# Research on application of inflatable rubber support in actual mining roadway

**Zhong-liang Lu[1, 2, 3, 4]*, Yin-zheng Li[1], Hong-li Wang[5]**

*1 School of Safety Science & Engineering Henan Polytechnic University, Jiaozuo, China*

*2 Key Laboratory of Gas Geology and Gas Control, Jiaozuo, China*

*3.Collaborative Innovation Center of Central Plains Economic Region for Coalbed /Shale Gas of Henan Province, Henan, Jiaozuo*

*4. The Collaborative Innovation Center of Coal Safety Production of Henan Provinc, Henan, Jiaozuo*

*5 School of Mathematics & Information Science, Henan Polytechnic University, Henan, Jiaozuo*

*Received 17 November 2014, www.cmnt.lv*

**Abstract**

The increasing mining depth lead to severe deformation of surrounding rock and greater ground stress, which brought great difficulties to the support and mining In order to further accelerate the support rate and simplify the support technology, thus solving the supporting problem under high stress, this paper developed an inflatable rubber support which has won the national patent for utility models. It could make the load applied on the steel support have uniform distributed and absorb part of the energy caused by roof weighting, thus effectively reducing the loads; with the weak stiffness, the rubber layer can buffer loads and achieve close contact with the roof of the roadway, so it could bear external loads quickly to prevent the surrounding rock deformation caused by the decoupling of the steel support and roadway in the initial stage. Therefore, the inflatable rubber support is of great significance for the improvement of supporting reliability and the cost reduction.

*Keywords:* rubber support, local overload, energy dissipation, broken rock zone

## 1 Introduction

In China, due to different geological or economic conditions in mining areas, the number of currently used downhole support ways is enormous. Underground support not only needs to consider the static load effect, but also dynamic loads like the earthquake, blasting and mining influences. With the increasing depth of mining, various nonlinear mechanics phenomena become intensified-large deformation of surrounding rock, highland stress, and increasing difficulty in supporting, which brings a great deal of difficulty to supporting and mining[1]. Fully mechanized top coal caving mining is currently used for underground thick seam mining. With roof caving treating goaf roof, microscopic and macroscopic cracks will be formed in the surrounding rock under the huge impact during caving. Besides, with the progressing of stoping, the original fissure has also been developing, leading to an increase in the depth of the fissure area formed around the roadway near to the stope. For this reason, the load of the support increases, resulting in a deteriorated support condition affected by the deformation of the surrounding rock within the affected zone of stope, and thus, it may lead to damage to local support due to overload. Mining roadway is important to ensure the normal operation of mechanized mining. It is also a section of roof subjected to increased pressure. Therefore, it is essential to ensure the stability of the roof of the mining roadway.

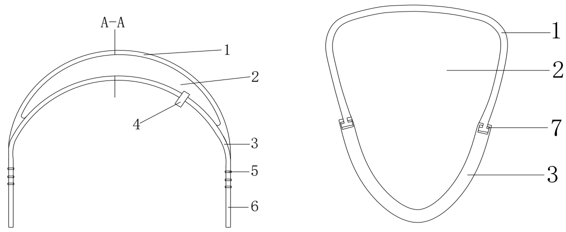
Currently, the coal roadway bolting rate of many mining areas in China is more than 60% [2]. However, with the advancing of working face, the initial open-off cut and normal mining roadway gradually enter the rear of the working face, and the high-strength prestressed bolting makes the open-off cut in the rear of the working face and roof of tunnels unable to cave along with the caving of the working face, leading to a significant increase in the initial mining caving and initial coal drawing interval and expanded hanging arch range in the rear of the upper and lower end of the working surface. Consequently, it is easy to form a dead end because of poor ventilation at the upper end of the working face. Gas may accumulate around the hanging roof triangle, often causing the gas to go beyond the limit [3]. Many scholars in our country have done a lot of research on the above issues, of which the most effective is the roadway anchor releasing theory proposed by Li Chong. However, the process is too cumbersome and time-consuming. In order to further speed up the supporting speed, simplify the process and reduce the supporting cost of mining roadway as well as improving the reliability of support, we have developed a new type of inflatable rubber support, which has obtained national patent for utility model. Using this support can reduce the labor consumption by 30%~50% and improve the speed of support by one~1.5 times. It is characterized by simplicity and scalability, helps to buffer sudden pressure applied to the support and distribute the load more evenly, while providing support with the ability to quickly bear external loads. In addition, the arch roadway with arch support is more favorable than the flat support in terms of statics, which bears lighter load but has large carrying capacity. Therefore, the inflatable rubber support is of great realistic significance in terms of improving the supporting reliability and reducing the cost.

* ***Corresponding author*** e-mail: zhonglianglu@126.com

## 2 Structure and function of the inflatable rubber support

The inflatable rubber support is different from general supports, which means that the steel frame is enclosed with the rubber layer. This support includes the steel arch, inner liner and rubber layer which is inserted in the slot of the steel arch. The cavity formed by the rubber layer and the steel arch wraps the inner liner which is connected to the outside by the air valve [4]. A pressure monitoring device is connected to the valve, which could be used to monitor the internal air pressure of the support by the data. The support can be divided into three parts: the upper part is the inflatable structure; while for the lower part, both ends are made of section steel. According to the statistics of the Donets Coal Science Institute, scalable architecture is suitable for the influence area of mining work and it could prevent the roadway from being maintained when the moving amount of the roof rock is less than 400~500mm. Although it may lead to the increase of metal consumption, about 10%~15%, it could save the maintenance cost, so the scalable structure is used at both ends of the bottom part of the inflatable rubber support, as shown in Fig.1.

The major functions of the rubber support are shown as follows: (1) The loads applied on the steel support are evenly distributed under stress; (2) the rubber layer and the internal air could absorb part of the energy, thus effectively reducing the loads; (3) due to its weak stiffness, the rubber layer could buffer loads; besides, it could contact with the roof of the roadway closely to prevent the surrounding rock deformation caused by the decoupling of the support and roadway.




1. Rubber Layer 2. Inner liner 3.Steel Arch 4. Air Valve
5. Scalable Connection Buckle 6. Section Steel

FIGURE 1 A schematic diagram of the support structure

Deflate the valve, set up the support at the supporting site and then use the air pump to conduct air inflation for the inner liner through the valve, so the inner liner will jack up the rubber layer with external high intensity and make it contact with the roof of the roadway, serving as the support. To disassembly the support, deflate it by the valve at first, so the inner liner and rubber layer become flat and then separate from the roof of the roadway, and then put it away.

## 3 Failure mechanism of the support of mining roadway

In the top-coal caving mining process, the stable equilibrium state of coal and rock mass structure becomes the non- stable equilibrium state due to the disturbance of mining, and then it returns to the stable equilibrium state. In this process, the energy is mainly consumed by the destruction and crushing of coal and rock mass and part of the energy is consumed in the transfer process; the rest of it may be applied on the rock mass and the supporting structure, which is likely to cause damages [5]. The larger coal seam depth may lead to the thick overlying rock and soil layers of the mining roadway, coupled with the greater gravitational potential energy and gas pressure of coal seam; therefore, if the surrounding coal and rock mass could withstand the loads of overlying rock layers and the gas pressure, the coal and rock structure is in a relatively stable equilibrium state; if it fails, the equilibrium state of the structure will be destroyed, thus the energy will be released rapidly and have an impact on the supporting structure, which may lead to the obvious deformation of the support without effectively cushioning effect, thus resulting in the unsteadiness and fracture.

## 4 Mechanics analysis of support

### 4.1 DISTRIBUTE THE LOCAL OVERLOAD EVENLY

In the underground roadway, the failure of coupling between the strength of surrounding rocks and the support often occurs, leading to non-uniform load acting directly on the support of equal strength, thus forming local overload to cause local damage and instability of the support [6]. Roadway U-shaped steel support, if its strength is calculated, generally has carrying capacity. However, its carrying capacity is often smaller than the calculated intensity in practical process because the instability of the support after bearing the force will disable its carrying capacity. It deforms under the effect of the force, which is the main reason for its destruction. When the load q is small, the axial deformation may be ignored, resulting in only the axial pressure in the dome without bending moment and shear force, i.e., it is in the initial state of no bending. When the load q reaches a limit value, arch support may suddenly be subjected to buckling, resulting in deviation from the original axis, and thus instability. The experiments and checking show that the load causing symmetric deformation in critical state is enormously larger than the anti-symmetric deformation, and therefore the critical load of U-shaped steel support shall be calculated in the form of anti-symmetric deformation [7].

The differential equation for stable support is listed as follows:

$$\frac{d^6u}{d\phi^6}+\frac{d^4u}{d\phi^4}+\beta^2\left(\frac{d^4u}{d\phi^4}+\frac{d^2u}{d\phi^2}\right)=0 \cdot \qquad (1)$$

In the formula: $\beta=\sqrt{1+\frac{qR^2}{EI}}$ ; u stands for the tangential displacement for deformation; EI represents the flexural rigidity of section steel; $v=\frac{du}{d\varphi}$ is normal displacement.

The general solution of equation (1) is listed as follows:

$$u=a_1+a_2\phi+a_3\sin\phi+a_4\cos\phi+a_5\sin\beta\phi+a_6\cos\beta\phi\ , \qquad (2)$$

$$v=\frac{du}{d\varphi}=a_2+a_3\cos\varphi-a_4\sin\varphi+\cos\beta\cos\beta\varphi-a_6\beta\sin\beta\varphi\ , \qquad (3)$$

$$\mathrm{M}=-\frac{\mathrm{EI}}{R^2}[a_2+a_5(1-\beta^2)\beta\cos\beta\varphi-a_6(1-\beta^2)\beta\sin\beta\varphi]\ . \qquad (4)$$

According to boundary conditions, algebraic equations containing the constants of integration- $a_1 \sim a_6$ can be obtained, then $a_1 \sim a_6$ are required to have solutions not all of which are zero. Thus, we can obtain a stable characteristic formula of semi-arch, which can be used to find the critical load.

Boundary conditions: u = v = 0, M = 0. In formula (4), M is the odd function of $\varphi$ , and then delete the even function, the following can be obtained:

$$M = \frac{EI}{R^2} a_6 (1-\beta^2)\beta \sin \beta\phi$$

When $\psi = \gamma$ , M=0, $\sin \beta\gamma = 0$ ; $\beta\gamma = n\pi$

Put them in $\beta = \sqrt{1+\frac{qR^3}{EI}}$

The minimum critical load is $q_{cr} = \frac{EI}{R^3}(\frac{\pi^2}{\gamma^2}-1)$

Simplify the arch support into the two-dimensional linear problem for calculation, and then apply the force F on the local part of the support with the length of $\theta R$, if the loads are uniformly distributed, the load $q_1 = \frac{F}{\theta R}$ ; if $q_1 > q_{cr}$, the support will collapse and be damaged, as shown in Fig.2.

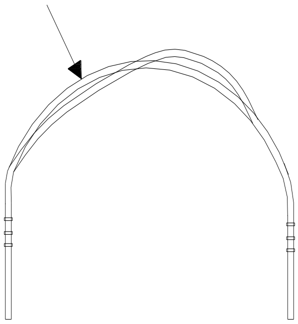


FIGURE 2 The schematic diagram of unstable and deformed rigid support under local stress

If the same force is applied on the rubber support and within the same area, the rubber support could transfer the loads to the metal arch uniformly by the internal air, $q_2 = \frac{F}{\frac{\pi}{2}R}$. As $\frac{\pi}{2} \gg \theta$, with equal local stress and area, $q_2$ may be less than $q_{cr}$, which could reduce the possibility of instability of the support, as shown in Fig.3.

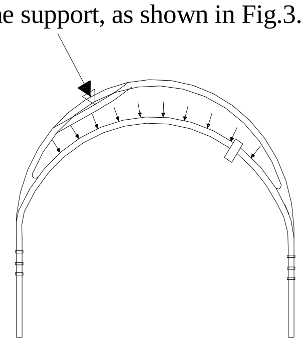


FIGURE 3 The schematic diagram of local stress of the rubber support

## 4.2 ENERGY DISSIPATIOM DURING ROOF WEIGHTING

Roof weighting will instantly generate a huge shock wave, with the energy quickly released to the supporting structure through coal and rock mass. If it instantly has a direct effect on the steel support, it will be violently impacted, generating enormous energy inside and causing slight fissures. During the process in which coal and rock mass circulates from steady to unsteady and then to steady state, force is repeatedly applied on the support and cracks slowly expand. Although it is still below the threshold stress intensity, and even below the bending point, damage can occur, which is called fatigue damage. However, when the inflatable rubber support is in the process of roof weighting, the released energy will be applied on the rubber layer in the upper part of the support, deforming the rubber layer. Compressed air, formed in the cavity between the rubber layer and the steel arch, will dissipate part of the energy and the remaining energy will be evenly exerted on the steel arch through the high-pressure air inside the rubber layer.

When the roadway uses the inflatable rubber support, shockwave will pass through the surrounding rock mass to the rubber layer of the material with weak rigidity. First, part of the energy is dissipated and then spread to and reflected by the steel arch when part of the shockwave energy has been absorbed. The reflected wave is still able to absorb part of the energy when going through the rubber layer, and at this time, the impact energy acting on a rigid support has been relatively small and will not cause damage to the steel support. The energy dissipation mechanism is shown in Fig. 4.

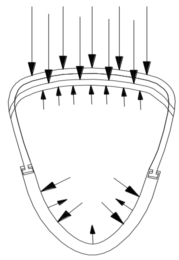


FIGURE 4 The schematic diagram of energy dissipation caused by the roof weighting of rubber support

Analyze the dissipation from the perspective of energy. In the process of roof weighting, the energy released by the coal and rock mass is Q, the energy consumed by destruction of surrounding rock is $Q_1$, the energy consumed by rubber material with low stiffness is $Q_2$, therefore, the remaining impact energy applied on the steel arch $Q_3 = Q-Q_1-Q_2$. If the load on the steel arch caused by $Q_3$ is less than its critical load, there will be neither significant impact fracture in the internal structure of the support nor the instability and destruction.

## 4.3 QUICKLY BEAR THE LOADS ON THE TOP TO PREVENT THE FORMATION OF BROKEN ROCK ZONE

As the ground stress is greater than the surrounding rock strength in the roadway excavation process, there will be broken rock zone and bulking deformation caused by it is the greatest load of the surrounding rock. Under the existing support conditions, it is unrealistic to use the supporting means to prevent the formation of broken rock zone, so the only way is to prevent the bulking deformation by the support [8].

Since the metal support cannot fully fit the surrounding rock initially, there is a natural closing process between the support and surrounding rock in the actual situation. Before the support comes into play, the surrounding rock is uncontrolled, so the hulking deformation occurs, and at this time, the loads acting on the support are only the weight of the deformed rock. The hulking deformation of surrounding rock makes the support contact with it, and then the deformation pressure may raise the characteristic curve of the support until the roadway deformation is stable. The hulking deformation pressure and deformation curve are as shown in Fig. 5 [8].

If the supporting material is rigid, with the convergence of surrounding rock, the stress applied on the support increases rapidly. The plastic deformation may not occur to the rigid structure, and due to the severe hulking deformation, the brittle fracture will happen, thus the surrounding rock is out of control and may even take drop. The P-U curve is shown as curve g-c-d. The inflatable rubber support could effectively adapt to the deformation pressure. In the Fig., g-c-e is the P-U curve of increasing-resistance inflatable support, while g-c-f represents the P-U curve of constant-resistance inflatable support.

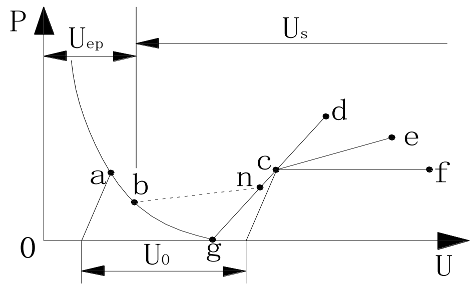



FIGURE 5 The hulking deformation pressure of rock and deformation curve of general supports

If the inflatable rubber support is adopted, as the rubber layer has weak stiffness, which could closely contact with the roadway, there is no free space between the support and the surrounding rock, therefore the natural closing process in the P-U curve does not exist. It is impossible to prevent the formation of broken rock zone effectively as the uncontrolled deformation stage will never occur to the surrounding rock. Therefore, the point c in the P-U Curve may move to the left when the inflatable rubber support is adopted, which means it could quickly bear the external loads. The P-U curve is as shown in Fig.6.

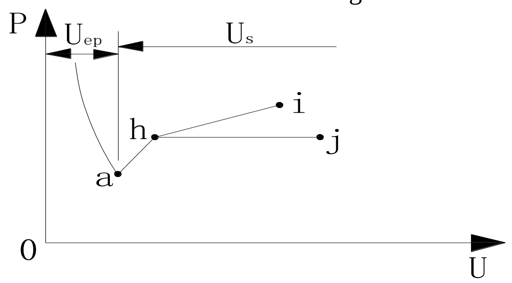



FIGURE 6 The schematic diagram of hulking pressure and deformation of roadway rock with the inflatable rubber support

## 5 Application test of rubber support

As the inflatable rubber support is the new proposed approach, it has not been widely applied under the well. Nowadays, it has been tested in the mining roadway in a mine of Shanxi and achieved good results.

Nowadays, in the mine, only No.3 coal mining is exploited with the thickness of 6.57m and the fully mechanized top coal caving method. The geological data of No.3 coal mining is as shown in Table 1, the compressive strength of 9.16 ~ 14.83MPa with an average value of 11.20MPa. The elastic modulus is 2.244 ~ 4.071GPa with an average value of 3.085GPa. The Poisson's ratio is 0.241 ~ 0.362 with an average value of 0.301. The consistent coefficient is 0.944 ~ 1.394 with an average value of 1.201.

TABLE 1 The engineering geological data of No.3 coal mining

| Location | Compressive strength/MPa | Elastic modulus/GPa | Poisson's ratio | Consistent coefficient |
|---|---|---|---|---|
| 1306Gas roadway | 12.32 | 4.071 | 0.300 | 1.267 |
| 1407Working face | 9.16 | 2.244 | 0.241 | 0.944 |
| 1306Transport roadway | 14.83 | 2.941 | 0.362 | 1.394 |
| 22Material roadway in the mining area | 9.60 | | | |
| 1310Transport roadway | 10.12 | | | |
| Average value | 11.20 | 3.085 | 0.301 | 1.201 |

The false roof of directly covers the No.3 coal seam and the lithology is black carbonaceous mudstone with unstable thickness, usually 0.25 ~ 0.44m. It has local and joint development, low rigidity, poor stability, and is easy to fall if the roof is wet.

The immediate roof is located above the No.3 coal seam or the false roof and is composed of gray and black mudstone and sandy mudstone, sometimes shown as interbed in-state sandstone and mudstone. The thickness is 1.00 ~ 7.00m with the average value of 5.35m and up to18.85m in some areas. This roof fracture is well developed. Its compressive strength is 21.30 ~ 50.20MPa with an average value of 30.52MPa; the tensile strength is 0.44 ~ 2.64MPa with an average value of 1.79MPa; the elastic modulus is 28.56 ~ 44.00 GPa with the average value of 34.35GPa; the Poisson’s coefficient is 0.27 ~0.426 with an average value of 0.35.

The upper roof is located above the immediate roof or directly above the No.3 coal seam. It has thick layer and is composed of fine-grained gray quartz arkose and coarse sandstone locally. It contains mafic minerals and mica sheets with blocks, sorting, medium grinding roundness, calcite cementation; the fracture is developed and filled with calcite. This region is well developed with great changes in the thickness, generally1 ~ 10m and up to 21.27m in some areas, and the average value is about 5.91m. Its compressive strength is 26.30~100.80MPa with an average value of 61.44MPa; the tensile strength is 2.66~13.00MPa with an average value of 5.94MPa; the elastic modulus is 12.01~49.00 GPa with the average value of 30.47 GPa; the Poisson’s coefficient is 0.30~0.36 with an average value of 0.33.

Adopt the inflatable rubber support in intake entry Face. It has a width of 3800mm, height of 3400mm and inflation pressure of 1.2MPa. The support spacing is 4.5m with the steel mesh as protective roof and diamond wire mesh as face guard. Adopt the anchor-mesh-support for the areas of the return airway, which is distant away from the working face; while for the areas with the distance to the working face less than 200m, adopt the trapezoidal scalable support. Bolt has the diameter of 22mm, length of 2.4m, row spacing of 900mm and spacing of 850mm.

In the mining process, the roadway within the range of 30 to 50 meters away from the coalface is obviously influenced by the mining. With the trapezoidal scalable support, the deformation amount at both sides of the return airway, is up to 245mm at the position with the distance to the working face of 5 m; the roof subsidence value reaches 160mm, part of the support has cracks and local deformation is serious, coupled with the fracture of scalable connection card, which may result in the disengagement between the support and the roof. For the anchor-mesh-support roadway, the tuck net effect and anchor-cable breaking phenomenon occur to part of it, and the subsidence value of part of the roofs reaches 190mm. For the roadway with inflatable rubber support, the roof subsidence value is 110mm, and the deformation amount at both sides is 190mm; the support and roof achieve seamless contact without breaking surrounding rock. In the caving and mining process, there are no fracture and obvious cracks. The test results indicate that surrounding rock with less deformation could meet the safety needs of production and achieve good supporting effect.

## 4 Conclusions

According to deformation mechanism of mining roadway, it is necessary to eliminate the decoupling phenomenon between the support and surrounding rock to achieve successful support. The inflatable rubber support is to co-ordinate deformation of surrounding rock caused by the great plasticity through the materials with weak stiffness, aiming to prevent the deformation and failure as much as possible. Then it could maximize the self-supporting capacity of surrounding rock and achieve the supporting integration and load homogenization, thus ensuring the stability of roadway.

(1) The rubber support under stress could make the load posed on the steel support distributed uniformly. When under stress, the rubber support could transfer it to the metal roof by the internal air, so the local loads are converted into the uniform load, which could improve the stability of the support.

(2) As the rubber layer and the internal air could absorb part of the energy, the inflatable rubber support could significantly buffer and reduce the load and improve safety of the roadway. It provides a new method to protect the roadway.

(3) With the weak stiffness, the rubber layer can buffer loads and achieve close contact with the roof of the roadway initially, which could timely and effectively control the roof and prevent the surrounding rock deformation and hulking deformation caused by the decoupling of the support and roadway.

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**Authors**

**<Lu Zhongliang >, <1964.3>,< Zhenlai County, Jilin Province, P.R. China>**

**Current position, grades:** the Professor of School of Safety Science and Engineering, Henan Polytechnic University, China.
**University studies:** received his Master'degree in safety engineering from Liaoning Project Technology University in China.
**Scientific interest:** His research interest fields include Ventilation and dust removal.
**Publications:** more than 20 papers published in various journals.
**Experience:** He has teaching experience of 10 years, has completed ten scientific research projects.

**< Li Yinzheng >, <1990.11>,< Jiyuan County, Henan Province, P.R. China>**

**Current position, grades:** Postgraduate student, School of Safety Science and Engineering, Henan Polytechnic University, China.
**University studies:** received his B.Sc. in safety engineering from Henan Polytechnic University in China, He received his M.Sc. in safety engineering from Henan Polytechnic University in China.
**Scientific interest:** His research interest fields include Ventilation and dust removal
**Publications:** more than 2 papers published in various journals.

**<Wang Hongli >, <1971.2>,< Fuxin County, Liaoning Province, P.R. China>**

**Current position, grades:** the Associate Professor of School of mathematics and information science, Henan Polytechnic University, China.
**University studies:** received her B.Sc. in mathematics education from Bohai University in China.
**Scientific interest:** Her research interest fields include Opsearch.
**Publications:** more than 7 papers published in various journals.
**Experience:** She has teaching experience of 20 years, has completed two scientific research projects.