Study on the Relationship Between Suspended Solids Concentration and Tur-bidity in Coal Mine Water

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Abstract

Coal mine water in China is mainly mine water containing suspended solids (SS). The relationship between suspended solids and turbidity in mine water with different SS content gradients was studied and a model formula was established. Finally, the accuracy of the model formula is verified by the actual detection values of five kinds of mine water. Two conversion formulas for turbidity and suspended matter have been obtained in the study. When the suspended matter content is 0-200mg/L, the relationship curve between turbidity and SS is \( y = 0.9336x - 3.1393, R^2 = 0.9986 \); When the suspended matter content is 200-600 mg/L, the relationship curve between turbidity and SS is \( y = 0.5314x + 94.421, R^2 = 0.9905 \). Finally, the study has used the measured values of SS in other coal mines and the calculated values obtained from the formula to carry out error analysis. It is found that the error of the relationship between turbidity and SS with a suspended matter content of 0~200mg/L is controlled within 4%; the error of the relationship between turbidity and SS of mine water with a suspended matter content of 200~600mg/L is controlled within 5%. Considering the unavoidable error factors, it is considered that the model formula can be applied to the detection of suspended solids in actual mine water.

1 Introduction

Coal mine water \(^{[1-3]}\) is the underground water that accompanies the coal mining process. Generally, the coal-bearing strata are located below underground aquifers, and 97% of coal mines in China are underground mines. Therefore, a large amount of mine water must be discharged to ensure that coal mining is safe. Natural and man-made factors influence the production of mine water. Natural factors include geological conditions and surface water bodies. Human factors include water leakage from exploration boreholes and water accumulation in goaves. According to statistics, approximately 4.2 billion m\(^3\) of mine water resources are discharged during coal mining in China; thus, treating mine water resources is imperative \(^{[4-6]}\).

At present, China classifies mine water into five categories \(^{[7-10]}\): clean mine water, mine water containing suspended solids (SS), mine water with high salinity, acid mine water, and special polluted mine water. Among them, mine water with SS accounts for 60% of the five types of mine water. This type of mine water has the following water quality characteristics: neutral, mostly gray-black color, and high amount of suspended matter and turbidity. According to the actual measurement statistics of the SS content in mine water, the mines with SS content of less than 300 mg/L account for approximately 80%, while the mines with SS content of more than 500 mg/L account for less than 12%. Suspended matter in water refers to the solid matter trapped in a 0.45 um filter membrane from water and is dried to a constant weight at 103°C−105°C. Turbidity in water is the measurement of suspended and colloidal particles in water with size greater than 0.15−0.2 µm. Both suspended matter and turbidity are indicators that reflect the coarsely dispersed particles in the water, and a certain connection exists between the two.

SS content and turbidity are the most important water quality indicators for mine water containing suspended solids, and their real-time monitoring is required before and after treatment of mine water.
However, SS content is determined according to the national standard GB 11901-89, which is a gravimetric method\textsuperscript{[11–13]}; this method is simple but cannot be used for real-time monitoring. Turbidity is measured using the national standard GB 13200-91, which is an optical method\textsuperscript{[14]}. Compared with the method for measuring suspended matter, that of turbidity is simple, convenient, and involves real-time monitoring. Furthermore, the real-time monitoring of SS and turbidity may be realized by establishing the relationship between mine water turbidity and SS content, thereby allowing the SS content to be calculated based on turbidity. However, no existing relevant literature has discussed the relationship between wastewater turbidity and SS in coal mine water\textsuperscript{[15–20]}. Therefore, this area of research is important.

The accurate conversion relationship between SS and turbidity in coal mine water was determined by collecting six different coal mine waters, and one sample was selected as the original water sample to configure mine water with different SS content gradients. The actual SS and turbidity in water were measured using national standards. According to the actual measured turbidity and SS values, the relationship between the two was studied, and the relationship formula between turbidity and SS under different gradients was established. Finally, the five other actual detection values of coal mine water and the accuracy of correction model formula were verified.

SS in mine water refer to solid particles, such as coal dust, rock dust, and clay, produced by a series of physical, chemical, and biochemical reactions that occur when rock layers and buried coal come into contact with groundwater during coal mining. The SS in mine water are characterized by small particle size, low density, poor sedimentation effect, and poor sensory properties, and their content is generally tens to hundreds of milligrams per liter. Suspended matter is mainly obtained in moving water but can be separated in still water as light ones float while heavy ones sink. Mine water containing suspended solids is generally black, but its total hardness and salinity are not high.

Turbidity refers to the degree of obstruction of the solution to the passage of light, including the scattering of light by suspended matter and the absorption of light by solute molecules. The composition of mine water is simple and its organic solute content is low. The main factors affecting its turbidity are not only related to the content of suspended matter in the water but also to the size, shape, and refractive index of the suspended matter. When the concentration of suspended solids in the liquid increases or decreases, the turbidity value also increases or decreases. However, the amount of scattered light, chroma, and particle size, shape, and composition are all related to the reflection index. When the concentration of the suspended matter is the same but the material composition is different, scattering the same amount of light is impossible. Therefore, turbidity is related to suspended matter, but this relationship cannot usually be quantified.

The method for measuring SS is the national standard GB 11901-89, which is a gravimetric method. SS are dried after the mine water sample is filtered, weighed under laboratory conditions, and weighed after cooling. SS content can be determined by comparing the result of the subtracted mass of the two weighings with the sample volume. The turbidity measurement method is the national standard
GB13200-91, which is the optical method. A portable turbidity meter can be used for sampling and
determination in the laboratory or in the field. When determining turbidity, the sample should be shaken
vigorously. Suspended matter content and turbidity are both important water quality indicators of mine
water, but their measurement methods have certain differences. According to national standards, the SS
content must be determined in a laboratory, which requires a matching drying device and cooling device
and takes a long time. When the sample is sent from the mine to the laboratory for measurement, too
much time is consumed, the cost is increased, and obtaining continuous dynamic changes in the content
of SS in mine water is impossible. Turbidity is measured in much simpler and faster method. A sample
can be measured directly on the spot, and the method can realize continuous dynamic online monitoring
of mine water. Thus, exploring the relationship between SS content and turbidity in mine water is of
considerable significance for simplifying the determination of SS content and realizing the online
continuous dynamic monitoring of SS content.

2 Materials And Methods

2.1 Instruments and reagents

Instruments: 2100Q portable turbidity meter, vacuum pump, analytical balance, weighing bottles, CN-CA
filter membrane (pore size 0.45 um), dryer, oven, beakers (50, 100, 500, and 1000 mL).

2.2 Methods

2.2.1 Water quality analysis

The experimental water samples were obtained from seven different coal mines in the Henan, Shanxi,
Shaanxi, and Inner Mongolia provinces. The turbidity and suspended matter content in water were
determined according to the national standard for turbidity and suspended matter content.

(1) Determination of suspended matter content

In the experiment, the content of SS in coal mine water was determined using the national standard
GB11901-89 gravimetric method. Three parallel samples were set up during the experiment to ensure the
accuracy of the determined SS. An analytical balance was used to weigh the filter membrane and the
weighing bottle to \( m_1 \) when the filter is not filtered, and drying, cooling, and weighing were repeated until
the weight difference between the two weighings was \( \leq 0.2 \) mg. Then, a certain amount of different
turbidity is taken Place the mine water in a beaker. The mine water was stirred with a glass rod for 3 min
to mix the water sample evenly, and water samples from the upper, middle, and lower parts of the beaker
were obtained and placed into three beakers. A vacuum pump was used for suction filtration. The filter
membrane was placed in the original weighing bottle, moved into the oven, and dried at 103°C–105°C.
After drying, the weighing bottle was placed into a desiccator and allowed to cool to room temperature.
The analytical balance was used to weigh \( m_2 \) again. \( m_2 - m_1 \) is the suspended matter content of mine
water, and the average value of three water samples is the suspended matter content of the water sample.

(2) Turbidity measurement

In the experiment, the mine water turbidity was measured through the national standard GB 13200-91 optical method. A certain amount of coal mine water was poured in a beaker, and the water sample was mixed evenly by stirring with a glass rod. A 10 mL pipette was used to take 30 mL water samples in the upper, middle, and lower portions of the beaker for measurement, and the average value was taken as the actual turbidity value of the water sample.

2.2.2 Water sample configuration

The original sample from the Shaanxi coal mine water was used, and water samples with different SS contents were prepared by diluting in proportion. The configured water sample with a suspended matter content of 0–200 mg/L was configured with 5 mg/L as a gradient. The configured water sample with a suspended matter content of 200–600 mg/L was configured with 25 mg/L as a gradient.

3 Results And Discussion

3.1 Water quality characteristics of mine water

Coal mine water was collected from six different coal mines in China. The water quality indicators are shown in Table 1.

| Coal mine                | Exterior                        | Turbidity_ (NTU) | SS_ (mg/L) |
|--------------------------|---------------------------------|------------------|------------|
| Shaanxi Province coal mine | black, turbid                   | 2040             | 1456       |
| Henan Province coal mine | gray, less turbid               | 81.3             | 70.2       |
| Shanxi Province coal mine 1 | gray-black, less turbid | 420.25           | 330.5      |
| Shanxi Province coal mine 2 | gray, less turbid               | 104.6            | 96.5       |
| Inner Mongolia Province coal mine 1 | gray, less turbid | 172              | 156.5      |
| Inner Mongolia Province coal mine 2 | gray-black, turbid | 886              | 570.5      |

The results indicate that (1) the type of coal mine has a considerable effect on turbidity and SS content of the mine water; (2) the SS content of the mine water of different coal mines is lower than the turbidity.

The original mine water sample should have greater turbidity and SS than other samples to configure mine water with different SS gradients and is beneficial to water distribution. As such, the Shaanxi Province coal mine water was selected as the original sample of the experimental water distribution.
3.2 Relationship between mine water turbidity and SS when SS is 0–200 mg/L

The raw water from Shaanxi Province coal mine was used as the original experimental sample, and the experimental water samples with SS content of 0–200 mg/L were respectively diluted in proportion, and 5 mg/L was used as a gradient for configuration. The turbidity and SS of the configured waste water were measured according to the national standard. Three parallel samples were set for each water sample, and the average value of the three water samples was obtained as the final experimental data. The experimental results are shown in Table 2.
A certain error exists between the SS content in the water distribution and the actual measured SS content. Considering the test error factors, the task error is reasonable. According to the actual measured suspended matter content and turbidity value, the relationship curve between SS and turbidity is drawn as shown in Fig. 1.

Figure 1 shows that when the SS content is 0–200 mg/L, the relationship curve between mine water turbidity and SS is $y = 0.9336x - 3.1393$, $R^2 = 0.9986$.

| Amount of matched SS (mg/L) | Measured turbidity (NTU) | Measured amount of SS (mg/L) | Amount of SS to configure the water sample (mg/L) | Actual measured amount of SS (mg/L) |
|-----------------------------|--------------------------|-----------------------------|-----------------------------------------------|-----------------------------------|
| 5                           | 6.89                     | 3.39                        | 105                                           | 103.65                            |
| 10                          | 12                       | 8.4                         | 110                                           | 98.5                              |
| 15                          | 17.73                    | 13.2                        | 115                                           | 120.8                             |
| 20                          | 26.5                     | 21.6                        | 120                                           | 115.5                             |
| 25                          | 29.27                    | 24                          | 125                                           | 120.63                            |
| 30                          | 38.1                     | 32.5                        | 130                                           | 124.5                             |
| 35                          | 39.97                    | 34.83                       | 135                                           | 132.8                             |
| 40                          | 51.3                     | 46.6                        | 140                                           | 140.5                             |
| 45                          | 50.34                    | 45.1                        | 145                                           | 140.6                             |
| 50                          | 59.6                     | 53.3                        | 150                                           | 151                               |
| 55                          | 61.04                    | 55.25                       | 155                                           | 153                               |
| 60                          | 75.6                     | 67.2                        | 160                                           | 160                               |
| 65                          | 71.13                    | 62.5                        | 165                                           | 164                               |
| 70                          | 81.7                     | 71.5                        | 170                                           | 169.5                             |
| 75                          | 73.15                    | 66.2                        | 175                                           | 172                               |
| 80                          | 94.2                     | 84.85                       | 180                                           | 174                               |
| 85                          | 89.62                    | 81.2                        | 185                                           | 182                               |
| 90                          | 102.6                    | 93.5                        | 190                                           | 182.5                             |
| 95                          | 103.5                    | 93.75                       | 195                                           | 185.1                             |
According to the calculated relationship curve, the suspended matter content was calculated using the formula, and the error between the actual suspended matter content and the calculated value was determined. The results are shown in Table 3.

| Measured value of SS (mg/L) | Calculated value of SS (mg/L) | Error (%) | Measured value of SS (mg/L) | Calculated value of SS (mg/L) | Error (%) |
|-----------------------------|-----------------------------|-----------|-----------------------------|-----------------------------|-----------|
| 3.39                        | 3.29                        | 2.86      | 103.65                      | 102.03                      | 1.56      |
| 8.4                         | 8.06                        | 4.00      | 98.5                        | 101.27                      | 2.82      |
| 13.2                        | 13.41                       | 1.62      | 120.8                       | 121.22                      | 0.34      |
| 21.6                        | 21.60                       | 0.01      | 115.5                       | 118.23                      | 2.36      |
| 24                          | 24.19                       | 0.78      | 120.63                      | 122.90                      | 1.88      |
| 32.5                        | 32.43                       | 0.21      | 124.5                       | 128.97                      | 3.59      |
| 34.83                       | 34.18                       | 1.88      | 132.8                       | 132.79                      | 0.01      |
| 46.6                        | 44.75                       | 3.96      | 140.5                       | 136.20                      | 3.06      |
| 45.1                        | 43.86                       | 2.75      | 140.6                       | 140.26                      | 0.24      |
| 53.3                        | 52.50                       | -1.49     | 151                         | 147.82                      | 2.10      |
| 55.25                       | 53.85                       | 2.54      | 153                         | 154.17                      | 0.77      |
| 67.2                        | 67.44                       | 0.36      | 160                         | 163.98                      | 2.48      |
| 62.5                        | 63.27                       | 1.23      | 164                         | 166.78                      | 1.69      |
| 71.5                        | 73.14                       | 2.29      | 169.5                       | 173.31                      | 2.25      |
| 66.2                        | 66.88                       | 1.03      | 172                         | 174.80                      | 1.63      |
| 84.85                       | 84.81                       | 0.05      | 174                         | 175.65                      | 0.95      |
| 81.2                        | 80.53                       | 0.83      | 182                         | 179.19                      | 1.54      |
| 93.5                        | 92.65                       | 0.91      | 182.5                       | 180.22                      | 1.25      |
| 93.75                       | 93.49                       | 0.28      | 185.1                       | 183.67                      | 0.77      |

Through the model formula of SS and turbidity when the suspended matter is 0–200 mg/L, the error between the calculated SS value and the measured value can be effectively controlled below 4%, taking into account the inevitable error in the test process. Such factors indicate that the model formula can simulate the relationship between turbidity and SS when SS content is 0–200 mg/L.
3.3 Relationship between mine water turbidity and SS with SS of 200–600 mg/L

The raw water from Shaanxi Province coal mine was used as the original sample, and the experimental water samples with the SS content of 200–600 mg/L were diluted according to the proportion. Exactly 25 mg/L was used as a gradient for configuration. The turbidity and SS of the configured waste water were measured according to the national standard. Three parallel samples were set for each water sample, and the average value of the three water samples was considered as the final experimental data. The experimental results are shown in Table 4.

| Amount of matched SS_ (mg/L) | Measured turbidity _ (NTU) | Measured amount of SS_ (mg/L) | Amount of SS to configure the water sample _ (mg/L) | Actual measured amount of SS_ (mg/L) | Amount of matched SS_ (mg/L) |
|-----------------------------|---------------------------|-------------------------------|-----------------------------------------------|--------------------------------|-----------------------------|
| 200                         | 210.9                     | 204                           | 425                                           | 631.8                         | 431                         |
| 225                         | 268.5                     | 229                           | 450                                           | 678.9                         | 469                         |
| 250                         | 315.3                     | 246                           | 475                                           | 721.2                         | 478                         |
| 275                         | 361.5                     | 281                           | 500                                           | 773.13                        | 516                         |
| 300                         | 395.2                     | 306.2                         | 525                                           | 816.8                         | 545                         |
| 325                         | 428.5                     | 330.5                         | 550                                           | 895.3                         | 553                         |
| 350                         | 483.2                     | 362                           | 575                                           | 972.1                         | 579                         |
| 375                         | 533.6                     | 378.6                         | 600                                           | 992.15                        | 632                         |
| 400                         | 586.2                     | 413                           |                                               |                                |                             |

The results show a certain error between the SS content in the water distribution and the actual measured SS content. Considering irresistible test error factors, the task error is reasonable. According to the actual measured suspended matter content and turbidity value, draw the relationship curve between SS and turbidity as shown in Fig. 2.

Figure 2 shows that when the SS content is 200–600 mg/L, the relationship curve between mine water turbidity and SS is \( y = 0.5314x + 94.421, R^2 = 0.9905 \).

According to the calculated relationship curve, the suspended matter content was calculated using the formula, and the error between the actual suspended matter content and the calculated value was determined at the same time. The results are shown in Table 5.
### Table 5
Error analysis of SS calculated and measured values

| Measured value of SS_ (mg/L) | Calculated value of SS_ (mg/L) | Error_ (%) | Measured value of SS_ (mg/L) | Calculated value of SS_ (mg/L) | Error_ (%) |
|-----------------------------|-------------------------------|------------|-----------------------------|-------------------------------|------------|
| 204                         | 204.62                        | 0.30       | 431                         | 429.67                        | 0.31       |
| 229                         | 235.42                        | 2.80       | 469                         | 454.86                        | 3.02       |
| 246                         | 260.44                        | 5.87       | 478                         | 477.48                        | 0.11       |
| 281                         | 285.14                        | 1.47       | 516                         | 505.24                        | 2.08       |
| 306.2                       | 303.16                        | 0.99       | 545                         | 528.59                        | 3.01       |
| 330.5                       | 320.97                        | 2.88       | 553                         | 570.57                        | 3.18       |
| 362                         | 350.22                        | 3.25       | 579                         | 611.63                        | 5.64       |
| 378.6                       | 377.17                        | 0.38       | 632                         | 622.35                        | 1.53       |
| 413                         | 405.29                        | 1.87       |                             |                               |            |

As shown in Table 5, through the model formula of SS and turbidity when the suspended matter content is 200–600 mg/L, the error between the calculated SS value and the measured value can be effectively controlled below 5%, considering the inevitable in the test process. Errors and other factors indicate that the model formula can effectively simulate the relationship between turbidity and SS when the SS content is 200–600 mg/L.

### 4 Model Formula Calibration Verification Under Different Gradients

Through the above experimental research, the relationship model between suspended matter and turbidity under two different ranges of suspended matter content was obtained. When the suspended matter content was 0–200 mg/L, the relationship curve between mine water turbidity and SS was $y = 0.9336x - 3.1393$. When the SS content was 200–600 mg/L, the relationship between mine water turbidity and SS was $y = 0.5314x + 94.421$. The model formula was used for the actual measurement and calculation of the collected five other types of coal mine water to further verify the accuracy of the model formula. The test results are shown in Table 6.
Table 6
Actual and calculated values of mine water in five different coal mines

| Coal mine                                      | Measured value of SS_ (mg/L) | Calculated value of SS_ (mg/L) | Error_ (%) |
|-----------------------------------------------|------------------------------|--------------------------------|------------|
| Henan Province coal mine                       | 70.2                         | 72.76                          | 3.65       |
| Shanxi Province coal mine 1                    | 330.5                        | 316.56                         | 4.22       |
| Shanxi Province coal mine 2                    | 96.5                         | 94.52                          | 2.06       |
| Inner Mongolia Province coal mine 1           | 156.5                        | 157.44                         | 0.60       |
| Inner Mongolia Province coal mine 2           | 570.5                        | 565.59                         | 0.86       |

The following results are shown in Table 6: (1) the measured values of SS of mine water in Henan Province coal mine, Shanxi Province coal mine 2, and Inner Mongolia Province coal mine 1 are lower than 200 mg/L. Thus, the turbidity of mine water with an SS content of 0–200 mg/L was used. For the relationship curve of SS, the error between the calculated value and the actual value can be better controlled within 4%. (2) The measured values of SS in the mine water of Shanxi Province coal mine 1 and Inner Mongolia Province coal mine 2 are lower than 600 mg/L. Thus, the SS content was adopted. The relationship curve between mine water turbidity and SS is 200–600 mg/L. The error between the calculated value and the actual value can be better controlled within 5%.

In summary, the relationship between SS and turbidity in two different ranges was tested and calibrated. The error results show that the model formula can reflect the SS and turbidity of different coal mine waters. Therefore, the model formula can be applied for detecting SS in actual coal mine water.

5 Conclusion

The following conclusions were obtained in this work:

(1) By measuring the suspended solids and turbidity of water samples with different gradients, two models of the relationship between SS and turbidity under different ranges of SS content were obtained. When the SS content is 0–200 mg/L, the relationship between water turbidity and SS is \( y = 0.9336x - 3.1393 \). When the SS content is 200–600 mg/L, the relationship between mine water turbidity and SS is \( y = 0.5314x + 94.421 \).

(2) Using the turbidity and SS data of five kinds of coal mine water, the relationship model of SS and turbidity under two different ranges of SS content was calibrated and verified. The error results show that the model formula can well reflect the SS content and turbidity of water samples from different coal mines. The suspended matter in mine water was related to turbidity; thus, the model formula can be applied for detecting suspended matter in actual coal mine water.
Declarations

6.1 Availability of data and materials

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials.

6.2 Competing interests

The authors declare that they have no competing interests.

6.3 Funding

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6.4 Authors’ contributions

Song Du: formulation or evolution of overarching research goals and aims; design of methodology; provision of study materials; creation and presentation of the published work.

Wenbiao Jin: design of methodology; provision of study materials.

Guichuan Qiao: conducting a research and investigation process; application of statistical; specifically visualization.

Huiming Fang: assisting in the test.

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Figures
Figure 1

Curve of the relationship between turbidity and SS of mine water when SS content is 0–200 mg/L

Figure 2
Curve of the relationship between turbidity and SS of mine water when SS content is 200–600 mg/L