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# STUDIES ON PERFORMANCE PREDICTION OF HEAVY WEIGHT TRANSVERSE ROADHEADERS BASED ON FIELD DATA IN TUNNELING PROJECTS

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In Japan (especially Hokkaido), the performance prediction of a heavy weight roadheader is a critical issue in assessing technical and economic feasibility of its application in any tunneling project. This refers to accurate estimation of the production rate, machine utilization, and bit consumption for different geological units to be encountered on the alignment of the tunnel.

To develop models for reliable performance prediction of heavy weight (300kW class) transverse roadheader, the Working Group of the Geo-Fronte Research Association jointly with the Tunnel Research Association in Hokkaido has established a database of heavy weight roadheader field performance, which based on the interview for engineer's of any tunnel construction projects. This database contains field data from the civil construction operations all over Japan, includes a variety of heavy weight roadheaders and different geotechnical conditions.

This paper will present and discuss the performance prediction models developed from this database, especially for excavation of tunnel by heavy weight (300kW class) transverse roadheaders.

***Key Words :*** *heavy weight roadheader, crossdead, tunnel excavation performance, prediction*

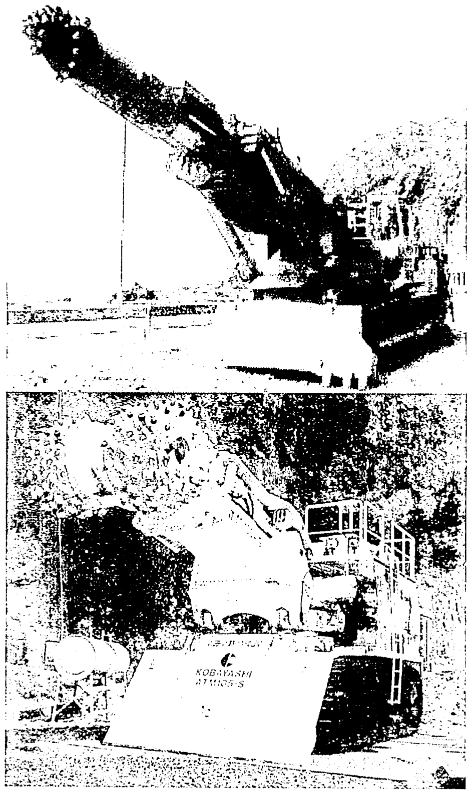
## 1. INTRODUCTION

In Japan (especially Hokkaido), the performance prediction of a heavy weight road header is a critical issue in assessing technical and economic feasibility of its application in any tunneling project. The main performance issues are machine type selection, scheduling of tunnel excavation and/or term of works of tunneling projects, and estimation of cutting bit cost.

So far, mostly empirical approaches (past experiences and statistical analysis) have been used to develop performance prediction models. That's partly because the variability of geological conditions, the operator sensitivity, the machine weight, cutting type, and design related parameters don't allow for establishment of a theoretical performance prediction model. So, collection of field data becomes very important for developing empirical performance prediction models.

Therefore, to develop models for reliable performance prediction of heavy weight (300kW class) roadheader, the Working Group of the Geo-Fronte Research Association jointly with the Tunnel Research Association in Hokkaido have established a database of heavy weight roadheader field performance, which based on the interview for engineer's of any tunnel construction projects.

A roadheader cutting booms are based on *either the* axial (in-line or spiral-type) or transverse (cross head



**Pictue1** Cutting action of an axial (upper:RH-10J) and transverse (lower:ATM105) roadheader

**Table1** Summary of Empirical Performance (Revised from Breeds[1])

| Author (year) | Geological Parameters | | Machine Parameters |
|---|---|---|---|
| | Intact Rock | Rock Mass | |
| Gehring (1989) | UCS | - | - |
| Neil, et al (1994) | UCS,BTS,SE,Fn,Fc | RQD | Hp,D,S,rpm,others |
| Biligin, et.al (1988) | UCS | RQD | Hp |

UCS:Uniaxial Compressive Strength, SE:Optimtum Specific Energy, RQD:Rock Quality Designation, BTS:Brazilian Tensile Strength, Fn:Normal Force,. Fc:Cutting Force, Hp:Cutter head Power, rpm:Revolution Per Minute, S:Line Spacing, D:Cutterhead Diameter

or drum-type) concepts. The axial-type cutter head has an axis of rotation in line with the axis of the cutter boom. Rotation and slewing of the cutter head is in the same direction.

On the other hand, the axis of rotation of a transverse type cutter head is perpendicular to the axis of the boom (See Picture 1).

Both types of cutter head have their critical areas, where the necessary compromise between pick position and operating requirements will result in an inadequate cutting effect by the picks in this area. For the axial type cutter head the tip of the head must be fitted with specially positioned picks to achieve sufficient sumping. On transverse type cutter heads the picks at the left and right end of each half of the cutter head cannot be positioned, as mentioned above, since their picks will have to cut the periphery of the tunnel.

There are several empirical models for estimating the production and cutting rates of roadheaders. Table.1 shows a summary of the most cited empirical models for prediction of Instantaneous cutting rate (ICR) which is production rate for the actual cutting time (bank $m^3$/cutting hour) of axial and transverse roadheader.

The empirical models for estimating the production and cutting rates of heavy weight axial and transverse road headers have been developed by Gehring[2]. The paper by Neil, Rostami, Ozdemir and Gretsch[3] developed for axial and transverse road headers performance and prediction model, in different weight classes and different types of rock masses. And also, Biligin, Yazici and Eskikaya[4] are developed for axial and transverse road headers performance and prediction model, in different weight classes.

As it can be seen, there are generally two types of parameters affecting roadheader cutting rates a) mechanical parameters and b) geological parameters.

To represent the geological parameters, the most widely used intact rock property is Uniaxial (Unconfined) Compressive Strength (UCS). Also, rock mass property which means crack of rock mass is commonly re- presented by Rock Quality Designation (RQD).

This paper will present and discuss the performance pre- diction models developed from the aforementioned database, especially for excavation of tunnel by heavy weight (300kW class) transverse roadheaders. One common model, which is also employed in this paper, is the empirical models for estimating the production and cutting rates of heavy weight (300kW class) transverse roadheaders.

## 2. DATABASE ON FIELD PERFORM-ANCE OF HAVY WEIGHT ROAD HEADERS

There are many parameters influencing the cutting performance of a heavy weight axial and transverse roadheader, some of which are listed in Table.2.

### (1) Roadheader Parameters

The friction moment between floor and the crawler tracks of the machine is the limiting factor for inducing higher forces into the rock. Since the friction moment for a certain roadheader is more or less proportional to the weight of the machine, only an increase in weight will allow an increase of cutting force at the cutter head.

And, it is well known that the heavier the roadheader, the more stable the cutter head and the more efficient cutting. That's why the higher

**Table2** Some of Parameters Affecting Cutting Performance of Roadheaders

| A. Mechanical Parameters | B. Geological Parameters |
|---|---|
| (1)Roadheader parameters | Rock mass Properties |
| Roadheader type (shielded, truck mounted, twin boom, telescopic, etc.) | (1)Rock Quality Designation (RQD)<br>Discontinuities (fault and shear zones, joints, bedding, etc.) |
| Roadheader weight and dimensions | Joint set properties (orientation, spacing, roughness, etc.) |
| Roadheader force capacities (sumping, arcing, slewing, lifting, lowering) | Hydrogeological conditions<br>Adverse geology (mixed face, squeezing ground, etc) |
| (2)Cutterhead Parameters | (2)Physical and Mechanical Properties of Intact Rock |
| Cutterhead type (axial and transverse) and shape (cylindrical, conical, spherical, etc.) | Rock cutting properties (specific energy, pick forces, size distribution of cuttings, etc.) |
| Cutterhead dimension (diameter, length, cone, angle, etc.) | Strength Properties (UCS, tensile strength, young's modulus, cohesion, etc.) |
| Cutterhead power (kW) and rotation speed (rpm) | Surface hardness properties (shore and Schmidt hammer rebound values) |
| Cutterhead lacing design (line spacing, circumferential spacing, cut spacing, attack angle, etc.) | Texture properties (porosity, mineral/quartz content and grain size, microfractures, etc.)<br>Abrasiveness properties (cherchar abrasively index, etc.) |
| Total cutter number on cutterhead<br>Bit type (conical, radial, etc.) | Seismic properties (velocity of P and S waves) |
| Bit dimensions (shank and gauge length, tip diameter and angle(s), etc.) | Other properties (density, water content, swelling and freezing properties, etc.) |

**Table3** Technical data of Heavy Weight Transverse Roadheders

| Manufacturer | TAMROK(SANDVIK) VOEST-ALPINE | ALPINE-WESTFALIA |
|---|---|---|
| Model | ATM105 | WAV300 |
| Cutterhead Type | Transverse | |
| Weight (tonnnes) | 110 | 83 |
| Power of Cutter motor (kW) | 300 | 300/200 |
| Excavation Height (mm) | 6280 | 8300 |
| Excavation Width (mm) | 9400 | 8860 |

instantaneous cutting rate is experienced from the heavier roadheaders.

### (2) Cutter Head Parameters

The two types of cutting head produce an advantageous or disadvantageous effect on the ICR or cutting performance of the machine depending on the composition of the rock. The advantages and drawbacks of the various cutting procedures are dealt with below systematically.

With an axial-type cutting head the slewing force and the circumferential force lie roughly in the same direction, the forces required for the slewing movements are therefore, determined by the circumferential force. The cutting operation creates two exposed surfaces.

With a transverse-type cutting head the slewing force is approximately at right angles to the circumferential force. The required slewing force is relatively low since the circumferential force does not have to be overcome. The cutting operation creates three exposed surfaces which lie at right angles to one another.

And also, most common machine characteristic used for performance prediction is cutterhead power. For example there are roadheaders in the market that have the same cutter head powers but different weights.

### (3) Rock Mass Properties

And, rock mass properties are commonly represented by RQD and Discontinuities. These are the easiest and the most reliable parameters to obtain in the ground con- ditions.

### (4) Physical and Mechan- ical Properties of Intact Rock

Also, rock physical and mechanical properties are commonly represented by UCS, Schmidt hammer rebound values and Cherchar abrasively index.

Therefore, we are developed models for reliable performance prediction of heavy weight (300kW class) road header, the Working Group of the Geo-Fronte Research Association jointly with the Tunnel Research Association in Hokkaido has established a database of heavy weight roadheader field performance, which based on the interview for engineer's of any tunnel construction projects.

This database contains field data from the civil construction operations all over Japan, includes a variety of heavy weight road headers and different geotechnical conditions. And, the field performance data from more than 200 tunnel construction projects have been collected and compiled in the heavy weight roadheader performance database at the present.

## 3. PRELIMINARY ANALYSIS OF THE COLLECTED FIELD DATA

In this section we present the preliminary results of the analysis of the available data, to identify, the relationships between field performance of the Gehring's data and the data of tunnel construction projects.

And the multiple-variable regression analyses were performed by using all the available data.

### (1) Instantaneous Cutting Rate (ICR)

To investigate the difference between the Gehring's data and the data of tunnel construction projects, two comparison studies were conducted by actual tunnel excavation results. The first examined the ICR and an approximate UCS or cutting energy of two more or less equivalently powered machines (Table 3). Also, another compared actual site test

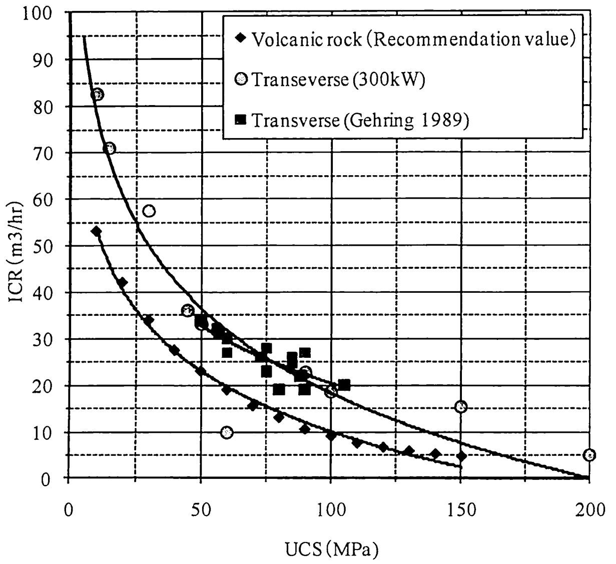



**Fig.1** Comparion of instantaneous cutting rate (300kW)

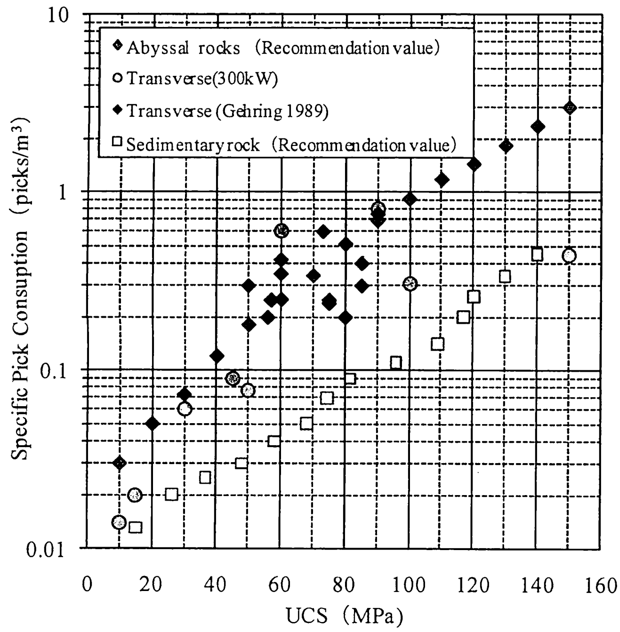



**Fig.2** Comparison of pick consumption (300kW)

results[4].

From the results, it is clear that the cutting performance of the difference increases with increasing com- pressive strength (Fig.1). At a value of 80MPa, the average cutting performance for the transverse type cutter head to approximately 23 $m^3$/h, an improvement in per- formance of almost 100% it can be assumed that this difference is within the variance of such an on-site investigation.

### (2) Specific Pick Consumption

Next, the comparison of pick consumption for both type roadheders is shown in Fig. 2. For general considerations, the pick consumption should only be seen in relation to the cutting performance.

Fig. 1 and 2 show the ICR and pick consumption as a function of UCS, respectively. The results of the preliminary analysis produced some means for establishing relationships between the field performance of heavy weight (300kW ) roadheaders and the geological and mechanical parameters.

## 4. PREFORMANCE OF TRANSEVERSE ROADHEDER BASED ON THE FIELD DATA

The actual site comparison is based on under-ground measurements of the actually cutting at any given time would performance of a roadheader Alpine Miner ATM105 and WAV300 with a 300kW.

### (1) Instantaneous Cutting Rate (ICR)

After classification of the data for only transverse roadheaders and for volcanic and sedimentary rocks (such as sandstone, mudstone, andesite, basalt, tuff, chart) which are generally hard, massive, and brittle under dynamic rock cutting conditions, the relationship between the ICR and UCS were obtained as shown in Figure 3, which still shows some scatter.

When summarized by cutter head power (300kW), the relationship between the ICR and UCS was obtained as shown in Figure 3. Although it was possible to see a trend, the data was still short. After normalization by roadheader weight, was found a very good relationship between the ICR and Cutter head power/UCS. This approach proved to yield more accurate performance predictions.

### (2)Total Performance[5]

Next, to come from ICR to actual performance figures a number of additional influences need consideration like, as follow.

a. Time demand of rock protection/support
b. Logistic tuning and capacity of haulage
c. Skill of personal
d. Restriction of operation due to other activities in the tunnel
e. Actual available working period

In practice a range of machine utilization (ratio between cutting time and total working time) between approx. 20-40% for optimum conditions (no support, best organization, no standstill) and figures between 10 and 20% (high amount of support) can occur.

### (3) Pick Consumption

Pick consumption is inevitably connected with rock cutting. So, a pick consumption is as well guided by rock strength as also by rock abrasivity,

**Table4** Range of CAI – Values

| CAI Values | Rock class |
|---|---|
| CAI<0.6 | soft marl and limestone, claystone, potash, phoshate, gypsum, coal |
| 0.6<CAI<1.0 | medium hard marl and limestone, shale, soft mudstone and siltstone laterite, anhydrite |
| 1.0<CAI<1.5 | softsandstone, medium hard siltstone and mudstone, hard marls and limestone, soft phyllite, carbonate lead - zic ore, bauxite, volcanic tuff (not welded) |
| 1.5<CAI<2.0 | medium hard sandstone and graywacke, hard siltstone and mudstone, medium hard phyllite and schist (not quarizitic), other carbonatic ore like gold ore or manganese ore, weathered basalt and andesite, serpentinite |
| 2.0<CAI<3.0 | hard sandstone and graywake(not quartzitic), hard phyllite and schist (not quartzitic), sulfidic ore with little content of pyrite, slightly weathered igneous rock(basalt, diabas, andesite) |
| CAI>3.0 | quartzitic rock type, sulfidic ore with higher pyrite content, allplutonic rocks, (like granite, diorite), welded tuff, unweathered volcanic rocks, most of metamorphic rock (gneiss, phyllite and schists with higher quartz content) |

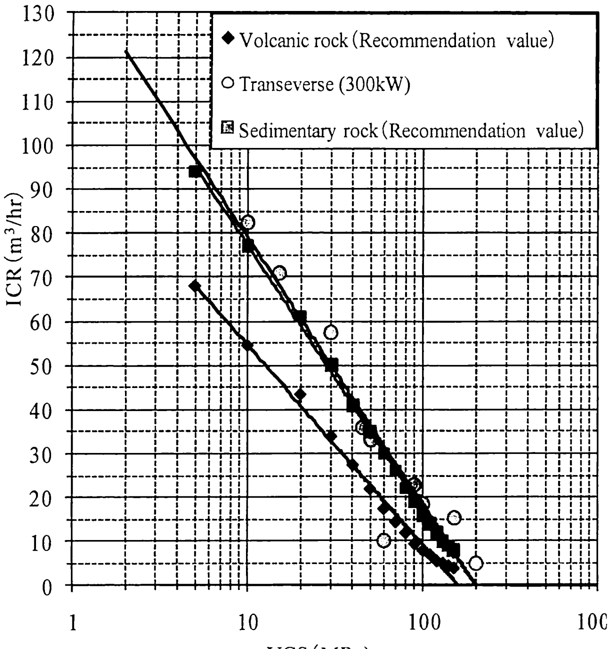


**Fig.3** Comparion of ICR (300kW)

here expressed by the most common value, the Cerchar Abrasivity Index (CAI) (see APPENDIX A).To have a better judgment about the range of CAI-values, some examples are shown in Table.4.

So the diagram of Fig. 4 can only give a very approximate picture and is only valid for a certain pick type.

After classification of the rock using the CAI-values, was found a very good relationship between the pick consumption and UCS. This approach proved to yield more accurate pick consumption predictions.

## 5. PREDICTION OF TRANSEVERSE HEAVY WEIGHT ROADHEADER PERFORMANCE

Net cutting rate or instantaneous cutting rate is to be understood as the performance per unit time, where the cutter head is in actual cutting contact with the rock.

### (1) Prediction of Instantaneous Cutting Rate

There are many parameters influencing the cutting performance of a heavy weight transverse roadheader, some of which are roadheader weight, cutter power, cutter type, site condition and rock strength as also by rock abrasivity and crack condition. It is certainly not feasible to predict the performance from such scatter data. To simplify the analysis and develop more accurate performance prediction models, some of these parameters have to be eliminated while some others have to be added to the models.

In the conventional study, the first indicative estimation of instantaneous cutting rate can be following the equation below [5].

$$ICR = (7.0 / UCS) \cdot N \qquad (1)$$

ICR: Instantaneous cutting rate ($m^3$/hr)
UCS: UniaxialCompressive Strength (MPa)
N: Install cutter head power (kW)

Next, the equation for the regression curves for the transverse type cutter head is shown eq. (2) [2].

$$ICR = 719 / UCS^{0.78} \qquad (2)$$

ICR:($m^3$/hr) , UCS: (MPa)

And, the following empirical performance prediction equation (3) of instantaneous cutting rate is for tunnel excavation by transverse roadheaders proposed by Coupur 1999[6].

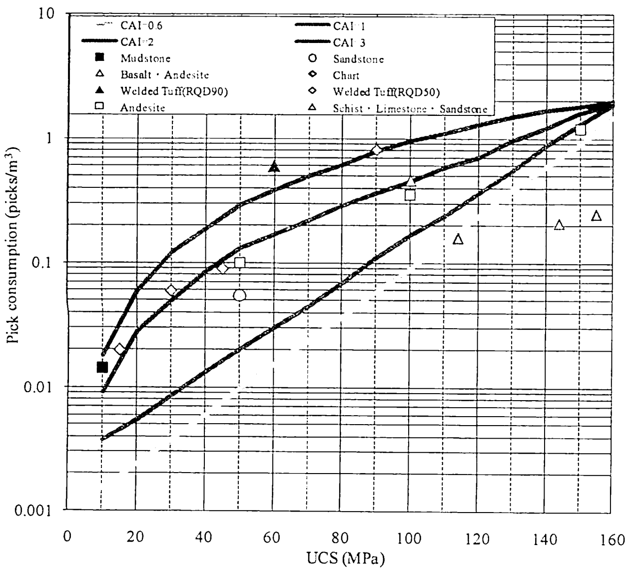



**Fig.4** Indicative prediction diagram for specific pick consumption

$$ICR = 27.511e^{0.0023 \cdot P \cdot W / UCS} \quad (3)$$

ICR: ($m^3$/hr) , W: Roadheder Weight (metric ton)

P: Cutter head Power (kW) , UCS: (MPa)

Most common machine characteristic used for performance prediction is cutter head power and /or weight of the roadheader. These are the easiest and the most reliable parameters to obtain in the field.

A review of the models offered to date shows that the authors have tried to obtain one unique formula to cover every ground condition, which is a kind of simplification of tunnel excavation process.

In this paper, the following empirical performance prediction equation (4) of instantaneous cutting rate proposes for tunnel excavation by transverse roadheaders, which was found by classification and normalization of the field performance data and regression analysis.

$$ICR = 27.511e^{a \cdot P \cdot W / UCS} \quad (4)$$

ICR:($m^3$/hr) , UCS:(MPa)

W:(metric ton) , P:(kW)

a: Site effect Parameter (0.006)

So, the relationship between the ICR and UCS were estimated by equation (4) as shown in Figure 5(a), (b). The Fig. 5(a), (b) are given a very approximative picture and are only valid for a certain heavy weight transverse roadheder.

When different combinations of parameter were used for normalization, similar trends were obtained. Cutter head power and roadheader weight together with UCS provided for more accurate predictions of ICR in different massive rock types.

This equation can also be used for selection of roadheaders for excavation in tunnels to meet a target production.

## 6. CONCLUSTION

There are many parameters influencing the performance of heavy weight transverse roadheaders which create some variations between machine field performance and predicted rates.

For the example, Geological origin of the rock, rock group or type, uniaxial compressive strength, Brazilian tensile strength, rock quality designation, quartz content, roadheader type and weight class, cutter head type and diameter, and bit type were found to be the most important parameters.

Therefore we are developed an extensive database on field performance of roadheaders and is being continuously updated by collecting more field data, which are improved the capabilities and the accuracy of these models.

But, this study still needs more field data to better define the relationship between the performance and the influencing parameters. This database of heavy weight roadheader field performance and the results of this study so far have been very promising.

**ACKNOWLEDGMENT:** We express the will of thanks for the Working Group of the Geo-Fronte Research Association and the Tunnel Research Association in Hokkaido to establish a database of heavy weight roadheader field performance.

## APPENDIX A

From the time of its earliest development in the mid 1960s, the Cerchar Abrasivity Index (CAI) test has gained increasing popularity as a means of assessing the abrasivity of rock. This is in part due to it being a simple, fast and effective method of measuring and comparing the abrasivity of different rock samples[7]. The test has found common use within the mining and tunnelling industries to estimate wear rates and cost of equipment replacement. Indeed, the Cerchar test is now considered by some as one of the 'standard' parameters for hard rock classification[8].

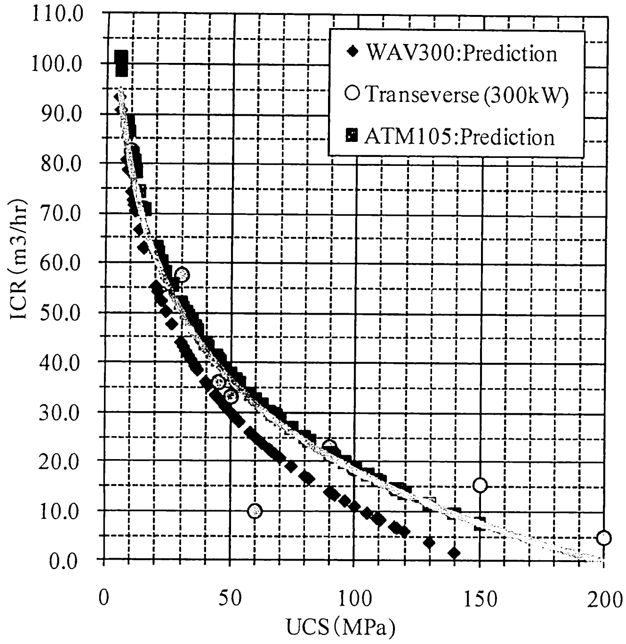



**Fig.5 (a)** Prediction of ICR for heavy weight transverse roadheder (1)

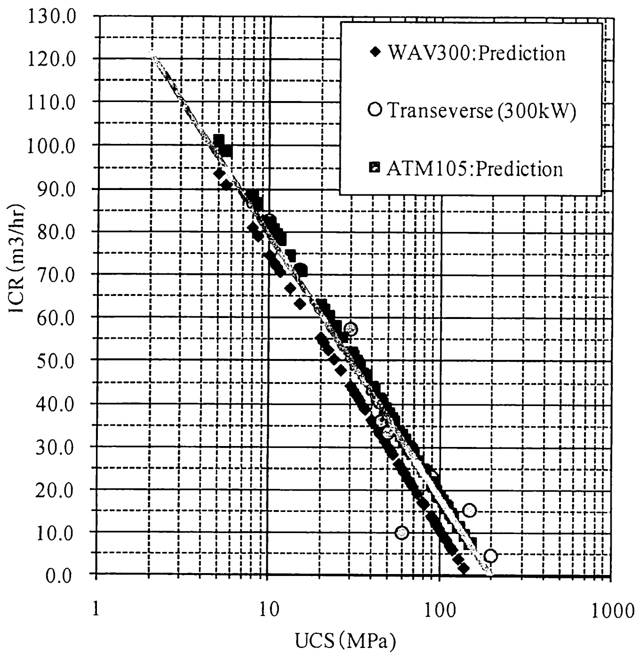



**Fig.5 (b)** Prediction of ICR for heavy weight transverse roadheder (2)

Over the years, the Cerchar test has been subject to significant study especially with respect to what effect test conditions and the geotechnical properties of rock might influence test results[9),10)]. One test parameter that has been subject to some debate is the metallurgy of the steel stylus (sometimes referred to as the 'pin' or 'needle') used in the Cerchar test, particularly with respect to its hardness. Currently there is no one standard that has been unanimously adopted and variants to the test continue to be used making comparison of results somewhat tenuous. Indeed, classifying results according to CAI might be misleading without knowing the precise specifications of the stylus used in the test.

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