DEVELOPMENT IN STEEL ROADWAY SUPPORT
- A TRACK RECORD -

Rudi Podjadtke
Bochumer Eisenhütte Heintzmann GmbH & Co. KG, Bochum, Germany
Holger Witthaus
RAG Deutsche Steinkohle, Herne, Germany
John Breedlove
Heintzmann Corporation, Cedar Bluff, WV, USA

Abstract

In a short chronological review the development concepts and improvements in steel roadway support are shown. The successful standardization concept of RAG Deutsche Steinkohle and currently used support systems are important topics. The history of optimizing the material properties for the steel arch support with different alloys up to the tempering used today is discussed. The present-day application of the steel support is additionally presented. Today, it represents a system component of modern roadway support also for highly stressed roadways. In addition to the yielding roadway arch support, this overall system - the combination support - consists of the additional components of a rockbolting system and concrete backfilling. The comparison of the application areas for each individual partial system with the overall system illustrates its high performance capability. Actual practical experience with the state of the art typed steel arches are pointed out exemplarily. Understanding the complete system permits the selection of the economically optimal support for all conditions.

Introduction

For almost 100 years support elements made of steel provide the basis for a yielding support construction (Figure 1). The bibliography refers to a summary of all support elements and support systems used in German hard coal mining industry [1]. This article describes in detail the development and the current state of steel support construction.

Figure 1: Yielding roadway arch support with concrete material backfilling

In 1932, "Bochumer Eisenhütte Heintzmann", the original German mining supply company, was the first to introduce the concept of a yielding roadway arch support without any joints in the form of the "TH Channel Profile".
The paired TH profile (A/B) developed by Heinrich Toussaint and Egmont Heintzmann on the basis of a submarine engineering concept was then introduced into German deep coal mining in 1933. The further development (Figure 2) up to the single profile as well as the continuous constructive optimization of the profiles and their connection technology led to the TH profile 70 as it is used today.

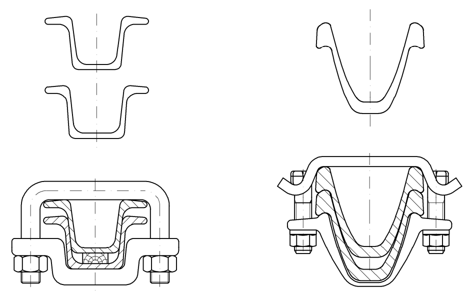

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Figure 2: Development of the TH profiles,
a: A/B profile, b: TH 70 profile

In addition to the established European areas of application in France, Spain, Poland, Italy, to name but a few, the "Bochum product" was successfully introduced into Colombia, Mexico, Peru, Chile, Japan and on the African continent with a increasing demand for tunnel construction. This was the start of the global success story of TH support.

Technological development steps and the state of the art today

In contrast to the rigid and jointed arch support, the basic idea of the yielding steel arch support lies in its capability to slide inwards if a high load-bearing capacity is exceeded and not to fail early by plastic deformation. And in so doing the yielding steel arch support maintains or even increases its load-bearing capacity in spite of roadway deformation. This yielding capability is achieved by the overlapping configuration and position of the associated connections.

Profile construction

The design profile of the support pioneered by Toussaint and Heintzmann was in sharp contrast to all other support profiles of that time inasmuch as it featured a section modulus in the two axes that was as balanced as possible.
As is generally known, for a steel roadway arch the circle or parabola shape (Figure 3) is the most favorable support form for supporting the rock, as this approaches most readily the natural arch formation. In contrast to a straight beam, e.g. the doorframe form of the same profile and cross-section, this form has a load-bearing capacity which is 3x to 6x higher.

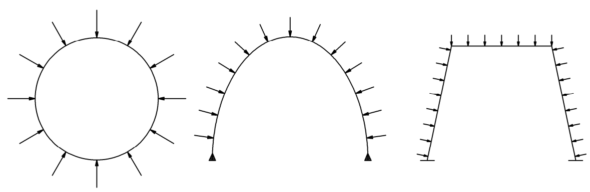


Figure 3: Support forms

With an application of the arch form, Toussaint believed it can be achieved without an excess section modulus in the y axis such as is featured by the single-web support profiles. In comparison to the single web profile, their z axis (Figure 4) is only approximately ¼ of the y value.

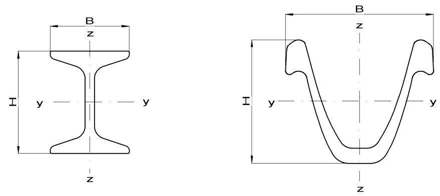
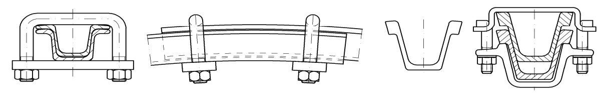


Figure 4: Axes of the GI profile, TH profile

The equal resistance quantities Wz to Wy approximately 1, which these caused, were thus able to take up the actions or external forces such as compression (buckling), bending (normal force), inclined bending (torsion) and naturally also a certain degree of tilting stability across the elastic to plastic deformation range.
Based on this design idea, as a first channel profile for mining, the Toussaint-Heintzmann profile, designated as TH profile, was created.
This paired design form, consisting of external and internal profiles, was spaced with hard wood in the overlapping area and bolted with U-bolts. In this way, this design form met the requirements of the mining industry which, in connection with the transition to ever increasing depths and with ever more difficult rock-mechanical conditions, also had to impose ever stricter requirements with regard to roadway support.

From 1937, as a replacement, the slot profile (Figure 5a) with bottom and web friction was used.
The high share of tooling costs, double storekeeping and the forced design of roadway arches in the case of special constructions led to a further rethink of the paired profile. Furthermore, it was not possible to place the segments as doubles up to the overlapping area at all points subject to particular high stresses.



a b

Figure 5: Steel profile forms a: Slot profile, b: TH profile 48

In 1948 the design evaluation of the experience gained from underground operations led from the originally paired form of the TH profile in the weights 10 – 35 kg/m to the form of the TH single profile 48 (Figure 5b) in the weight classes 13 – 44 kg/m. In addition to the many advantages of the single profile, this profile had been significantly refined in comparison to the previous paired profiles. This profile featured a higher cross-section stability and thus had a more favorable behavior before and within the overlap area. This was achieved by an improved lever arm ratio (Figure 6) and a stronger profile bottom. At the time Toussaint took the view that, in the plastic deformation range, the profile could be kept as resistant to bending as possible by positioning the webs of the profile at a very steep angle.

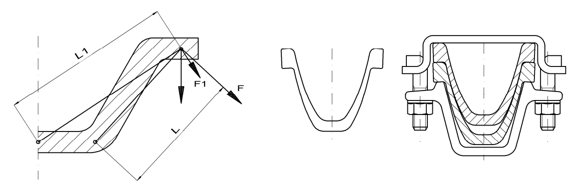


Figure 6: Lever arm ratio TH profile 58

However, on the other hand he ignored the fact that the lever arm ratio from profile bottom to profile flange (F x L) is of major significance for the gaping resistance of the profile. For this large value F x Ll the profile bottom was too weak.
Uncertainties in the overlap area - caused by the clamping effect in the case of profile 48 and an unclear spacing of the profiles in relation to one another - led to the development of the TH profile 58 ten years later. This TH profile 58 was rolled in weight classes 21 – 36 kg/m.

The balanced static values of the profiles, easy installation, increased stability during installation even in fissured rock, the high load-bearing capability in connection with yielding at the deformation limit of the segments, the long service duration and the reusability after cold re-erection led to an ever greater application of the TH support world-wide in all mining countries.

In this TH profile from 1958 the pure clamping effect between the webs was consciously avoided, in order to achieve a function between insertion resistance and bolt torque.

In 1970, not least due to roadway cross-sections increasing again and greater extraction depths, it was necessary to optimize the sliding and guiding characteristics of the TH profile 58. The statically improved cross-section change of the profile webs and flanges guaranteed an optimum primary force introduction of the bolt forces into the flange channels. Thus, the yielding resistance had a clearly defined value and the connection was free from maintenance. The newly developed TH profile 70 (Figure 7) in the weight classes 16.5- 44 kg/m is without equal today.

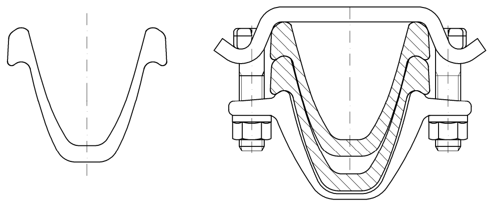


Figure 7: TH profile 70 with connection clamp

Connection technology

In parallel to profile development, it was always an intensive improvement of the connection technology that took place. Thus, in accordance with the TH development types, the yielding characteristics also changed respectively (Figure 8):
1. The A/B profile had a setting load by means of the U-bolts, an undefined load suspension by tilting the U-bolts and load fluctuations by movements of the connection element (Fig. 8a).
2. The TH 48 achieved a setting load by means of the connection, reached a very high servo effect via web friction, and an insertion with limited definition (Fig. 8b).
3. As the standard connection, the TH profile 70 features an insertion resistance in dependence of the bolt torques. This is the state of the art in all mines today (Fig. 8c).

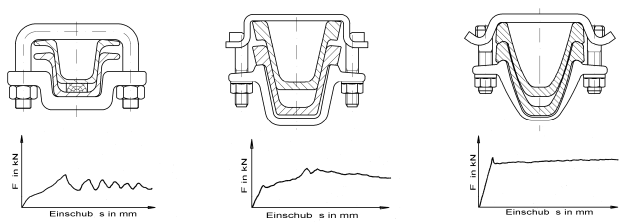


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Figure 8: Yielding characteristics

With the relatively small friction surfaces of a channel profile at the profile flanges and the required high yielding forces, in order to make full static use of the support, the critical surface pressure between the profiles and the connection is exceeded.
Here, the friction resistance (FR), calculated according to the formula (Figure 9) with F = normal force and μ = friction figure, is not sufficient.

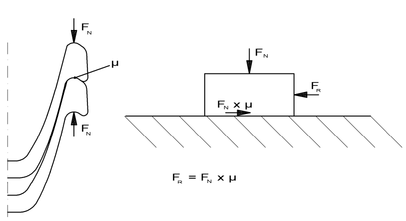


Figure 9: Friction surfaces of the TH profile

If the connection were to be designed in accordance with this law, then the insertion resistance would be significantly too small. Consequently, the formula must be expanded: FR = FN x (μ + μ`). This value μ` can be explained such that a controlled "seizing" or "scraping" occurs between the joints and fastenings and the profile, that is, a material displacement takes place.
Here, in addition to the profile, the joint for the channel profiles has a fundamental significance for a perfect functioning of the yielding arch support. With its help, transverse forces and bending moments (Figure 10) between the profile segments will be transferred. At the same time a gaping of the profiles in the overlap area is prevented. The yielding connection is based on the combination of the principles of frictional locking in the direction of the profile axis and positive locking in the other spatial directions.

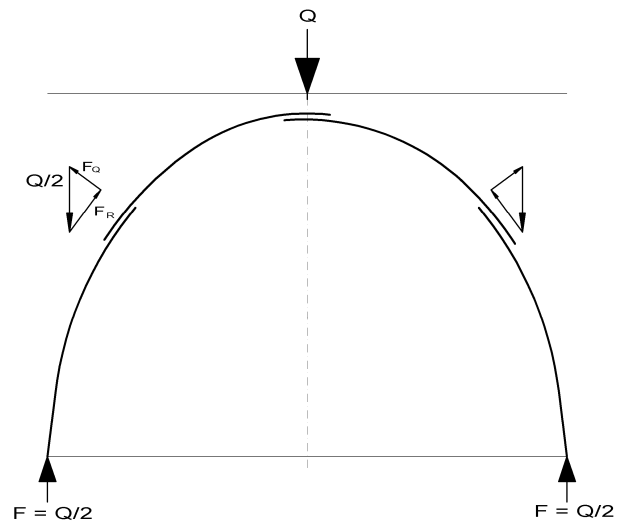


Figure 10: Force progression in the case of the standard connection

Construction and assembly of the yielding connection must meet two requirements:
1. The clamping force generated by the bolt preload force of the connection bolts must be sufficiently high in order to ensure the stability-relevant load bearing capacity of the yielding arch.
2. The clamping force must not be too high in order to prevent any sliding.

DIN 21530 [2] describes the basic requirements of present day support systems in mining - such as the profile classes, subdivision of the arch support, the so-called accessories such as the connection technology, bolting etc., and the stresses, bending support behavior and also the yielding resistances.
Almost all designs including the parallel developments were examined in more than 300 tests on the arch test stand of the DMT in Essen. Here, from roof lowering to wall movements, tests were made for the yielding behavior, bending capability across the bending moments, normal forces or transverse forces, whatever the load type. Even the world-wide largest practical load test (Figure 11) - using the inversely bent ring support with limited elasticity and made of tempered TH profiles 44 with a diameter of 13.00 meters , converged to 11.50 meters – has confirmed in practice the theory and recommendation of the "Bochumer Eisenhütte Heintzmann" with regard to the support system.

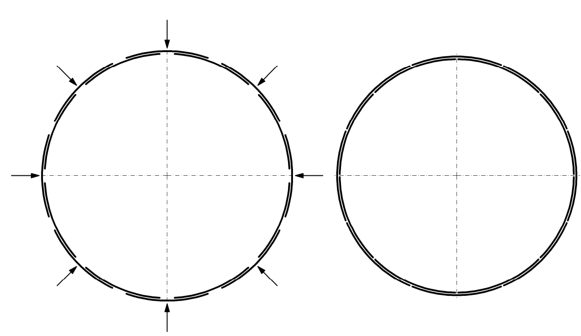
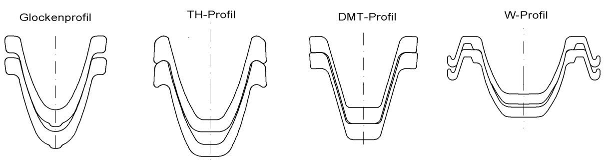


Figure 11: The effect of a TH ring in the case of force application

Thus, there are approximately 3.2 million tons, that is, approximately 100,000 km - corresponding to approximately 2.5 times the circumference of the earth - of TH arches and rings in successfully operational use today, not only in deep coal mining but also world-wide in salt and ore mining as well as in water power plant construction and tunnel construction.

In this review the developments in parallel to the TH profile should not be forgotten either. This includes the bell-shaped and DMT profiles and own new developments such as the W profile (Figure 12). These support elements could not reach the technical support advantages of present-day TH profiles. In principle, for 75 years now, no other systems for support construction are even on the horizon today that represent a technically comparable and economically viable alternative.



a b c d

Figure 12: a: Bell shape profile, b: TH profile , c: DMT profile and d: W profile

Steel grades

For selecting the steel to be used for mining support purposes, other criteria are decisive than in building construction and other application areas. Whilst the components in the area of the construction industry are designed up to yield strength, taking into account safety coefficients, thus excluding plastic deformations by design, it is not possible for applications in mining to exclude plastic deformations of the support element. This leads to the following requirements for all load-bearing steel support elements:

1. High yield point and strength, so as to ensure that any profile deformations still remain in the elastic area, if possible.
2. Good deformation capability, that is, major deformations may be supported without fracture due to high yield and contraction values.
3. High viscosity values for a fractureless plastic deformation.

In terms of material technology these requirements are contradictory (Figure 13). Thus, e.g., an increase in yield strength also involves - as a matter of principle - a reduction in the viscosity of the steel. This is compensated for, in metallurgical terms, in part by the use of different alloy components.

In the 1930s and 1940s, Thomas or Siemens-Martin steel was used for TH profiles. For the ever stricter requirements to be met by the load bearing and operational use behavior of the TH profiles, the mine support steel 32Mn3 was realized in the 1950s. Based on this kind of steel the next development step was 31Mn4 steel in the 1980s.

For the tempering of high-strength mine support steel (Figure 14), the "Bochumer Eisenhütte Heintzmann" introduced its own process from 1950 to 1955, and has developed this ever further since then. Since then up to 2,000,000 tons of tempered steel were fitted up to today. In economical terms, it was thereby possible to increase instantly the entire load bearing and operational use behavior of the support by 50 percent (Figure 15).

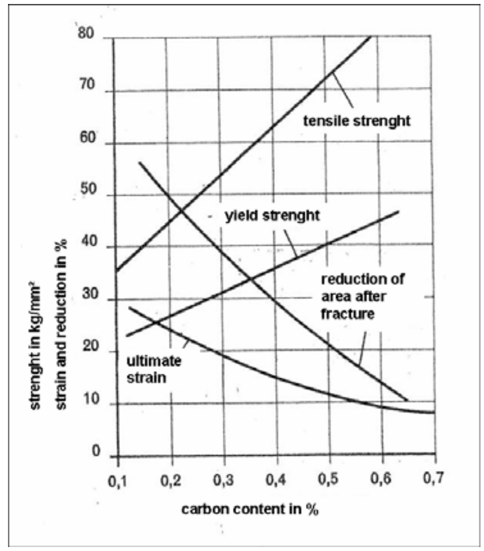


Figure 13: Influence of the carbon content

steel type 31 Mn 4 condition		yield strenght N/mm² min.	tensile strenght N/mm² min.	ultimate strain ($L_0 = 5\,d_0$) A5 % min.	notch bar impact value mean value J_{min}	notch bar impact value min value J_{min}
hot rolled	+ U	350	550	18	18	15
tempered	+ QT	520	650	18	60	40
tempered	+ QT 630	630	790	17	78	75

Figure 14: Characteristic values of the steel grade 31Mn4

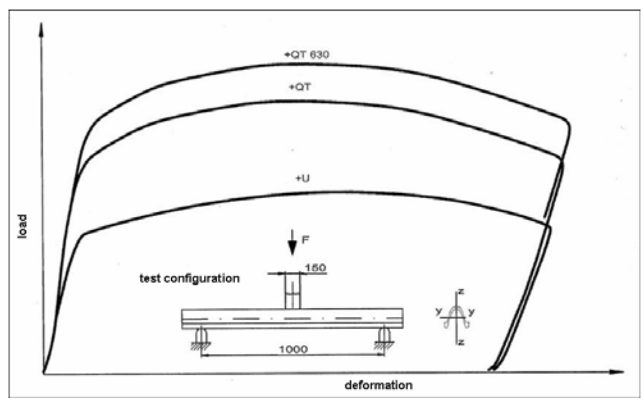


Figure 15 Load-deformation diagram in dependence of the tempering

In order to meet the further increases in load by the greater extraction depth on the one hand and the required safety reserves of RAG Deutsche Steinkohle on the other hand, it was considered to improve the quality of the steel by additional alloy elements. According to present-day criteria this proved to be too expensive. Thus, as a result of a co-operation with RAG Deutsche Steinkohle in connection with an R&D project, the option of a further increase in strength by a conventional tempering of the steel 31Mn4 was investigated. The task was to increase the yield point or strength by approximately 20 percent to 630 or 780 N/mm² without strongly influencing the toughness and notched impact strength or the ductility of the steel.

The result of the investigation was an increase in working capacity by at least 10 percent. Via the bolt torque, the insertion behavior was also adjusted upwards in keeping with the new load value.
The planned test use in the "Auguste Victoria" mine is intended to confirm the laboratory test results in actual operational use.

The miner's point of view

Before the results of current operational trial applications are described in more detail, the perspective of the manufacturer in this success story is to be supplemented by the user's view.
Today, the use of steel TH support at RAG Deutsche Steinkohle is characterized by a large number of requirements and boundary conditions. Initially, three important key points must be emphasized:

1. Roadway support for highly stressed roadways
2. Standardization of roadway support
3. Dimensioning according to a standard planning system designed specifically for RAG.

For standard planning and the development of roadway support, detailed explanations are found in the specialist book "Strata control of in-seam roadways".
The demand due to the great depth and the continuously expanding mine structures has already been emphasized at the outset by our chairman: For controlling the considerably stressed roadways, we require a high support resistance and a support that will be resistant even in the case of high deformations.
The requirement for high support resistance, as described in the first part, cannot be met by any other support element as convincingly as by the TH support in its current development stage with a work capacity that has been increased again by approximately 10% due to the tempering of the material.
Proven by practical experience and the research results from 1987, the yielding arch support - above all in combination with embedding by means of a full surface backfilling with concrete - has been proven as an indispensable support for the roadways in German hard coal mining. Its application limits will only be reached at > 80% convergence and width losses > 35% of the development cross-section.
This status is valid to this day in spite of the results from several attempts to achieve a further - shall we say "revolutionary" - optimization of roadway support. Over the past 15 years, RAG pursued several different paths in this regard:

1. Application of numerical simulation calculation for profile optimization by DMT
2. Benchmarking and brainstorming with knowledge experts from the international mining and tunnel construction sectors in research projects
3. Application of bionic studies with experts from the University of Karlsruhe
4. Contact to engineering offices for structural design
5. Know-how transfer during international conferences and symposia
6. International project work

Thus, it will not sound disrespectful, even for support engineering specialists, if one were to speak of TH support as the "cart-horse" of support construction. To this day, this type of support is able to meet sufficiently the requirements

1. High deformation tolerance,
2. Long service life,
3. Combination with other partial systems (support and suspensions),
4. Variations for different requirement profiles of longwall working,
5. Opening the coal face in the case of a longwall passage and
6. Remedial capability,

to name but a few important features.

However, as we do not always control roadways sufficiently in our deep deposit with the support resistance of the yielding arch alone, and additionally under the massive influence of the multi-seam extraction, we continued the success story of yielding arch supports in a very special fashion. Today, using standardized support techniques, we combine yielding steel arches with a rockbolt system and an early load-bearing concrete backfilling.
From a mechanical point of view, a rigid and a yielding system must be combined here, whose interaction can hardly be quantified. In tests with models and practical trials, the potential for significant increases in the load-bearing capacity of yielding arch support - in combination with a concrete backfilling - showed itself already in the 1980s. Although this can only be described to a very limited extent in the mechanical sense with regard to our requirements for roadways with high convergence, it is undoubted.
The initial load bearing forces of an installed yielding arch without concrete backfilling are approximately 500 kN. In contrast to this a doubling of the initial load-bearing forces to 1,000 kN is achieved. with a concrete backfilling.
We know today that the embedding of the support by a backfilling is also very important for the yield function, although any backfilling will break at the slightest deformation, thus – as a load-bearing shell – being no longer clearly quantifiable. Obviously, however, the support construction returns some of its load-bearing potential to the load-bearing segment of the concrete shell, which is locally overstressed by tensile strength, bending tensile strength or pressure loads. It is especially for this reason that a minimum strength, minimum backfilling thickness and a complete system for concrete backfilling are very significant for support success. This is proven by tests with identical boundary conditions in roadway model tests carried out by the DMT in 2004 commissioned by RAG.

DSK roadway support system for highly stressed roadways

In terms of rock mechanics, the effect of a large support resistance and high initial load-bearing forces is enormous for highly stressed roadways - even in the case of an open base support. Although one does not succeed in preventing the rock in the environment of the roadway from fracturing, favorable breakage forms are forced that provide a significant basis for roadway control in the case of large rock deformations.
At today's state of the art, the best performing support system for in-seam roadways in German deep coal mining utilizes these interrelationships to the full: combination support type A led to the first success in implementing the advance headings of the roadways with rock bolting support only and thus also with a high support resistance of > 1,000 kN/m and to supplement this support subsequently with yielding arches backfilled with concrete.
What distinguishes this system in comparison to other support types can best be described by means of the roadway deformations: In a standardized form, Table 1 shows what advantages of convergence reduction are achieved during development. A significant advantage is that even in the event of large roadway deformations an optimum residual width is achieved by a reduction in wall movement.

Support type	Support resistance	Convergence	Wall movement
Manual by rock-blocks backfilled yielding arch	1 (100%)	1 (100%)	1 (100%)
Yielding arch with concrete backfilling	2	0.67	0.67
Combination support	5	0.5	0.3

Table 1: Support resistance, convergence, wall movement as standardized characteristics for different support systems

The development of the support systems from 2000 – 2005 clarifies an increasing share of development is supported by using combination support constructions (rockbolting + steel arches + concrete backfilling).

2000 13% share of combination supports
2005 39% share of combination supports

This shows the trend that with increasing requirements from stress and depth the application of high performing support systems must also be adapted [3]. If we take a look at world-wide roadway development in deep coal mining, which today experience a development in depths of up to 1,000 m, then the following consequence must also be recorded here: German deep coal mining did already go through this phase in the past. During that time we conceived and tested various different support systems and had a not insignificant annual research budget for this purpose available. Thus, the competence we achieved by our work can not only be applied to maximum requirement situations but also provide assistance where simple support systems come to their limits. This certainly applies primarily to steel TH supports, but also to rockbolting systems. The process competence reaches from support development in close co-operation with the manufacturer, via mechanization and operational organization, to a consistent quality assurance in development and in extraction.

Application of the TH profile +QT 630

Meanwhile we have tested the new profile by Bochumer Eisenhütte in several trial operations. All operations so far naturally are characterized by a still ongoing roadway life, that is, use of the roadways has not yet been finally completed. Therefore we cannot provide a conclusive summary for these operations.
However, first we come to the application with the highest demands for support construction.
The advance heading of a long-life preparatory mine working has been operated for some time now in extremely squeezing strata conditions. Combination support type A (development as rockbolted roadway with additional secondary support behind) is unthinkable due to the assessment of the rockbolting capability of the strata and the endangered stability of an advance heading with rockbolting support. The advance heading of this operationally indispensable roadway is therefore effected with additional reinforcing measures under extreme boundary conditions; this even includes the roadway deformation in the course of development. This is proven by the logged measurements of convergence and wall movement in the roadway (Figure 16).

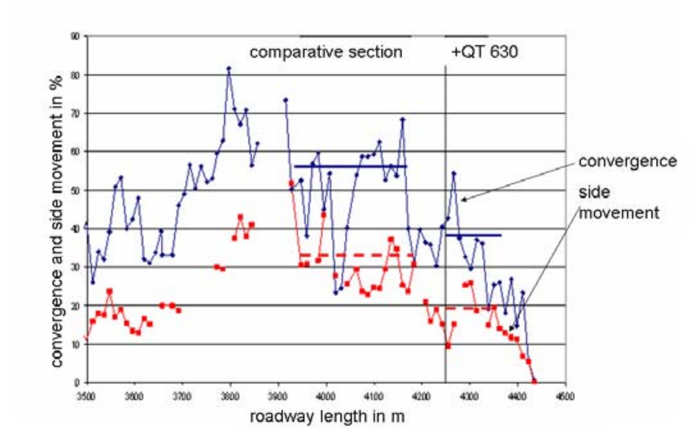


Figure 16: Convergence and wall movement along the roadway length, Application 1

If we look at the development of roadway deformation across its service life after development, the challenge for support will become even more apparent. Within just a few days an enormous load develops from the fracture deformation around the roadway, which the yielding support must take up with the maximum possible resistance and a high deformation tolerance (Figure 17). Whilst the roadway section with conventional arches of weight class 40 kg/m (broken line) responds within 100 days after development with approx. 45% convergence and approx. 30% wall movement, the support +QT 630 (unbroken lines) can record a more favorable response with a deformation within 100 days of approx. 40% convergence and approx. 20% wall movement.

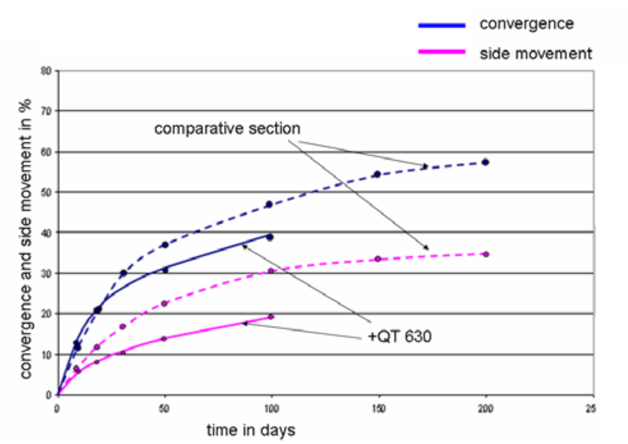


Figure 17: Time-depended development of convergence and wall movement, Application 1

This example shows clear advantages of the new highly tempered profile, but due to the strong deformation already occurring behind the advance heading it must be assumed that this also comes to its application limits.
A further example for the application of the +QT 630 profile can be quoted for the development of a roadway along a coal pillar in the "Saar" mine. Here, the application was effected with the objective to optimize the spacing between support units in the roadway. In the course of development in a section with a lower load this was

increased from formerly 0.8 m to 1.0 m, with the yielding arch support and concrete backfilling being reinforced by a rockbolting system behind the advance heading. Since, here, stronger deformations are only expected during the later utilization as a tailgate; this allows the use of standard tempered yielding arches to appear as being on the limits as planned. Figure 18 shows the measured convergence and wall movement for the section with +QT630 and a comparison section. Here, a large difference of the measured convergence becomes apparent which, however, is also explained by a higher rock stress in the comparison section.

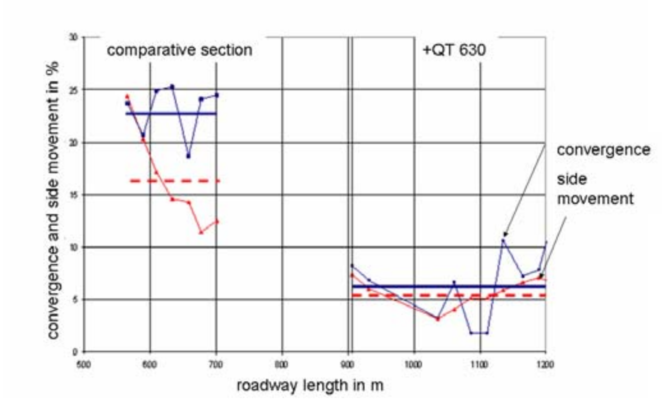


Figure 18: Convergence and wall movement along the roadway length, Application 2

Nevertheless, using the measured values logged so far, the example shows that the more highly tempered material meets its support function excellently even in the case of an increased spacing between the support units.

Figure 19 shows a roadway with combination support type A. The photograph illustrates that there are no visual differences between the known normally tempered yielding arches and the highly tempered support construction shown here.

Figure 19: Roadway in combination support type A

DSK standardization concept

During the development phase, a wide range of support parts has accrued in individual mine company divisions with different histories. Due to the merger of the various mine companies into today's RAG Deutsche Steinkohle, it became possible to standardize the roadway support. Such a measure for economical and logistic optimization demands a manufacturer-neutral specification of all relevant requirements. In this regard RAG prepared a product standard that defines the valid standard.

Standard segments and cross sections

The task was to define a standard from more than 150 different roadway cross-sections.
In order to meet the various different requirements of the individual operations with regard to coal seam thickness, lateral inclination and longwall technology used, the standard defined cutting lengths and bending radii.
Today, from only eight different cutting lengths, it is possible to produce all roof, face and central segments from just one single rolled length. Residual pieces are avoided by a combination in the actual sequence when manufacturing the individual segments.
In this way, the present-day status of steel support standardization reaches an essential simplification with regard to manufacture and management and is still capable to offer solutions flexibly adapted to the different operational requirements.

Connection elements

Likewise, in connection technology a large number of design varieties have been produced in the course of yielding arch development. Even in terms of time the last step of this development was used for standardization.
The standard connection construction was created as a connection for the profile weight classes from TH 34 to TH 44. Doing without a carrier cam at the top connection enabled the use of the main and guide clamps as identical standard clamps.
Design and assembly of the slide joints must in principle meet two requirements: The clamping force generated by the bias of the connection bolts must on the one hand be sufficiently high to ensure the stability-relevant load bearing capacity of the yielding arch. On the other hand the clamping force must not be too high in order to prevent any sliding. Therefore, the bolt torques will be rechecked after initial fitting. Here, in compliance with the aspect of standardization, design and construction measures and organizational improvements go hand in hand, because the quality assuring control of the roadway-driving operations, too, has been introduced according to standard processes.

Selection of the proper roadway support

For every application, planning has the task to define the suitable roadway support. The experience with the utilization of the yielding arch has led to dimensioning rules in German deep coal mining that enter into a standard planning system. Planning itself has already been described several times in this conference [5,6,7]. The procedure for support planning is characterized by the available information and the knowledge of the behavior of the support system. Without repeating the details here, it is worth pointing out that, with regard to the TH support, the support success over decades of application has led to a wide basis of experience which permits an empirical dimensioning.

Accordingly, there are planning elements available to define the proper cross-section size, select the correct profile strength, and specify the optimum spacing between the support units.
The experience gained was also verified in international projects for its transferability to other deposits. Specifically here it becomes very clear that the support cannot be considered on its own but that the technical and infrastructure options of the entire mine must be

taken into consideration. Assuming a high quality of execution (e.g. arrangement of the segments, overlap lengths, connection elements, torques, bolting) as the basis, it becomes clear that the empirical fundamentals can be transferred. Quite surprisingly it can be observed again and again that variants of the yielding arch design with other profile forms and other connections feature a reduced working capacity in practice. The reason for this is a frequent earlier support failure in the case of converging roadways.
Finally, it must be stated that for different technical support challenges in the past, present and future the TH yielding arch support is an indispensable partner for RAG. The most recent developments of the highly tempered profile + QT 630 have shown to be positive in initial trial operations and are an example for the positive co-operation of our mines with a reliable supplier over many years. However, the proving tests in practical application for the latest development stage have not yet been completed; therefore it is not yet possible today to come to an ultimate conclusion of this success story.

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