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Research Article

Comprehensive Analysis of Stability of Coal Seam Composite Roof Based on Analytic Hierarchy Process

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The composite roof structure of coal roadway is complex, and its stability is related to lithology of strata, strata thickness, number of strata, strata location, and interlayer cohesive force. Based on a simplified model of the composite roof structure, simulation test, analytic hierarchy process (AHP), and Matlab, programs are employed to comprehensively analyze the structural stability of roofs. The structural stability of the composite roof is demonstrated to decrease with the lithology of strata, strata thickness, and interlayer cohesive force and increase in number of strata and distance of hard-and-thick strata from the roadway. The decreasing order of influence of these factors on the composite roof structure is as follows: lithology of strata, strata thickness, number of strata, strata location, and interlayer cohesive force. Lithology of strata is the main factor affecting stability. The bending strength decreases with the increase in number of strata, and the influence of strata position on stability decreases from the first layer to the fourth layer. According to the AHP, an expression for the comprehensive influence coefficient (k) for the stability of the composite roof structure is proposed, and the surrounding rocks are divided into three levels using this equation: grade I with $0.7 < k < 1$ (stable), grade II with $0.4 < k < 0.7$ (slightly stable), and grade III with $0 < k < 0.4$ (unstable). A scientific basis to evaluate the stability and control of the composite roof of a complex structure is thus provided.

1. Introduction

The composite roof structure of a coal seam is complex and changeable, and its stability seriously affects the stability of the surrounding rock of a roadway; this frequently affects the surrounding rock support of the roadway and leads to roof caving accidents [1–4]. Therefore, research on the structural stability of the composite roof is critical to the stability analysis of the surrounding rock of the roadway.

The composite roof generally comprises rock that is layered by soft or hard rock interbred or containing weak interlayers and has weak plane development characteristics for the stratum structure, many weak interlayers, small strata thickness, and low interlayer cohesion force [5–7]. Many scholars have studied and discussed the stability of composite roof structures of coal seams [8–12]. The main factors affecting the stability of the composite roof structure are considered to be the lithology of strata, strata thickness, number of strata, strata location, and interlayer cohesive force. The comprehensive strength index of the composite roof is introduced to analyze stability; however, the equation does not consider the influence of strata location, number of strata, and interlayer cohesion force [13–15]. The application of this equation has certain limitations. In this paper, the theoretical analysis, laboratory simulation test, and analytic hierarchy process (AHP) [16–19] are applied to propose an expression for the comprehensive influence coefficient (k) of the composite roof according to the influence of each main factor on the stability. This work provides support for more comprehensive and systematic analyses and evaluation of the structural stability of the composite roof.

2. Theoretical Analysis of the Stability of Composite Roof

For composite roof structures, the ratio of the thickness of each stratum to the span of coal roadway must satisfy the thin plate hypothesis [20, 21] (i.e., the thickness of the rock stratum is less than 1/5 of the span of coal roadway). In theoretical analysis, the composite roof is generally simplified for simply supported beam mechanical models [22]. As shown in Figure 1, the flexural strengths of the composite roof under different strata lithology, strata thickness, and number of strata are calculated to measure the stability of the composite roof structure. The maximum stress in the span of rock beam in each stratum is as follows:

$$\begin{cases} \sigma_1 = \dfrac{h_1 N}{h_1 + h_2 + h_3} \pm \dfrac{ql^2 E_1 h_1}{4k\left(E_1 b_1 h_1^3 + E_2 b_2 h_2^3 + E_3 b_3 h_3^3\right)}, \\ \sigma_2 = \dfrac{h_2 N}{h_1 + h_2 + h_3} \pm \dfrac{ql^2 E_2 h_2}{4k\left(E_1 b_1 h_1^3 + E_2 b_2 h_2^3 + E_3 b_3 h_3^3\right)}, \\ \sigma_3 = \dfrac{h_3 N}{h_1 + h_2 + h_3} \pm \dfrac{ql^2 E_3 h_3}{4k\left(E_1 b_1 h_1^3 + E_2 b_2 h_2^3 + E_3 b_3 h_3^3\right)}, \end{cases} \tag{1}$$

where σ_i represents the maximum stress in the rock beam span (MPa); $i = 1, 2, 3$; q stands for the vertical uniform load (kN); N displays the horizontal axial force (kN); l is the rock beam span (m); and b is the width of the rock beam. Taking b as 1 m, E_1, E_2, and E_3 are the elastic moduli of the rock; I_1, I_2, and I_3 are moments of inertia; and h_1, h_2, and h_3 are the thickness of the rock formation (m).

The above equation indicates that the tensile strength of the composite roof structure decreases with the elastic modulus and increase in the number of strata when the total thickness of the composite roof structure remains constant under certain conditions of q, N, and l, and the weak interlayer with lesser thickness easily forms a stress concentration area compared with other strata. Although it is concluded that the stability of the composite roof is related to the lithology, thickness, and number of strata, the mechanical theory does not consider the influence of strata location and interlayer cohesive force and cannot fully reflect the influence of the structural characteristics on stability. Therefore, based on the mechanics theory, the influence of structural characteristics of the composite roof on stability is studied by a simulation test.

3. Experimental Study on Stability of Composite Roof for Various Factors

3.1. Test Scheme. Under the action of vertical ground and horizontal tectonic stress, the latter will weaken the tensile stress of the lower edge of each rock layer of the composite roof structure of the coal roadway when the bending and sinking of the roof structure is low. Furthermore, the latter will produce a second-order effect when the bending and sinking of the roof structure is high, aggravating the flexural deformation of the rock stratum and easily leading to the instability and damage of the composite roof coal roadway. Therefore, the stability of the composite roof structure can be analysed by measuring the bending strength of the composite roof structure.

Based on the simplified composite beam mechanics theory of the composite roof structure [13], two different lithology test materials were selected to establish the experimental model ((a) in Figure 2): yellow and black sandstone. The physical and mechanical properties of these materials are listed in Table 1. In the course of the test, by varying the number of strata, position of the strata, and interlayer cohesive force, concentrated loads were applied to different composite beam structures (Figure 2), and the bending strength was tested (Table 2) to analyze the stability of the composite roof structure. Because the interlayer cohesion force of the composite roof is weak in practical engineering, low strength cement mortar is used to simulate the interlayer cohesion force of rock strata ((b) in Figure 2).

3.2. Analysis of Test Results

3.2.1. Influence of Lithology and Interlayer Cohesion on the Stability of Composite Roof. To study the influence of the composite roof structure on the stability of the roadway surrounding rock, a comprehensive strength index [13] was applied, which is defined as follows:

$$q_k = \frac{\sum_i^n q_i h_i}{h}, \tag{2}$$

where q_k displays the comprehensive strength index of the composite beam, q_i is the strength of each rock layer of the composite beam, h_i represents the thickness of each rock layer of the composite beam, and h is the total thickness of the composite beam.

The following observations can be drawn from the comparison of the bending strengths of the combined models of different lithologies (Figure 3):

(1) For the two-to-four-layer composite models, the flexural strengths decrease with the comprehensive strength index, ranging from black to yellow sandstones, and the average reduction rates of the flexural strengths of the combined models with interlayer cohesion force, but no interlayer cohesion force is 0.38. Thus, the lithology is indicated to have a great influence on the stability of the coal seam composite roof under vertical ground stress.

(2) The flexural strengths of the composite models without interlayer cohesive forces are lower than those of the composite models with interlayer cohesive forces, with an average reduction rate of 0.26, which indicates that interlayer cohesive force is one of the prominent factors affecting the stability of the composite roof of coal roadway.

(3) To consider the influence of interlayer cohesive force on the stability of composite roof, according to the linear relationships between the compressive strengths of the composite models without and with interlayer cohesive forces, as shown in Figure 4, the coefficient A is introduced to improve the expression of the comprehensive strength index; the coefficient A is 1 when there is no interlayer cohesive force and is 1.3333 when there is interlayer cohesive force. The comprehensive strength index q_{k1} is given by the following equation:

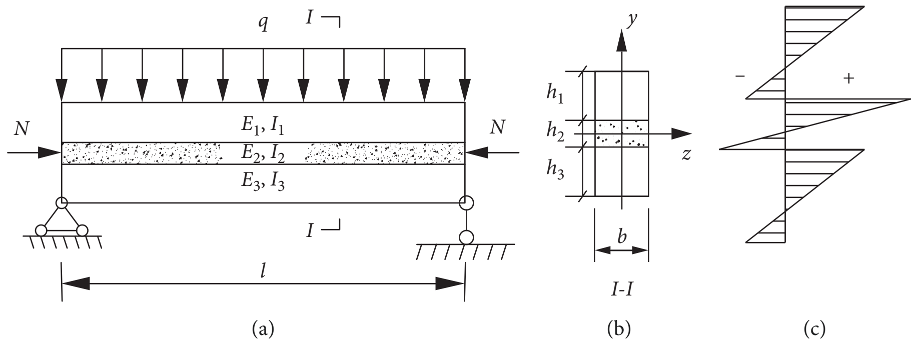

Figure 1: Mechanical model of the composite rock beam: (a) beam plane; (b) beam section; (c) stress distribution.

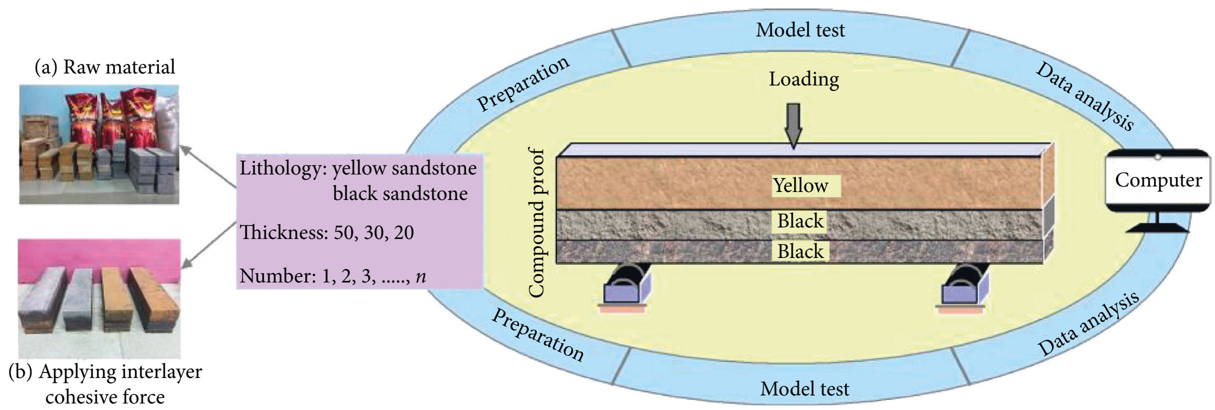

Figure 2: Simplified model of the bending test device.

Table 1: Physical and mechanical parameters of sandstone.

Kinds of strata	Dry density γ (kN/m^3)	Natural water absorption	Softening coefficient	Compressive strength σ (MPa)	Tensile strength σ_t (MPa)	Elasticity moduli E (10^4 MPa)	Poisson ratio μ	Internal friction angle ϕ (°)	Cohesion C (MPa)
Yellow sandstone	21.551	5.140	0.588	36.669	1.360	2.810	0.086	36.760	7.054
Black sandstone	25.224	1.910	0.812	64.171	2.390	2.020	0.070	37.344	9.891

$$q_{k1} = A\frac{\sum_i^n q_i h_i}{h}. \quad (3)$$

3.2.2. Influence of the Number of Rock Layers on the Stability of Composite Roof. By comparing the bending strengths of different combinations of layers (Figure 5), the following observations are made:

(1) Under the vertical load, the bending strengths of the combined models with the same thickness decrease with increase in the number of layers. The average bending strength ratio of the one-layer, two-layer, three-layer, and four-layer interlayer cohesive force models is 1.00 : 0.67 : 0.53 : 0.47, and the average reduction rates are 0.00, 0.34, 0.47, and 0.54, respectively. When the number of layers in the combined model are more, the rate of reduction is lower, and with the increase of the number of layers, the stability of the roof is reduced by the influence of the variation of number of layers; furthermore, the stability of the roof stratum for more than four layers is stabilized by the influence of the number of layers. Table 2 indicates that the combined strength indexes of the one-to-four-layer combined models are the same for identical thicknesses, indicating that the comprehensive strength index does not consider the influence of the number of layers on the stability of the composite roof.

(2) To analyze the influence of strata number, the coefficient B_i is introduced to improve the equation of the comprehensive strength index, whose value is shown in Table 3. The value of B_i is determined using the ratio of the average bending strength of the

Table 2: Comparison of bending strengths of combined models of different lithologies.

Layer number	Combination mode (mm) (from top to bottom)	Bending strength (MPa)		Comprehensive strength index	Comprehensive influence coefficient	
		Noncohesive layer	Cohesive layer		Noncohesive layer	Cohesive layer
One layer	① Black 100	10.480	—	64.170	1.000	—
	② Yellow 100	5.460	—	36.670	0.570	—
Two layers	① Black 50 + 50	6.530	8.370	64.170	0.613	0.678
	② Black 50 + yellow 50	5.160	7.170	50.420	0.525	0.576
	③ Yellow 50 + black 50	4.490	5.910	50.420	0.547	0.598
	④ Yellow 50 + 50	3.860	5.760	36.670	0.390	0.427
Three layers	① Black 50 + 30 + 20	5.310	6.840	64.170	0.545	0.610
	② Black 50 + yellow 30 + black 20	5.190	6.650	55.920	0.534	0.591
	③ Yellow 50 + black 30 + 20	3.830	5.040	50.420	0.448	0.499
	④ Yellow 50 + 30+20	2.980	4.500	36.670	0.319	0.356
Four layers	① Black 30 + 20 + 30 + 20	4.880	6.260	64.170	0.503	0.568
	② Black 30 + yellow 20 + black 30 + 20	4.560	6.030	52.250	0.419	0.473
	③ Yellow 30 + black 20 + 30 + 20	4.300	5.830	52.250	0.426	0.479
	④ Yellow 30 + 20 + 30 + 20	2.560	3.820	36.670	0.287	0.324

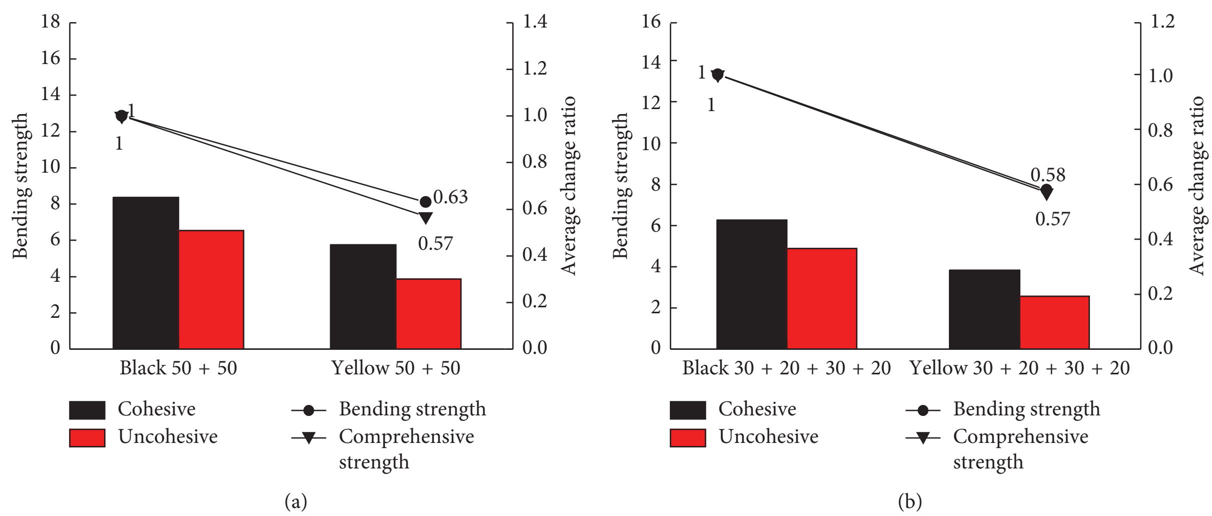

Figure 3: Contrast diagrams of bending strengths of different lithology of strata: (a) two layers; (b) four layers.

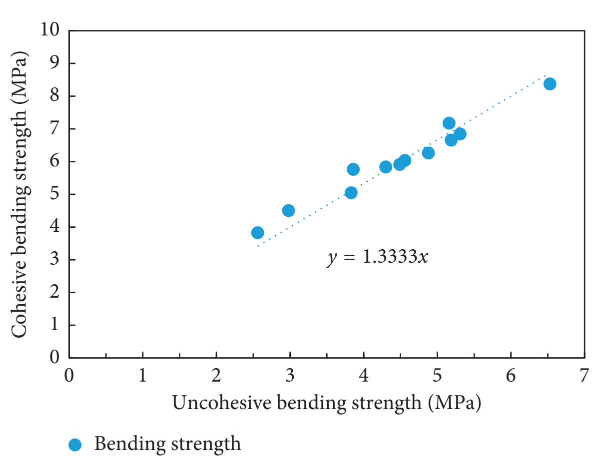

Figure 4: Linear relationship between interlayer cohesive force and no interlayer cohesive force.

combined model of different layers of the same thickness of the composite beam (one layer : two layers : three layers : four layers = 1 : 0.67 : 0.53 : 0.47) are considered. An increase in the number of layers in the rock layer reduces the stability of the roof. When the rock layer reaches more than four layers, the composite roof structure tends to stabilize, and the value of B_i above the four layers remains constant. The comprehensive strength index q_{k2} is given by the following equation:

$$q_{k2} = B_i \frac{\sum_i^n q_i h_i}{h}. \tag{4}$$

3.2.3. Influence of Position on the Stability of Composite Roof. Figure 6 is a comparison of the flexural strengths of the combined models at different locations. Furthermore,

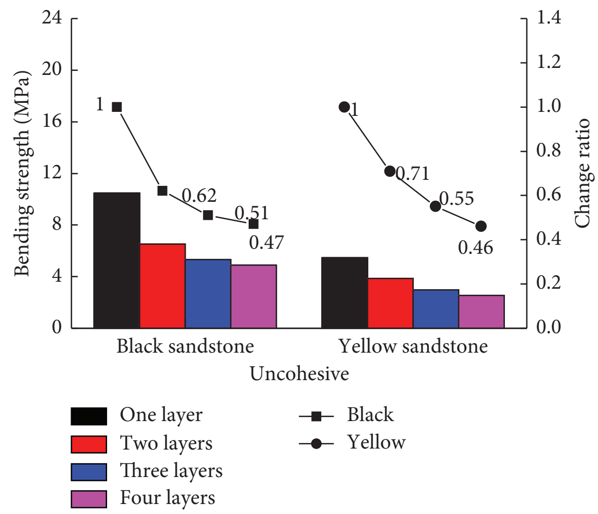

Figure 5: Comparison of bending strengths of combined models with different layers.

Table 3: Influence coefficient B_i of the number of strata.

Layer number	One layer	Two layers	Three layers	Four layers or more
B_i	1.00	0.67	0.53	0.47

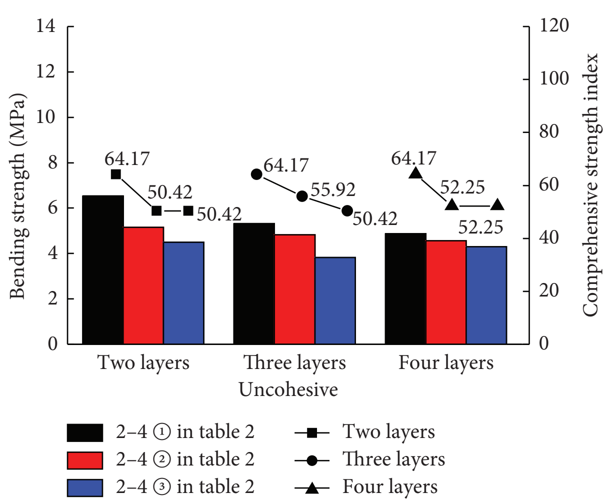

Figure 6: Comparison of bending strengths of combined models at different locations.

combining with the data of Figure 6 and Table 2, the following are noted:

(1) By changing the position of each rock stratum, the farther the black sandstone with better lithology and the thicker the rock stratum from the roadway, the higher the strength of the composite roof structure. However, with the increase in the number of strata, the influence of strata location on the strength of the composite roof is smaller. Because the horizontal load is not applied to the composite beam during the test, the influence of rock strata location on the composite beams is contrary to the deformation and failure law of the roof of the actual coal roadway [23]. Thus, in conclusion, the closer the hard thick rock layer is to the roadway, the greater the bending strength of the composite roof, and the influence of each rock layer on the overall strength decreased from the first layer to the fourth layer.

(2) From the two-layer to four-layer combination models, the comprehensive strength indexes are equal; however, the flexural strengths are different. This indicates that the comprehensive strength index does not consider the influence of rock strata location on the stability of the composite roof structure. The comprehensive strength index is further improved as given below.

The analysis demonstrates that, under the action of a vertical load, when the thickness of the composite roof structure of the coal roadway is constant, the stability decreases with strata lithology, strata thickness, and interlayer cohesive force and the increase in strata number and distance of the hard-and-thick-strata from the roadway. The factors affecting the composite roof structure can thus be arranged in the decreasing order as follows: lithology of strata, strata thickness, number of strata, strata location, and interlayer cohesive force.

4. Comprehensive Analysis of Various Factors Based on AHP

4.1. Principles of AHP. AHP is a method of quantitative analysis based on qualitative analysis. The purpose of this method is to decompose complex problems into several levels and several factors and to compare the importance of these two categories to determine their weights [24, 25]. The steps are illustrated as follows:

(1) Determine the factors for analysis.

(2) Construct a judgment matrix according to the principles of AHP. The relevant indicators and factors of each layer are compared using the 9-level scale method (summarized in Table 4) to establish the judgment matrix F. Here, b_{ij} is the element in the judgment matrix, $F = (b_{ij})\ n \times n$, where $b_{ij} > 0$, $b_{ji} = 1/b_{ij}$, and $b_{ii} = 1$.

(3) The maximum eigenvalues of the judgment matrix and the corresponding eigenvectors were calculated using Matlab software, and the relative weights of each factor are obtained.

(4) Judgment matrix consistency test: owing to the subjective judgment of the person involved in the establishment of the judgment matrix, the judgment may be inconsistent. To ensure the validity of the evaluation, the consistency ratio CR is required to check the consistency of the judgment matrix:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \tag{5}$$

Table 4: 9-scale method.

Degree of importance	Definition
1	Representing two factors, the former is as important as the latter
3	Representing two factors, the former is slightly more important than the latter
5	Representing two factors, the former is generally more important than the latter
7	Representing two factors, the former is more important than the latter
9	Representing two factors, the former is absolutely more important than the latter
2, 4, 6, 8	Representing two factors, the former is more important than the latter between the above adjacent levels

where CR represents the consistency ratio. When $CR < 0.1$, the degree of inconsistency of F is within the allowable range, and the judgment matrix is feasible. Here, CI displays a consistency indicator, $CI = (\lambda - n)/(n - 1)$, where λ is the maximum eigenvalue of the judgment matrix F. n is the sum of the eigen roots of F. RI is the average random consistency test index [26]. The value of RI for $n = 1, 2, 3, \ldots, 10$, is shown in Table 5.

4.2. Calculation of Rock Layer Position Weight

4.2.1. Constructing a Judgment Matrix. According to a qualitative analysis of the factors influencing the stability of the composite roof structure by simulation tests combined with the principle of AHP, the relative importance degree between the two rock layers is analysed. According to the 9-scale method, the judgment matrices F_1, F_2, and F_3 of the 2, 3, and 4 layers can be constructed as follows:

$$F_1 = \begin{bmatrix} 1 & 2 \\ \frac{1}{2} & 1 \end{bmatrix}, \quad F_2 = \begin{bmatrix} 1 & 2 & 3 \\ \frac{1}{2} & 1 & 2 \\ \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix}, \quad F_3 = \begin{bmatrix} 1 & 2 & 3 & 4 \\ \frac{1}{2} & 1 & 2 & 3 \\ \frac{1}{3} & \frac{1}{2} & 1 & 2 \\ \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix}. \tag{6}$$

4.2.2. Calculation Results and Analysis. The contribution rate of the composite roof rock stratum (the weight of each rock layer) is summarized in Table 6. The maximum eigenvalues and eigenvectors of the matrices F_1, F_2, and F_3 are calculated using Matlab software. The maximum eigenvalues are $\lambda_1 = 2.0000$, $\lambda_2 = 3.0092$, and $\lambda_3 = 4.0310$, and the eigenvectors are normalized to calculate the weight ratios of each rock layer as $w_1 = [0.6667, 0.3333]$, $w_2 = [0.5396, 0.2969, 0.1634]$, and $w_3 = [0.4673, 0.2772, 0.1601, 0.0954]$.

By substituting each of the rock stratum eigenvalues into equation (5), the consistency ratios $CR_1 = 0.0000$, $CR_2 = 0.0089$, and $CR_3 = 0.0116$ are calculated, all of which are less than 0.1000, indicating that F_1, F_2, and F_3 are within the allowable range of inconsistency and meet the consistency test.

According to the AHP, the contribution rates (w_i) of each rock layer of the two-layer, three-layer, and four-layer composite roof are obtained, and the comprehensive strength index expression q_{k3} of the composite roof is improved as follows:

$$q_{k3} = \frac{\sum_i^n w_i q_i h_i}{h}. \tag{7}$$

4.3. Calculation of Weights of Influencing Factors of Composite Roof Structure

4.3.1. Constructing a Judgment Matrix. According to the research of the experiment and inquiry with experts, the degree of influence of the formation lithology, thickness of the stratum, number of strata, position of the stratum, and cohesion of the interlayer on the stability of the composite roof is qualitatively given. The judgment matrix F_4 can be constructed according to the 9-scale method as follows:

$$F_4 = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ \frac{1}{2} & 1 & 2 & 3 & 4 \\ \frac{1}{3} & \frac{1}{2} & 1 & 2 & 3 \\ \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & 1 & 2 \\ \frac{1}{5} & \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix}. \tag{8}$$

4.3.2. Calculation Results and Analysis. Matlab software was used to calculate the maximum eigenvalue and eigenvector of matrix F_4, in which the largest eigenvalue is $\lambda_4 = 5.0681$. The eigenvectors were normalized to calculate the weight ratio of each rock layer as $w = [0.4185, 0.2625, 0.1600, 0.0972, 0.0618]$. By substituting the eigenvalues λ_4 of each rock layer into equation (5), the consistency ratio

Table 5: Values of RI.

Matrix order	1	2	3	4	5	6	7	8	9	10
RI	0.0000	0.0000	0.5149	0.8931	1.1185	1.2494	1.3450	1.4200	1.4616	1.4874

Table 6: Rock layer strength contribution rate w_i.

Strata location (number of strata)	Two layers	Three layers	Four layers and above
First layer	0.6667	0.5396	0.4673
Second layer	0.3333	0.2969	0.2772
Third layer	–	0.1634	0.1601
Fourth layer and above	–	–	0.0954

Table 7: Classification table based on the comprehensive influence coefficient of the composite roof structure.

Factor	Rank	Comprehensive strength coefficient	Strata characteristics	Bending strength (MPa)
	I	$0.7 < k < 1$	Stable	6.53–10.48
q_k	II	$0.4 < k < 0.7$	Slightly stable	3.86–6.53
	III	$0 < k < 0.4$	Unstable	0.00–3.86

CR = 0.0150, which is less than 0.1000, indicating that F_4 is within the allowable range of inconsistency and satisfies the consistency test. Therefore, the influence of stratum lithology, rock thickness, stratum layer, rock stratum location, and interlayer cohesive force on the stability of the composite roof structure is 0.4185, 0.2625, 0.1600, 0.0972, and 0.0618, respectively.

5. Classification of Composite Roof Stability Based on the Comprehensive Influence Coefficient

5.1. Composite Roof Comprehensive Influence Coefficient. According to the analysis of the factors affecting the stability of the composite roof structure, the influence of strata lithology, rock thickness, strata layer, interlayer cohesive force, and the comprehensive influence coefficient of the composite roof structure is determined. Because equations (3), (4), and (6) are derived based on equation (2), the influence of lithology and thickness of strata has been considered in equation (2); the degrees of influence of strata lithology, strata thickness, number of strata, location, and interlayer cohesive force on the stability of composite roof structure are 0.4185, 0.2625, 0.1600, 0.0972, and 0.0618, respectively. When the influence of number of strata, strata location, and interlayer cohesive force is further considered, the degrees of influence of number of strata, strata location, and interlayer cohesive force based on the strata lithology and strata thickness are then 0.23, 0.14, and 0.09, respectively. Considering the comprehensive equations (2)–(4), and (6) and the ratio of the influence of the interlayer cohesive force, strata location, and number of strata location on the stability of the composite roof structure (0.23 : 0.14 : 0.09) along with the lithology of the rock stratum, the expression k of the comprehensive influence coefficient of the composite roof structure is derived:

$$k = \frac{\left(0.09A\left(\sum_i^n q_i h_i/h\right) + 0.14\left(\sum_i^n w_i q_i h_i/h\right) + 0.23B_i\left(\sum_i^n q_i h_i/h\right)/0.46\right)}{q_{i\max}}, \tag{9}$$

where k is the comprehensive influence coefficient of the composite roof structure, w_i is the strength contribution rate of each stratum of composite roof $(0 < w_i < 1)$, q_i is the strength of each weak layer of composite roof, h_i is the thickness of each weak layer of composite roof, h is the total thickness of composite roof strata, and A is the coefficient of adhesion between layers. Taking A as 1 when there is no interlayer cohesive force and A as 1.3333 when there is interlayer cohesive force, $q_{i\max}$ is the best rock layer strength for composite roof stability, B_i is the layer coefficient of each rock layer of the composite roof, and these values are summarized in listed Table 3.

5.2. Composite Roof Stability Classification. Because the coal seam composite roof has many weak interlayers, different rock layers with different strengths, and large thickness differences, the stability is the result of the combination of lithology of strata, strata thickness, strata location, number of strata, and interlayer cohesive force. The stability of the composite roof structure is further classified according to the results of the comprehensive influence coefficient calculation, as summarized in Table 7.

6. Conclusion

In this study, based on the simplified theoretical theory of composite beam mechanics, combined with the simulation test, AHP, and Matlab software, the influence of the rock layer strength, thickness of the rock stratum, number of strata, position of the stratum, and interlaminar adhesion force is considered comprehensively; the comprehensive influence coefficient of the composite roof structure is proposed, and its stability is further analysed. The following detailed conclusions are drawn:

(1) Under the vertical load, the stability of the composite roof structure of the coal seam decreases with the lithology of the stratum, interlayer cohesive force, and thickness of the stratum as well as the increase of the stratum and distance between the hard thick stratum and the roadway; the influence degree of each factor on the composite roof structure from large to small is as follows: lithology, thickness of strata, number of strata, location of strata, and interlayer cohesion force. After changing the position of the weak strata, the closer the hard and thick strata are to the roadway, the greater is the flexural strength of the composite roof, and the influence of the number of strata on the overall strength decreases from the first layer to the fourth layer. After introducing the comprehensive strength coefficient, it is found that the index does not consider the influence of the number of layers, location of the strata, and interlayer cohesive force on the stability of the composite roof structure, which requires further improvement based on future investigations.

(2) Considering the influence of the location of the rock stratum, the number of strata, and the interlayer cohesive force on the composite roof structure, the comprehensive strength index equation is improved. Furthermore, the weight between the influencing factors of the composite roof structure stability and the weight of the position of each stratum on the stability of composite roof are obtained quantitatively using the AHP. Based on this, the equation of the comprehensive influence coefficient is proposed, which provides a basis for the stability analysis of the composite roof structure.

(3) The stability of the composite roof structure can be divided into three levels using the equation of the comprehensive influence coefficient: stable ($0.7 < k < 1$), slightly stable ($0.4 < k < 0.7$), and unstable ($0 < k < 0.4$). The smaller the comprehensive influence coefficient is, the worse the stability of the composite roof structure is in the coal seam.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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