for non-coal rocks were put forward.

2. Basic Mechanical Parameters

The basic mechanical parameters of the coals and non-coal rocks in China were collected from the previous literature, as shown in Tables S1 and S2 in the Supplementary Material files. The statistical parameters of the basic mechanical parameters of coals and non-coal rocks are shown in Table 1. The detailed location of the coals and non-coal rocks in this study are shown in Figure 2. The basic mechanical parameters of coals and non-coal rocks are shown as Figure 3. From the statistical results, it can be concluded that the distribution ranges of basic mechanical parameters of non-coal rocks are much wider than that of coals, except for the Poisson ratio. The Poisson's ratios of coals and non-coal rocks share a similar distribution range, while the other three parameters have great differences in the distribution ranges. The ranges of σ_c, σ_t and E are 0–50 MPa, 0–4 MPa and 0–46 GPa for coals, respectively, and 10–310 MPa, 0–20 MPa and 1–82 GPa for non-coal rocks, respectively. It can be easily found that the maximum uniaxial compressive strength of non-coal rocks is more than six times higher than that of coals. In addition, the maximum uniaxial tensile strength and maximum elastic modulus of non-coal rocks are about five times and two times higher than those of coals, respectively, and it is widely known that rocks with higher elastic modulus and uniaxial compressive strength generally have higher brittleness and stronger bursting liability [6,28–30].

The basic mechanical parameters of coal and non-coal rocks were divided into four parts by the same division standard, and the proportion of data points in each interval was counted and plotted in Figure 4. It is obvious that the uniaxial compressive strength σ_c, uniaxial tensile strength σ_t, and elastic modulus E of coals are concentrated in the smallest interval, whereas, the above three parameters of non-coal rocks are mainly concentrated in the two medium intervals, as shown in Figure 4a–c. The Poisson's ratio proportion pie charts of non-coal rocks and coals have no significant differences, as shown in Figure 4d. These results indicate that there are considerable differences between the basic mechanical parameters of coals and those of non-coal rocks. It is thus questionable to evaluate the bursting liabilities of non-coal rocks by using the same classification criteria of coals. Taking the uniaxial compressive strength as an example, the proportions of heavy bursting liability, weak bursting liability and no bursting liability for coals are 59.6%, 29.8%, and 10.7%, respectively, while they are 97.5%, 2.5%, and 0 for non-coal rocks when the bursting liability of non-coal rocks was evaluated by the uniaxial compressive strength classification criterion of coals, as shown in Figure 5. Therefore, it is necessary to define more reasonable evaluation criteria for non-coal rocks.

Table 1. Statistical parameters of the basic mechanical parameters of coals and non-coal rocks.

Statistical Parameter	Rock Type	σ_c/MPa	σ_t/MPa	E/GPa	μ
Variance	coal	94.19	0.68	58.41	0.005
	non-coal	1964.89	12.89	385.65	0.003
Standard deviation	coal	9.71	0.82	7.64	0.067
	non-coal	44.33	3.59	19.64	0.056
Median	coal	15.85	1.08	3.41	0.24
	non-coal	94.10	6.48	26.23	0.23
Maximum	coal	50.00	3.89	45.126	0.45
	non-coal	313.00	19.07	81.381	0.455
Mean	coal	17.46	1.18	5.87	0.26
	non-coal	97.38	7.05	30.47	0.24
Minimum	coal	1.36	0.07	0.039	0.09
	non-coal	10.19	1.34	1.00	0.03

Figure 2. Regional distribution of the coals and non-coal rock examples used in this study.

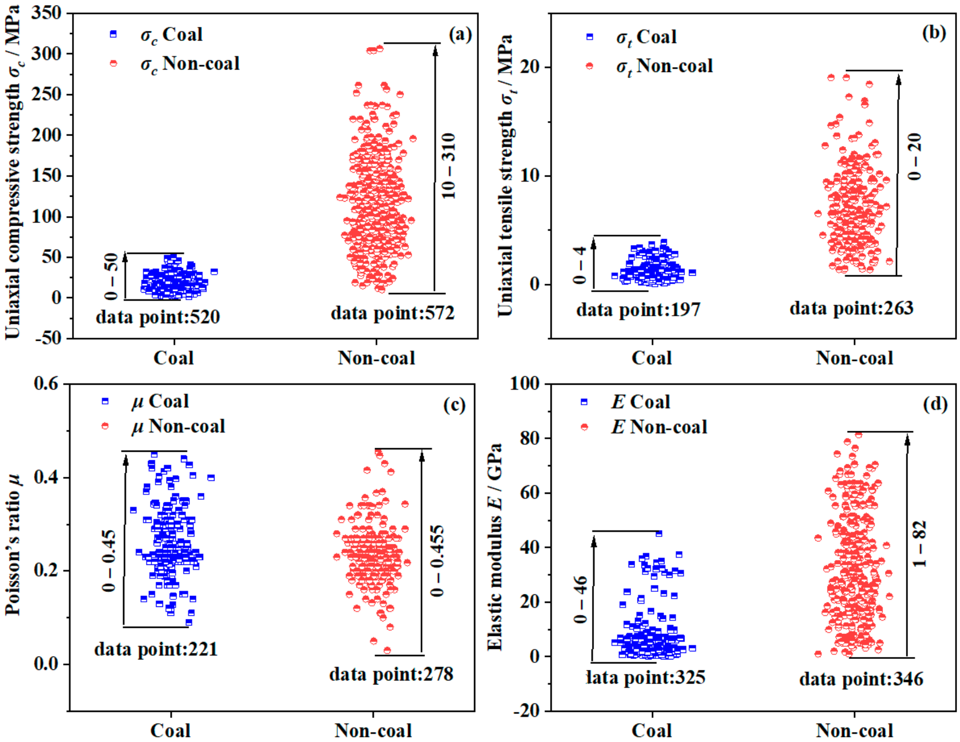

Figure 3. Statistics of basic mechanical parameters of coals and non-coal rocks: (**a**) uniaxial compressive strength σ_c, (**b**) uniaxial tensile strength σ_t, (**c**) Poisson's ratio μ, and (**d**) elastic modulus E.

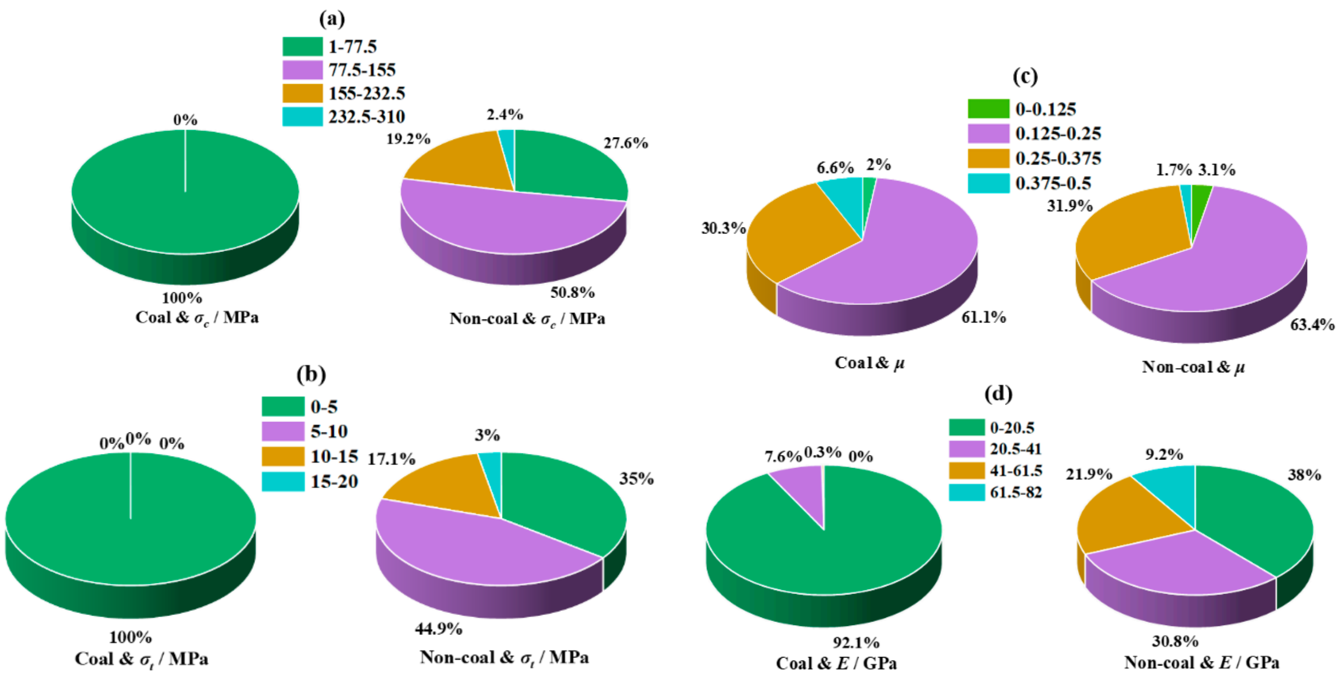

Figure 4. Proportion statistics of basic mechanical parameters: (**a**) uniaxial compressive strength σ_c, (**b**) uniaxial tensile strength σ_t, (**c**) Poisson's ratio μ and (**d**) elastic modulus E.

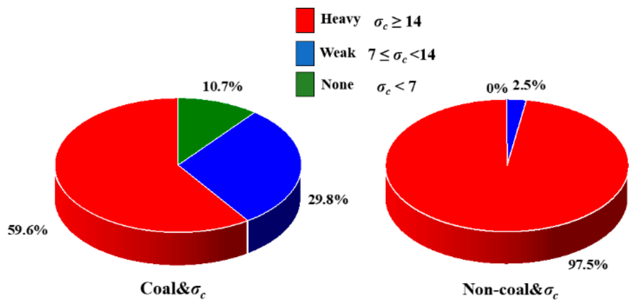

Figure 5. Proportion statistics of bursting liabilities of coal and non-coal rocks using the classification standard by uniaxial compressive strength of coal.

3. Bursting Liability Indices

The bursting liability indices often used in the bursting tendency evaluation of rocks are put forward on different theory principles, and the differences of rockburst tendency indices between coal and non-coal rocks are still unclear. In this chapter, the theory principles of each indices were summarized, and the differences of rockburst tendency indices between coal and non-coal rocks were analyzed.

3.1. Calculation Principle

The calculation principles of bursting liability indices are summarized in Figure 6. The elastic strain energy index W_{ET} is the ratio of elastic strain energy Φ_{SE} to plastic strain energy Φ_{SP}, which is determined from uniaxial loading-unloading compression tests. The elastic strain energy index W_{ET} is a parameter related to the elastic hysteresis loop of rocks, and the unloading point is set approximately to 80–90% of the uniaxial compression strength σ_c, as shown in Figure 6a.

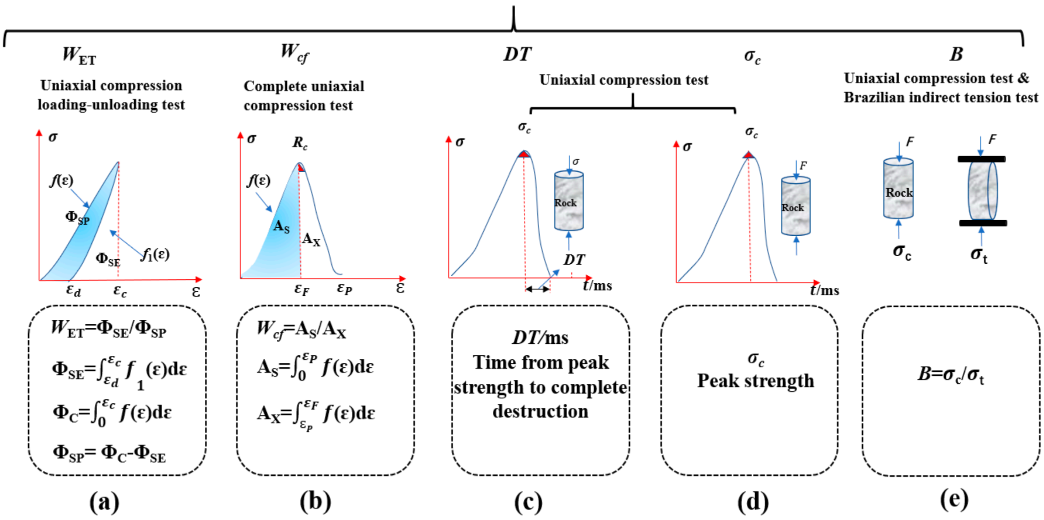

Figure 6. Calculation methods of bursting liability indices. Notes: Φ_{SE} is the elastic strain energy, and it is the area under the unloading curve; Φ_C is the total strain energy, and it is the area under the loading curve; Φ_{SP} is the plastic strain energy, and it is the area enclosed by the loading curve and the unloading curve; ε_c is the total stain in loading-unloading curve; ε_d is the permanent non-elastic strain; ε_P is the total stain in comprehensive loading curve; ε_F is the stain before pre-peak strength in comprehensive loading curve; A_S is the accumulated deformation energy; A_X is the dissipate deformation energy; σ_c is the uniaxial compressive strength; σ_t is the uniaxial tensile strength.

With the increase of the permanent (irreversible) strain ε_d, the elastic strain energy index W_{ET} decreases, and the accumulation ability of elastic strain energy Φ_{SE} of rocks decreases, which makes the bursting liability decrease. The bursting energy index W_{cf}

is the ratio of the accumulated deformation energy A_S to the dissipate deformation energy A_X, which is determined from the complete stress-strain curve of rocks in uniaxial compression tests.

The area of pre-peak curve is defined as the accumulated deformation energy A_S, and the area of post-peak curve is defined as the dissipate deformation energy A_X, as shown in Figure 6b. The duration time of post-peak segment of rocks in uniaxial compression tests is defined as the dynamic fracture duration time DT, as shown in Figure 6c. Peng et al. [25] defined the strength brittleness index B as the ratio of uniaxial compressive strength σ_c to uniaxial tensile strength σ_t, as shown in Figure 6e.

3.2. Distribution Range

In order to compare the bursting liabilities of coals and non-coal rocks, the distribution ranges of bursting liability indices of coal and non-coal rocks are calculated and shown in Figure 7. The bursting liability data are basically collected from the underground engineering data in China (Figure 2), as shown in Tables S3 and S4 in the Supplementary Material files. The statistical parameters of the rockburst indices of coals and non-coal rocks are shown in Table 2.

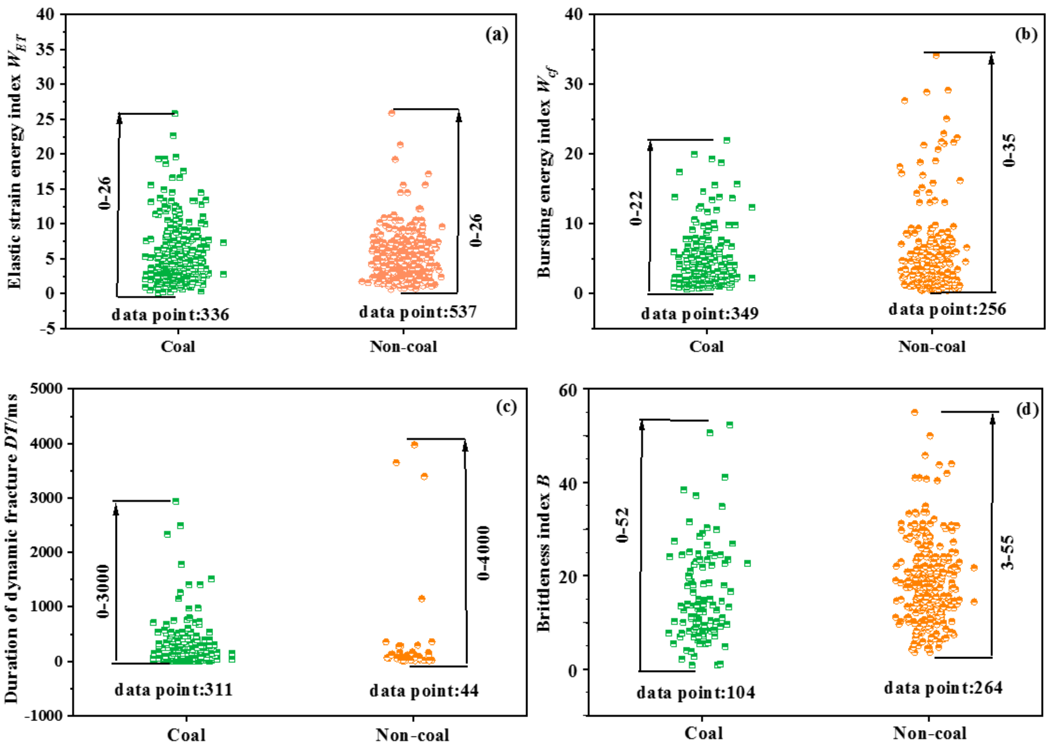

Figure 7. Statistics of bursting liabilities of coals and non-coal rocks: (**a**) elastic strain energy index W_{ET}, (**b**) bursting energy index W_{cf}, (**c**) dynamic fracture duration time DT, (**d**) brittleness index B.

As shown in Figure 7, the distribution ranges of the bursting indicators, such as elastic strain energy index W_{ET}, bursting energy index W_{cf} and brittleness index B, are 0–26, 0–22 and 0–52 for coals, respectively, and which are 0–26, 0–35 and 0–55 for non-coal rocks, respectively. It is easily concluded that there are few differences for W_{ET}, W_{cf} and B between coal and non-coal rocks in the distribution range. However, there are large discrepancies for DT and σ_c between coal and non-coal rocks, as shown in Figures 3a and 7c. The distribution ranges of DT and σ_c are 0–3000 ms and 0–50 MPa for coals, respectively, and 0–4000 ms, and 20–310 MPa for non-coal rocks, respectively. The distribution ranges of σ_c and DT for coals are much smaller than these for non-coal rocks.

Table 2. Statistical parameters of the rockburst indices of coals and non-coal rocks.

Statistical Parameter	Mines	*DT*/ms	W_{ET}	W_{cf}	*B*
Variance	coal	131544.10	16.48	13.56	81.92
	non-coal	872103.17	8.44	33.01	77.47
Standard deviation	coal	362.69	4.01	3.65	10.36
	non-coal	933.86	2.90	5.75	8.80
Median	coal	158.00	3.89	2.73	13.54
	non-coal	86.03	4.22	2.84	17.50
Maximum	coal	2943.00	25.80	22.00	52.31
	non-coal	3977.00	25.89	34.18	55.00
Mean	coal	261.89	5.19	4.07	16.42
	non-coal	378.13	4.77	5.00	18.53
Minimum	coal	0.09	0.15	0.66	2.19
	non-coal	4.87	0.60	0.44	3.60

4. Classification Standards of Bursting Liability Indices

Based on the aforementioned analyses, the classification criteria of the bursting liability indices for coals in Methods for Testing, Monitoring and Prevention of Rock Burst Part 2: Classification and Laboratory Test Method on Bursting Liability of Coal (GB/T 25217.2-2010) [24] are reasonable, and it is necessary to discuss the classification criteria of bursting liability indices for non-coal rocks. In addition, it is well known that the different bursting liability indices are established by different theory foundations. When the different indices were applied to predict the bursting liability of rocks, it is urgent to study the uniformity of the bursting liability results by the classification criterions of different indices.

4.1. Applicability and Uniformity of Bursting Liability

4.1.1. Bursting Liabilities of Non-Coal Rocks Using Classification Criterions of Coals

The bursting liability classification results of coals and non-coal rocks based on the classification standards in GB/T 25217.2-2010 [24] were obtained, and the percentages of different bursting liability types (heavy, weak, and none) were drawn in the pie charts, as shown in Figure 8. In Figure 8a–c, taking σ_c = 50 MPa (the σ_c maximum value of coals) as the split point, the non-coal rocks with σ_c > 50 MPa and those with 0 < σ_c < 50 MPa were discussed separately. The ratios of the three indicators' bursting liability classification results are presented in Table 3.

Table 3. Rockburst tendency ratios of coals and non-coal rocks.

Rock Type	Index	Rockburst Tendency Proportion			Approximate Ratio
		Heavy	Weak	None	
Coal	W_{ET}	42.8%	46.7%	10.5%	9:9:2
	W_{cf}	32.8%	49.8%	17.4%	3:5:2
	DT	29.9%	53.5%	16.6%	3:5:2
Non-coal rocks	W_{ET}	44.7%	45.5%	9.8%	9:9:2
	W_{cf}	31.1%	45.6%	23.3%	6:9:5
	DT	11%	31.5%	57.5%	1:3:6

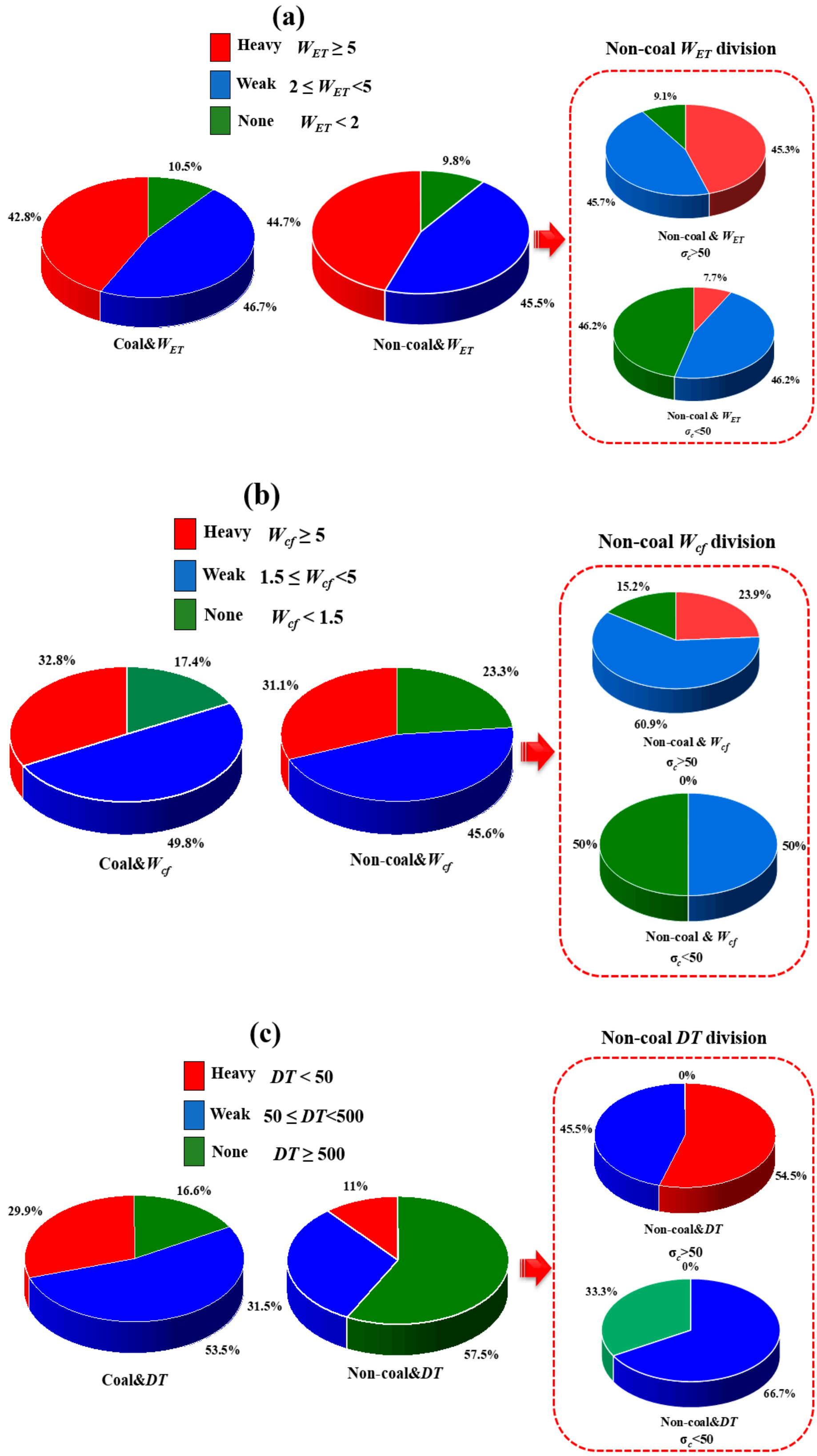

Figure 8. Percentages of coal and non-coal rocks with different bursting liabilities: (**a**) elastic strain energy index W_{ET}, (**b**) bursting energy index W_{cf}, and (**c**) duration of dynamic fracture DT.

Overall, the W_{ET} bursting liability degrees (heavy, weak, and none) of coals and non-coal rocks, were 42.8%, 46.7%, 10.5%, and 44.7%, 45.5%, 9.8%, respectively, as shown in Table 3 and Figure 8a. The W_{cf} bursting liability degrees (heavy, weak, and none) of coal and non-coal rocks, were 32.8%, 49.8%, 17.4%, and 31.3%, 45.6%, 23.3%, respectively, as shown in Figure 8b. It can be clearly concluded that there are obvious similar distribution properties between W_{ET} and W_{cf} for coal and non-coal rocks. The percentage ratio among heavy, weak and no bursting liability for elastic strain energy index W_{ET}, bursting energy index W_{cf} and dynamic fracture duration time DT of coals is approximately 9:9:2, 3:5:2, and 3:5:2, respectively, and those of non-coal rocks are 9:9:2, 6:9:5, 1:3:6, respectively, as shown in Table 1. For W_{ET}, W_{cf} and DT of coals, the weak bursting liability occupies the largest proportion, followed by heavy bursting liability, the least is for no bursting liability. For W_{ET}, W_{cf} and DT of non-coal rocks, the distribution lows of W_{ET}, W_{cf} are similar with that of coals, but that of DT is different with that of coals. The no bursting liability of non-coal rocks occupies the largest proportion, about 57.5%, so the classification criteria of W_{ET} and W_{cf} of coals can be used to determine the bursting liabilities of non-coal rocks, while that of DT cannot be used.

When the uniaxial compressive strength σ_c of non-coal rock is lower than 50 MPa, the percentage of non-coal rocks with heavy bursting liability is only 7.7%, and these with weak and no bursting liabilities are both 46.2%. Therefore, the bursting liability classification results of coals and non-coal rocks with $\sigma_c < 50$ MPa using W_{ET} are significantly different. However, the bursting liability classification results of coals and non-coal rocks with $\sigma_c > 50$ MPa using W_{ET} share a similar distribution characteristic. Similarly, the bursting liability classification results of coals and non-coal rocks with $\sigma_c < 50$ MPa using W_{cf} are significantly different, these with $\sigma_c > 50$ MPa using W_{cf} share a similar distribution characteristic, as shown in Figure 8b. Thus, it can be concluded that the classification criterions of W_{ET} and W_{cf} for coals are suitable for the bursting liability classifications of non-coal rocks. For the index DT, however, the proportion distributions of bursting liability evaluation results of coals and non-coal rocks are quite different, similar to the results evaluated by σ_c (Figure 5). For non-coal rocks, 57.5% are divided to the rocks with no bursting liabilities using DT classification criterions of coals, which is 16.6% for coals. Therefore, the classification standards of DT and σ_c for coals are unreasonable to classify the bursting liabilities of non-coal rocks.

4.1.2. Uniformity of Bursting Liability Classification Results Using Different Indices

For the same rock, when different bursting indexes are used, the rating results may be inconsistent. For example, when the dynamic fracture duration time DT and the elastic strain energy index W_{ET} were used to evaluate the bursting tendency of coals, 32% of the rating results were consistent, while 68% of the rating results were inconsistent. The consistency and inconsistency rate of bursting liability evaluation results of coals using two different indices are shown in Figure 9. The consistency rate of the bursting liability evaluation results by using elastic strain energy index W_{ET} and uniaxial compressive strength σ_c is 58%, which is higher than that of any other two indexes. The inconsistency rate of the bursting liability evaluation results by using elastic strain energy index W_{ET} and dynamic fracture duration time DT is 68%, which is higher than that of any other two indexes. Overall, for any two indices, the consistency rate of the bursting liability evaluation results of coals is about from 32–58%, and the inconsistency rate is about from 42–68%. Therefore, it is necessary to build a comprehensive rating method to evaluate the bursting liabilities of rocks.

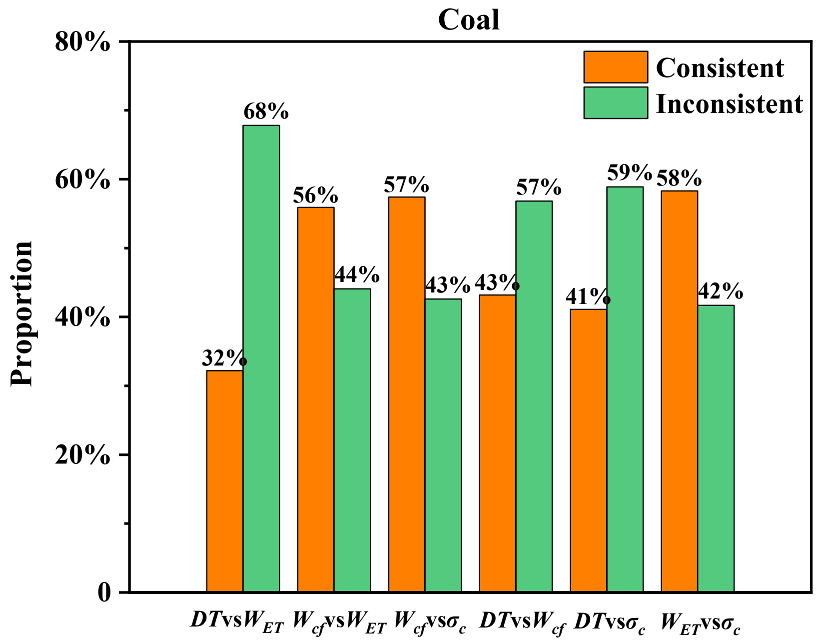

Figure 9. Consistency and inconsistency proportions of bursting liability evaluation results of coals using different indices.

4.2. Classification Criterions of Bursting Liabilities for Non-Coal Rocks

4.2.1. Bursting Liability Criteria of Elastic Strain Energy Index W_{ET} and Bursting Energy Index W_{cf}

As shown in Figure 8, there is a similar W_{ET} and W_{cf} distribution and percentage characteristics of coals and non-coal rocks, so it is feasible to use classification criteria of bursting liability indices W_{ET} and W_{cf} of coals to determine the bursting liabilities of non-coal rocks.

4.2.2. Bursting Liability Criterion of Brittleness Index *B*

According to the statistical results in Figure 7d, the distribution ranges of the brittleness index *B* of coal and non-coal rocks have no obvious differences. From the analysis in the sections above, it has been proved that the indexes W_{ET} and W_{cf} are reasonable to predict the bursting liabilities of non-coal rocks. Thus, the comparison screening method and statistical analysis have been used in this paper to establish the classification standards of brittleness index *B*. The bursting classification results of rocks determined by *B* is consistent with that of W_{ET} and W_{cf}. If the bursting classification results of W_{ET} and W_{cf} are inconsistent, the higher bursting category was chosen as the classification results of rocks determined by *B*. The data of brittleness index *B* and the bursting rating results have been shown in Figure 10. The concentration area has been framed by a dotted black line, and the cutoff point of three bursting liability grades also given in Figure 10, which is about 9 for no bursting liability and weak bursting liability, and 17 for weak bursting liability and heavy bursting liability, so the new classification criteria are heavy bursting liability with $B \geq 17$, weak bursting liability with $9 \leq B < 17$, and no bursting liability with $B < 9$, which is similar to the scale put forward by Li et al. [26].

4.2.3. Bursting Liability Criterion of Strength Decrease Rate SDR

As shown in Figures 7c and 8c, the distribution range of index *DT* and the associated proportion of coal and non-coal rocks have clear differences, so the *DT* was not suitable to be used in evaluating the rockburst tendency of non-coal rocks. A new index, the strength decrease rate (*SDR*), is defined as the ratio of uniaxial compressive strength σ_c and dynamic fracture duration time *DT*. The units of *SDR* are MPa/ms and indicates the drop speed of the bearing stress of rocks in the post-peak stage. Supposed that the bursting classification results of coals determined by *SDR* is consistent with that of uniaxial compression strength σ_c and dynamic fracture duration time *DT* of coals. The *SDR* cutoff point between heavy and weak bursting liability is very close to 0.3 MPa/ms, and the *SDR* cutoff point between weak and no bursting liability is close to 0.015 MPa/ms, as shown in Figure 11. The cutoff points were also applied in the bursting tendency rating of non-coal rocks, so the classification criteria of *SDR* can be set as heavy bursting liability with *SDR* > 0.3 MPa/ms, weak bursting liability with $0.015 < SDR \leq 0.3$ MPa/ms and no bursting liability with $0 < SDR \leq 0.015$ MPa/ms. Thirteen types of rocks were used in uniaxial compression tests, and the *SDR* values of the rocks were obtained, as shown in Table 4. The bursting classification results of the rocks were consistent with the field situation.

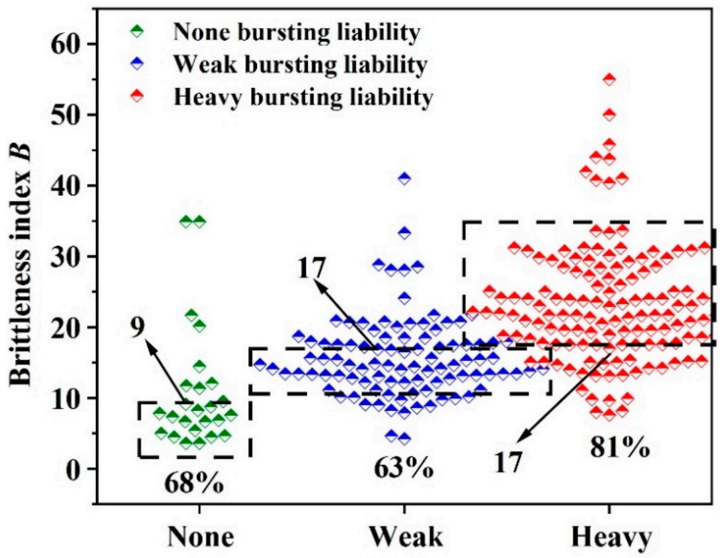

Figure 10. Bee colony map of the brittleness index *B*.

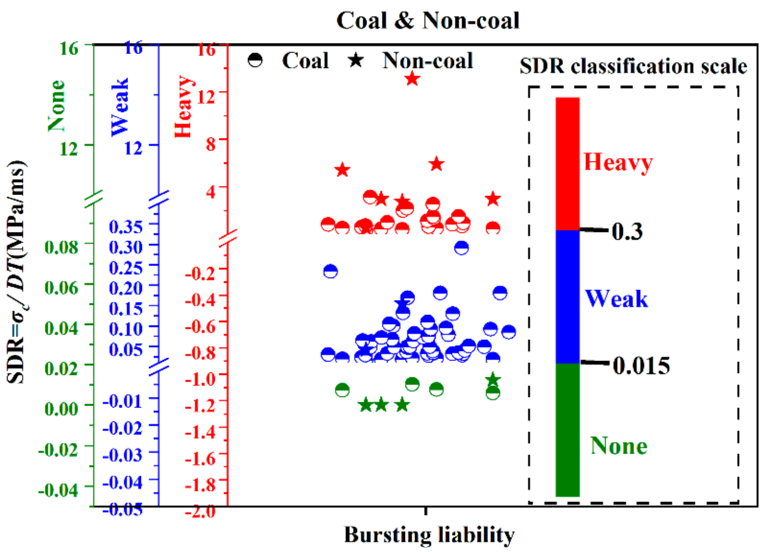

Figure 11. Distribution and classification scale of strength decrease rates (*SDRs*) of coal and non-coal rocks.

Table 4. SDR values of rocks tested in uniaxial compression tests.

Rock Type	*DT*/ms	σ_c/MPa	*SDR*(*MPa*/*ms*)	Rockburst Tendency
Yellow sandstone	187.17	44.96	0.240203275	Weak
White sandstone	297.29	36.87	0.124020317	Weak
Red sandstone	259.7534	74.96	0.288581401	Weak
Brown sandstone	392.884	67.54	0.171908248	Weak
Purple sandstone	121.6186	92.8	0.76304118	Heavy
Grey sandstone	110.1074	76.75	0.697046702	Heavy
Green sandstone	373.3643	69.14	0.185181068	Weak
Coarse marble	179.6753	64.7	0.360094014	Heavy
Fine marble	645.6298	99.2	0.153648422	Weak
Coarse granite	357.8491	76.27	0.213134531	Weak
Granite	94.0918	110.54	1.174810132	Heavy
Andesite	153.6499	193.43	1.258900917	Heavy
Coal	56.5551	39.55	0.69931801	Heavy

5. Discussion

For two different bursting indices, the inconsistent rate of the bursting liability evaluation results is about from 42–68%, so some comprehensive methods are necessary to be used to predict the bursting tendency of rocks, which we can summarize as follows: the geo-stress is a non-negligible factor for the occurrence of rock bursts, and the differences of the relationship between the uniaxial compression strength and geo-stress in coal bursting area and non-coal bursting area are discussed.

5.1. Comprehensive Bursting Liability Rating of Rock

It is widely known that the occurrence of rockbursts is a complex process and influenced by many factors. Therefore, if only a single bursting tendency index is used, the authenticity of evaluation results is unclear. Therefore, many comprehensive evaluation approaches were proposed to determine the bursting liability of rocks. Then, the process of establishing comprehensive evaluation methods has been drawn, as shown in Figure 12. The first step is distinguishing the rock types, i.e., coal or non-coal rock. After that, the comprehensive methods (i.e., fuzzy mathematical methods, linear or non-linear classification methods, simulation methods, support vector machine algorithms and so on) were used to rating the bursting liability rating of rocks. If the comprehensive rating results deviate for the actual situation, one has to go back to previous steps and re-establish the comprehensive method until the rating results are in accord with the actual situation.

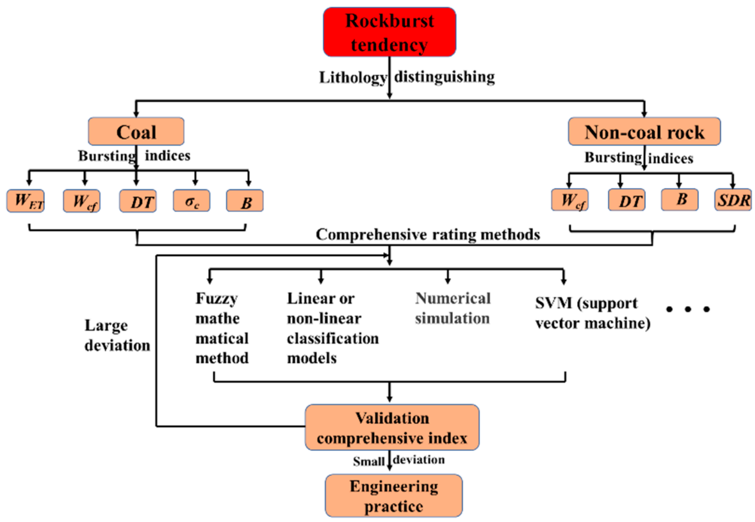

Figure 12. The establishment process of a comprehensive index of coal and non-coal rocks.

5.2. Geo-Stress Factors

With the depth of underground engineering increasing, the geo-stress levels are also increasing rapidly [31–34]. The geo-stress is an unignored factor affecting the occurrence of rockbursts, especially for non-coal rock engineering. As shown in Table 5, whether in a deep coal mine or in a shallow coal mine, the geo-stress values all exceed the uniaxial compressive strength of coals, and rockbursts occur in coal mines with buried depths of 230–1089 m, while in non-coal rock engineering, the non-coal rocks with a high uniaxial compressive strength do not experience rockbursts under low geo-stress levels. With the increase of the geo-stress levels, rockbursts occur in non-coal rock engineering, but the geo-stress values do not exceed the uniaxial compressive strength of non-coal rocks. In the Jinping II Hydropower Station, a rockburst did not occur in the marble with σ_c of 44.6–150.6 MPa under geo-stress of 11.2–22.3 MPa, and a rockburst occurred in the same marble under a geo-stress of 38.6–44.8 MPa, so the influence of geo-stress on rockbursts in non-coal rocks is worthy of being studied in depth.

Table 5. Uniaxial compressive strength and geo-stress statistics of bursting coal and non-coal rocks.

Rock Type	Underground Engineering	Geo-Stress (the Max)/MPa	σ_c/MPa	Depth/m	Rockburst (y/n)	Literature
Coal	Gaojiapu Coal Mine	37.29–38.67	18.18–20.47	820–1089	y	[35]
	Hujiahe Coal Mine	18.04–33.87	24.27–24.35	600–750	y	
	Mengcun coal mine	26.24–37.62	19.37–26.88	700–800	y	
	Ningnan coal mine	13.90–17.00	16.68–37.06	400–800	y	
	Xiaozhuang coal mine	21.23–30.17	13.23–20.62	487–691	y	
	Yadian coal mine	12.30–28.10	13.43–13.67	430–760	y	
	Zhaoxian coal mine	19.45–32.46	12.97–13.97	232–632	y	
	Chengshan coal mine	20–24	10	580	y	[36]
Non-coal rock	Jinping II Hydropower Station	11.2	44.6–150.6	130	n	[37,38]
		22.3	44.6–150.6	300	n	
		44.77	44.6–150.6	1800	y	
		38.6	44.6–150.6	2700	y	
		43	44.6–150.6	3005	y	
	Wanjiazhai Project	25	81–153	370	n	[39]
		29.5	70–20	460	y	
		30	70–20	480	y	
		29.5	70–20	460	y	
		30	70–20	480	y	

6. Conclusions

The basic mechanical parameters (i.e., Poisson's ratio μ, elastic modulus E, uniaxial compressive strength σ_c, and uniaxial tensile strength σ_t) and bursting liability indices (i.e., elastic strain energy index W_{ET}, bursting energy index W_{cf}, dynamic fracture duration time DT, and brittleness index B) of coals and non-coal rocks are compared in detail in this study. The main conclusions are as follows:

(1) The basic mechanical parameters (σ_c, E, and σ_t) of coal and non-coal rocks are quite different in distribution range. The σ_c, E, and σ_t maximum values of coals are 50 MPa, 46 GPa, 4 MPa, respectively. The maximum value of σ_c of non-coal rocks is six times higher than that of coals, and the maximum values of E and σ_t of non-coal rocks are about two and five times higher than that of coals, respectively. The μ values of coal and non-coal rocks share a similar distribution range.

(2) The W_{ET}, W_{cf} and B of coals and non-coal rocks share similar distribution ranges, and the distribution ranges of σ_c and DT for coals are much smaller than these for non-coal rocks. It can be concluded that the classification criteria of W_{ET} and W_{cf} for coals are suitable for non-coal rocks, while that of σ_c and DT are not suitable.

(3) The consistency rate of the bursting liability evaluation results of coals is only about 32–58%, and it is necessary to define a comprehensive method to evaluate the bursting liability of rocks.

(4) For non-coal rocks, the classification criterions of brittleness index B and strength decreases rate SDR (the ratio of uniaxial compressive strength σ_c and fracture duration time DT) have been redefined in this study as follows:
- The classification criterion of the brittleness index B: heavy bursting liability with $B \geq 17$; weak bursting liability with $9 \leq B < 17$; no bursting liability with $B < 9$.
- The classification criterion of the strength decrease rate SDR: heavy bursting liability with $SDR > 0.3$ MPa/ms; weak bursting liability with $0.015 < SDR \leq 0.3$ MPa/ms; no bursting liability with $0 < SDR \leq 0.015$ MPa/ms.

Supplementary Materials: The following are available online at https://www.mdpi.com/2076-3417/11/6/2641/s1, Table S1: Basic mechanical parameters of coals in China, Table S2: Basic mechanical parameters of non-coals in China, Table S3: Rockburst indices data of coals in China, Table S4: Rockburst indices data of non-coals in China.

Author Contributions: Conceptualization, K.D. and S.W.; Formal analysis, Y.S.; Funding acquisition, K.D. and S.W.; Investigation, Y.S.; Methodology, K.D. and S.L.; Supervision, K.D. and S.W.; Writing—Original draft, Y.S. and S.Y.; Writing—Review & Editing, K.D. and S.W. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the National Natural Science Foundation of China (Nos: 51904333, 51774326 and 41702350), and the Fundamental Research Funds for the Central Universities of Central South University (No. 2020zzts714).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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