Cutter assessments

F. J. Macias of SINTEF and NTNU, F. Dahl of SINTEF, and A. Bruland, of NTNU describe the Rolling Indentation Abrasion Test (RIAT) - NTNU/SINTEF's new approach to tool life assessments on hard rock TBM tunnel boring

Figure 1: Outline of the Rolling Indentation Abrasion Test (RIAT) method (left) and photo during testing (right).

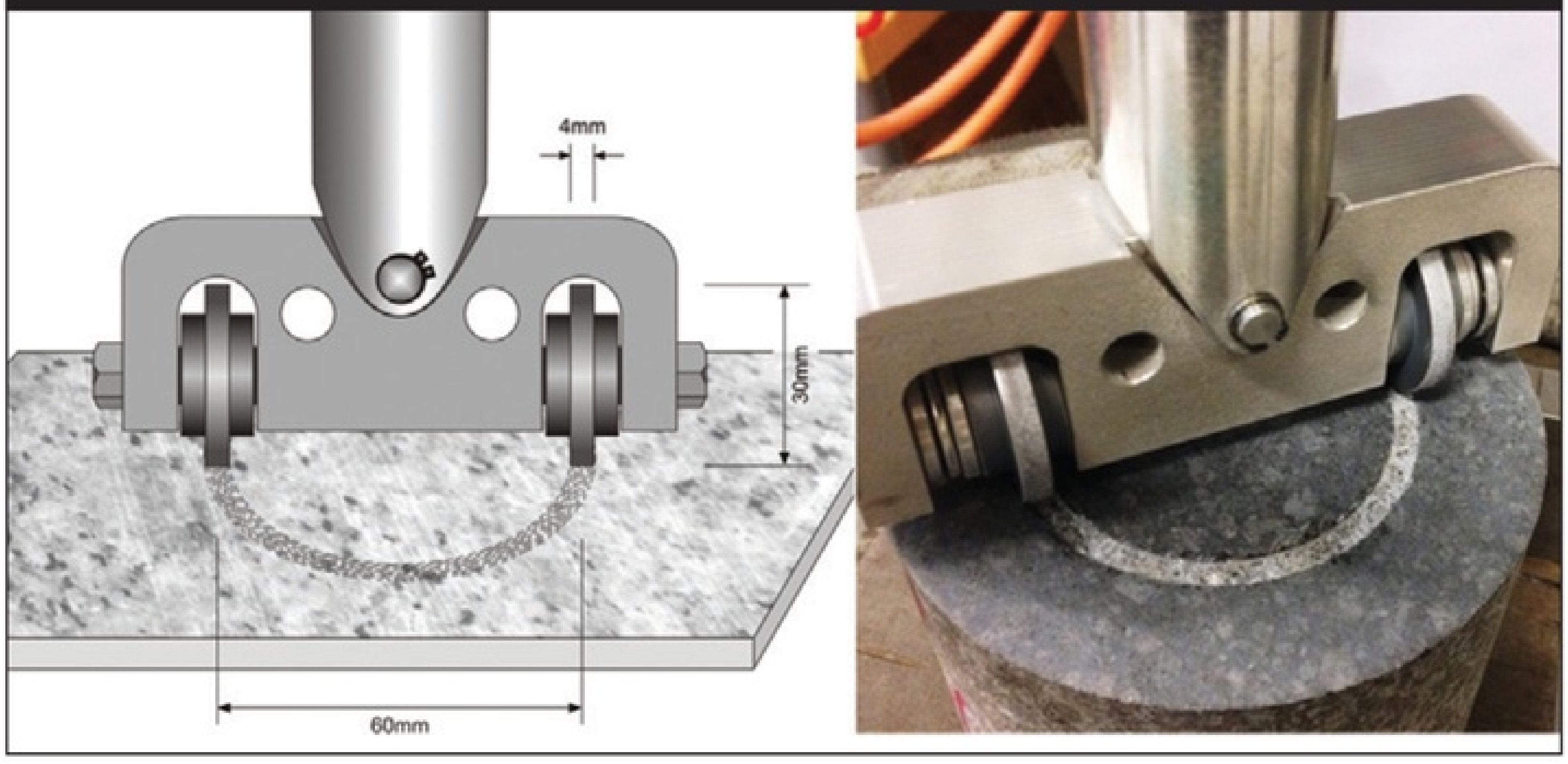
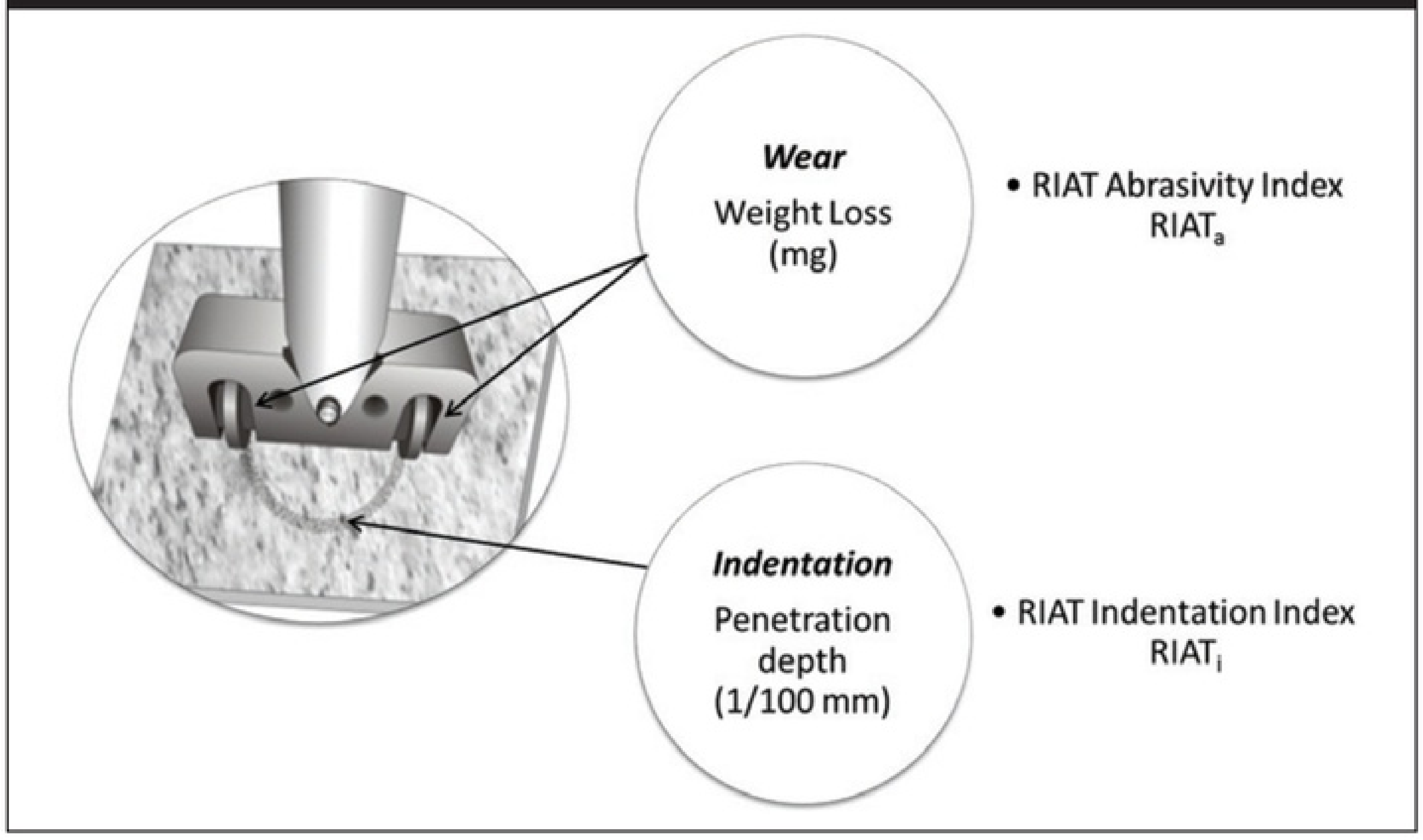


Figure 2: Description of the outputs resulting of the RIAT method.



CUTTER CONSUMPTION plays a significant role in performance and cost during TBM tunnel boring especially in hard rock conditions. Reliable assessments of cutter consumption will facilitate the control of risk as well as avoiding delays and budget overruns.

The new NTNU/SINTEF abrasivity test method RIAT (Rolling Indentation Abrasion Test) has been developed to reproduce wear behaviour on hard rock TBM tunnel boring (Macias et al., 2015, 2016; Macias, 2016). The RIAT procedure introduces wear by rolling contact on intact rock and the achieved results indicates a great ability of this new test method to assess abrasive wear on rolling discs.

There are several laboratory test methods (CAI, AVS, LCPC) which are traditionally used to assess cutter consumption. None of them were originally developed for TBM cutter wear assessment, as they uses sliding or impact contact in order to cause wear. The question is hence whether they are able to reproduce the wear behaviour encountered during TBM tunnel boring in a realistic way. The RIAT should however, by introducing rolling contact on intact rock samples, be able to asses cutter wear in hard rock TBM tunnelling as close to reality as possible in a down scaled test.

The main advantages of the RIAT are: wear caused by rolling contact, testing of intact rock samples, relatively small samples needed, cost effective method and in addition, a simultaneous measurement of the rock indentation resistance or rock surface hardness.

Description

The Rolling Indentation Abrasion Test method (RIAT) consists of miniature rolling discs, which are penetrating the surface of an intact rock sample. The RIAT tool is, as shown in Figure 1, fitted with two of these replaceable miniature cutter rings. The rotation, torque and vertical thrust of the tool are provided through a suitable drive unit.

Test procedure

The RIAT test is performed on a cut surface of an intact rock sample. The rolling velocity is defined as 40 revolutions per minute (rpm) with a normal thrust of 1,250 N. The used values have been defined by considering real cutter parameters in hard rock TBMs and previous evaluation approaches. The mini cutters have a constant tip width and they are made of AISI Type H13 Hot Work Tool Steel, a commonly used basic alloy for actual TBM cutter rings, with Rockwell Hardness HRC 50±1.

The main parameters for the test procedure are given in Table 1.

Table 1: Main parameters for the RIAT test method (Macias et al., 2015, 2016).

Parameter	Value
Thrust (N)	1,250
Rolling velocity (rpm)	40
Testing time (min)	30

Figure 2 summarizes the outputs of the RIAT method.

The RIAT Abrasivity Index ($RIAT_a$) is defined as the weight loss of the miniature cutter rings measured in mg subsequent to testing. In addition to the weight loss, penetration of the miniature cutters into the intact rock is also measured after testing. The penetration value of the RIAT test does hence provide an indication of the indentation resistance or rock surface hardness. The RIAT Indentation Index ($RIAT_i$) is defined as the penetration of the miniature disc cutter in 1/100 mm.

Evaluation of RIAT

Initial testing has been performed on eight rock types covering a wide range of hard rock abrasiveness, from low to high abrasivity. Figure 3 shows RIAT samples after testing.
The lowest and the highest RIAT abrasivity ($RIAT_a$) of the test performed are 3 (limestone) and 104 (quartzite) while for the RIAT indentation ($RIAT_i$) are 5 (Quartzite) and 380 (Limestone). No measurable indentation was possible to achieve for the Quartzite sample.

Figure 4 displays the results achieved by RIAT, $RIAT_a$ and $RIAT_i$, for the selected rock types.

Initial results indicates a great ability of the RIAT test method to assess abrasive wear in rolling discs for a wide abrasivity range of rocks. The RIAT method has also shown an improved ability to distinguish the abrasivity at the high end of the scale.

A distinguished correlation level was obtained between the abrasivity and indentation indices ($RIAT_a$ and $RIAT_i$) for the eight rock types (Figure 5). The graph indicates that, higher the $RIAT_a$, the lower the $RIAT_i$.

Figure 4: Results achieved by RIAT. $RIAT_i$ on the vertical axis left (dotted red line) and $RIAT_a$ on the vertical axis right (blue columns). Error bars show standard deviation (Macias et al., 2016).

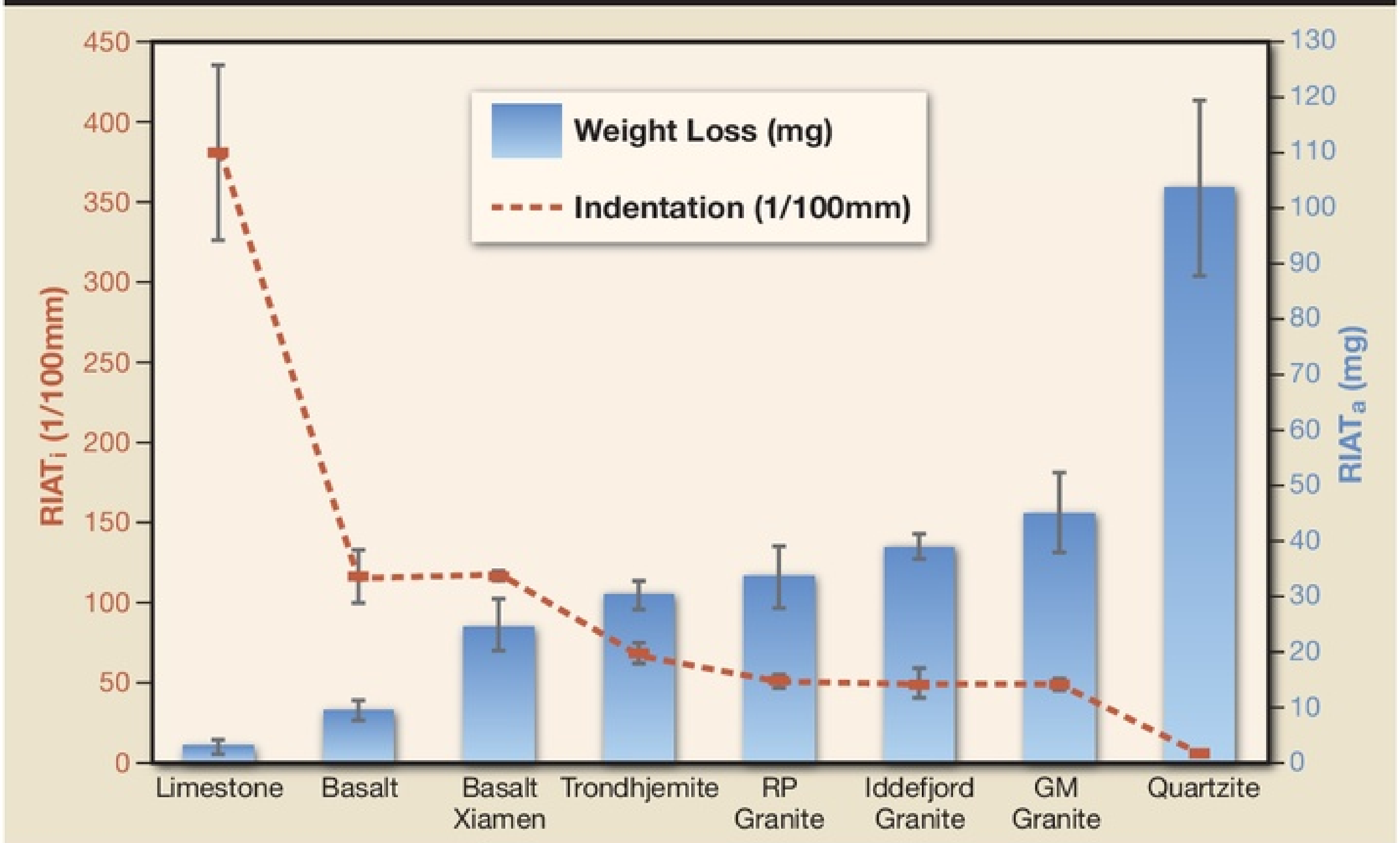


Figure 3: Rock samples after testing by RIAT. (a) Limestone, (b) Basalt, (c) Basalt Xiamen, (d) Trondhjemite (tonalite), (e) Rosa Porriño granite (RP granite), (f) Iddefjord granite, (g) Gris Mondariz granite (GM granite) and (h) Quartzite (Macias et al., 2016).

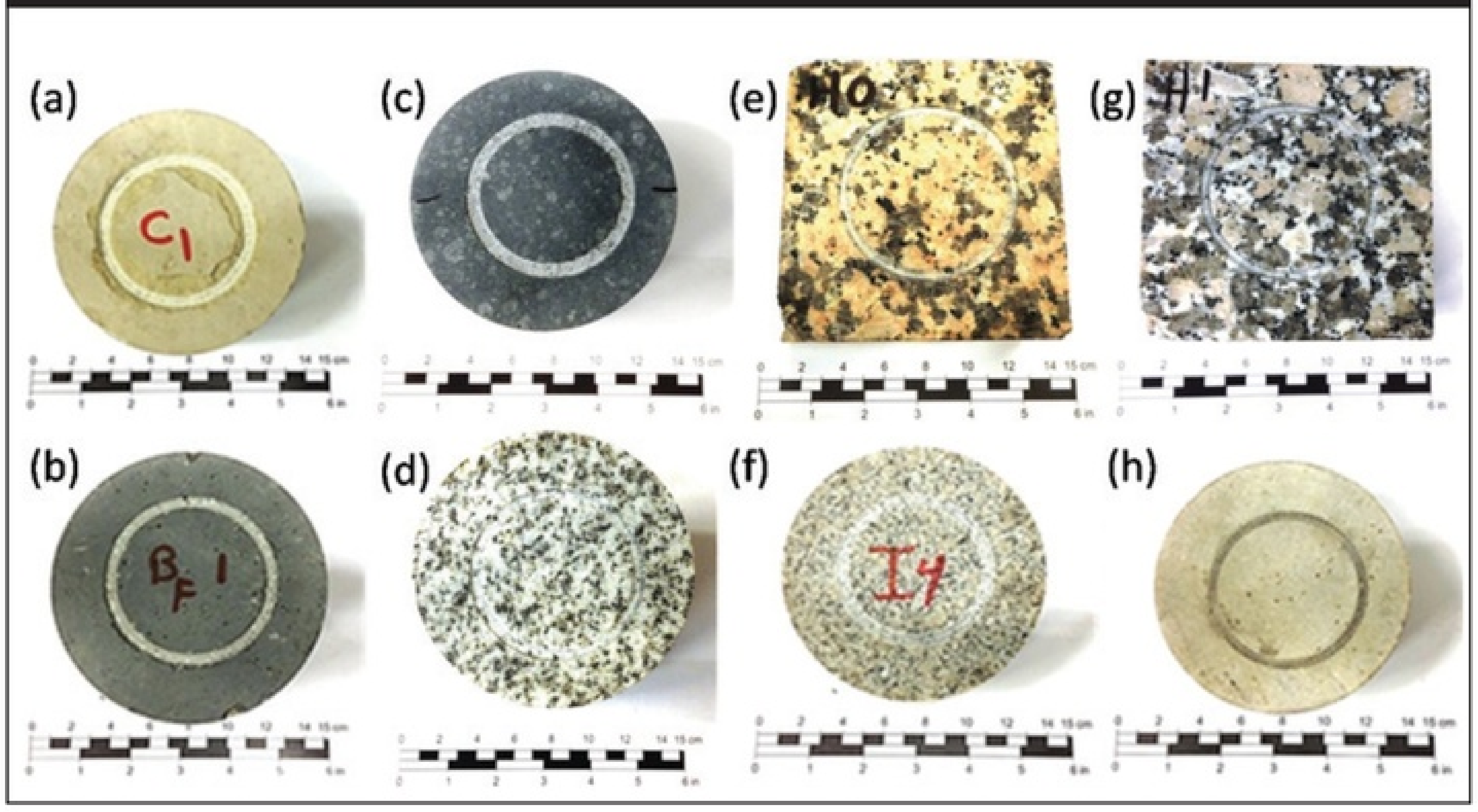


Table 2: Results achieved by the RIAT method (Macias et al., 2016).

Rock types	$RIAT_a$ (mg)			$RIAT_i$ (1/100 mm)		
	Mean	Standard deviation		Mean	Standard deviation	
		Value	%		Value	%
Limestone	3	1.4	47 %	380	55	14 %
Basalt	10	1.7	17 %	116	15	13 %
Basalt Xiamen	25	4.7	19 %	118	3	2 %
Trondhjemite	30	2.4	8 %	68	7	10 %
RP granite	34	5.5	16 %	51	4	7 %
Iddefjord granite	39	2.2	6 %	50	9	18 %
GM granite	45	7.1	16 %	49	3	7 %
Quartzite	104	16.0	15 %	NM*	NA	NA

*For practical reasons 5.

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Correlations with other abrasivity indexes

A comprehensive laboratory test program, including well established and widely used tests, has been performed for evaluation of the RIAT test method. The laboratory testing includes NTNU drillability tests (S_{20}, SJ, AVS) obtaining DRI™ and CLI™ (Bruland, 1998 and Dahl et al, 2012, www.drillability.com), Cerchar test (CAI) according to ASTM (2010), uniaxial compressive strength (UCS) according to ISRM (1978) as well as density and mineralogical composition by XRD- analysis. The obtained RIAT results have been analysed and correlated with the conventional test results, which are shown in Table 3.

Figure 5: Relationship between $RIAT_a$ and $RIAT_i$ based on the eight rock types tested. Fitting with the maximum correlation level is chosen (Macias et al., 2016).

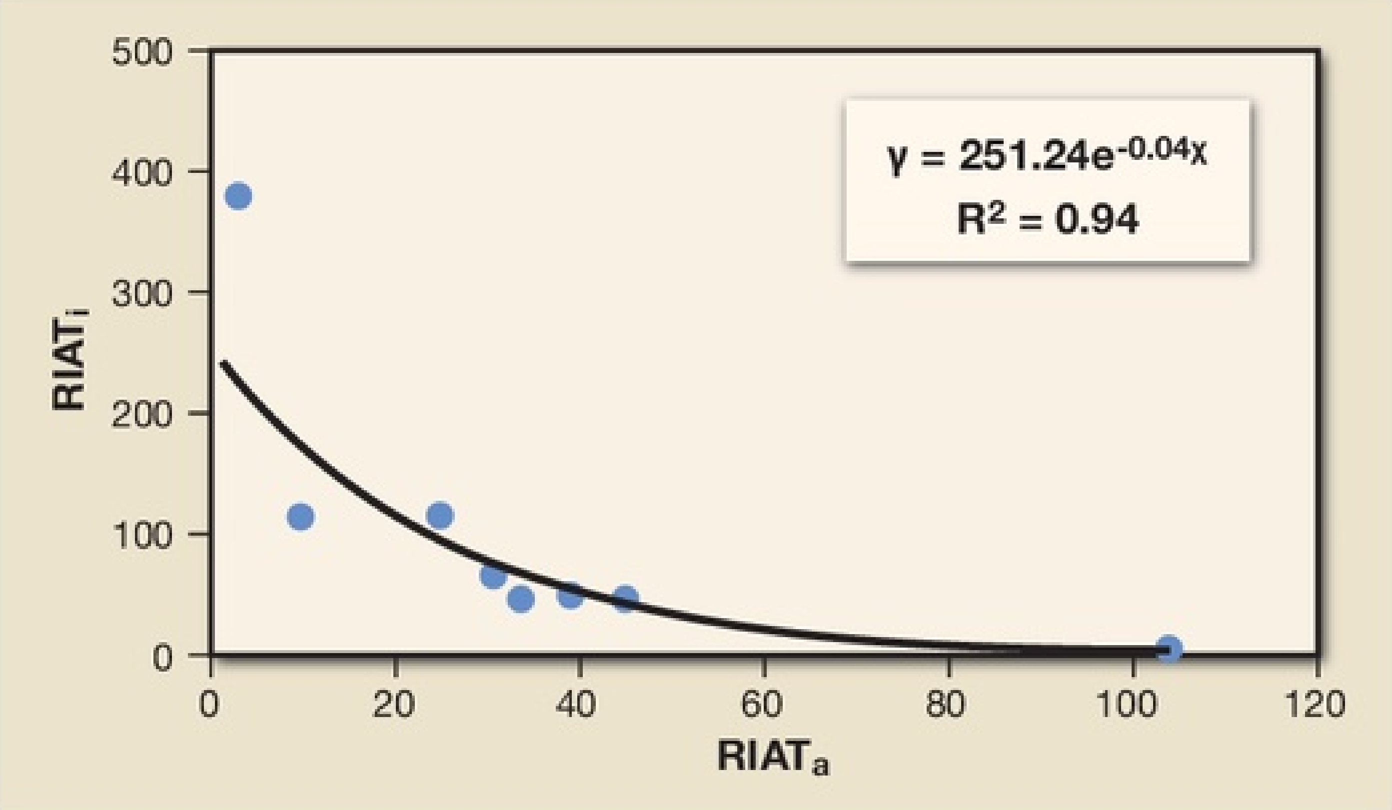


Figure 6 and Figure 7 show the relation charts of $RIAT_a$ with AVS and CAI_s.

A distinct correlation exists between $RIAT_a$ and AVS for the tested rocks. The best fitting is exponential due to the improved distinction in the upper rock abrasivity range determined by RIAT.

The RP granite showed an irregular result in the relation between $RIAT_a$ and AVS. This is most likely related to that rock types which have relatively large grains of quartz, as the RP granite, can generate quartz grains with freshly broken and sharpened angles, during the required sample preparation (crushing to < 1.0 mm.) for AVS testing. The quartz grains with sharpened angles might lead to a higher abrasivity on the AVS steel tool due to the abrasion process with sliding contact over the crushed rock.

There is apparently not a clear correlation between $RIAT_a$ and CAI_s (Figure 7). The CAI_s result for the quartzite can be regarded as lower than what could be expected for this rock type. This problem, which is associated with CAI_s in connection with testing of very hard rock types, has been indicated by several researchers. The cause of the problem is due

Table 3: Laboratory test results for Limestone, Basalt, Basalt Xiamen, Trondhjemite, RP granite, Iddefjord granite, GM granite and Quartzite. NTNU drillability tests (S_{20}, SJ, AVS, DRI™ and CLI™), Cerchar test (CAI_s) uniaxial compressive strength (UCS) and density (Macias et al., 2016).

Rock type	S_{20}	SJ	AVS	DRI™	CLI™	CAI_s	UCS (MPa)	Density (g/cm³)
Limestone	53.2	66.7	0.5	63	90.9	2.0	175	2.60
Basalt	34.7	9.2	8.5	34	14.3	3.0	261	2.95
Basalt Xiamen	39.6	3.0	19.5	34	6.8	2.7	279	3.00
Trondhjemite	56.1	3.6	27.5	51	6.3	4.3	196	2.68
RP granite	67.4	8.8	38.0	67	7.9	4.5	170	2.63
Iddefjord granite	61.9	5.0	31.5	58	6.8	3.4	188	2.60
GM granite	60.4	4.5	35.5	56	6.2	4.0	169	2.65
Quartzite	52.3	1.6	42.2	43	3.9	2.5	359	2.60

Figure 6: Relation charts of RIATa with AVS for the tested rock types (Macias et al., 2016).

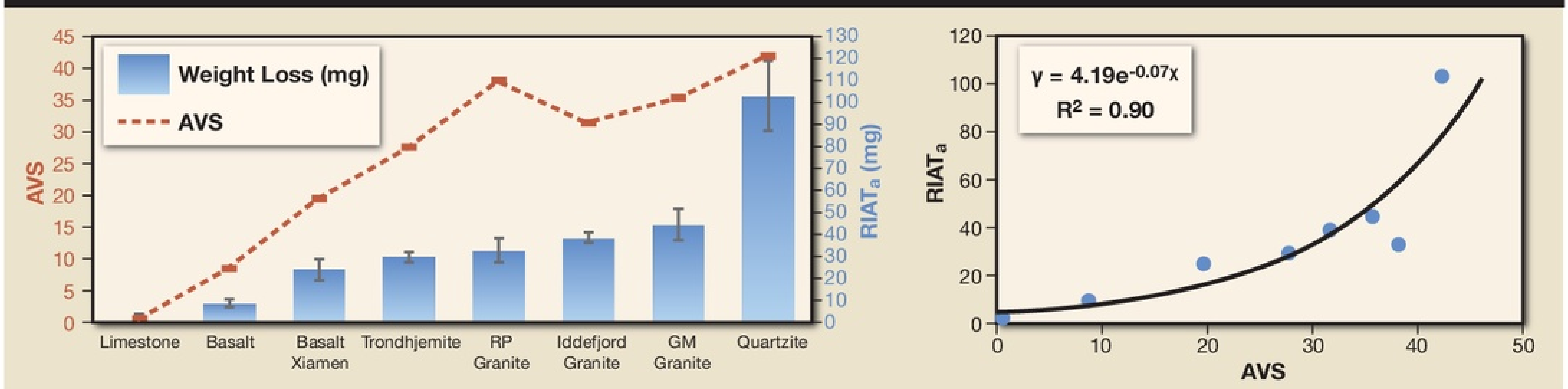
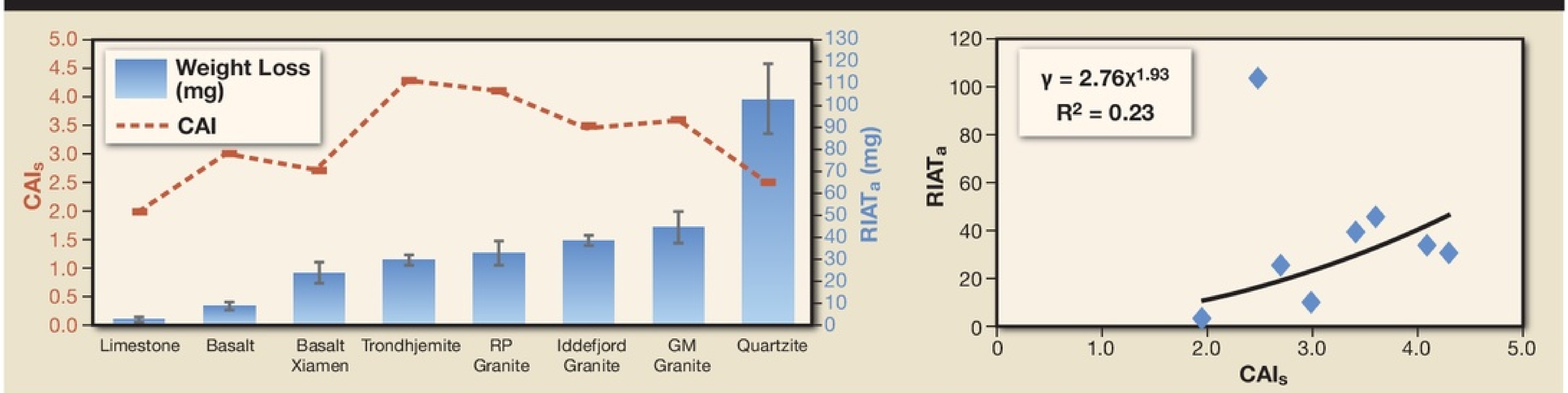


Figure 7: Relation charts of RIATa with CAIs for the tested rock types (Macias et al., 2016).



to that the tip of the stylus is not able to fully penetrate the surface of the rock resulting in a "skating effect" and hence an underestimation of the wear.

Figure 8 shows the relation between the $RIAT_i$ and the Siever's J-value.

The values show the same general trend and good correlation with the total data, but it should be noted that this mostly is due to the limestone value (Figure 8 (b)). There is hence no correlation when the results for the limestone are left out (Figure 8 (c)). This can be explained by the fact of different rock breaking behavior; while the Sievers' J test use drillhole depth, the $RIAT_i$ uses the depth of a disc rolling track to measure the rock surface hardness.

Figure 9 shows the relation of the $RIAT_a$ and $RIAT_i$ with the Cutter Life Index™, which is assessed on the basis of SJ-value and AVS. CLI expresses the cutter life for cutter disc rings in boring hours (Bruland, 1998).

Figure 8: Relation charts of $RIAT_i$ with SJ for the eight rock types tested. Correlations for the total data (b) and leaving out the limestone result (c) (Macias et al., 2016).

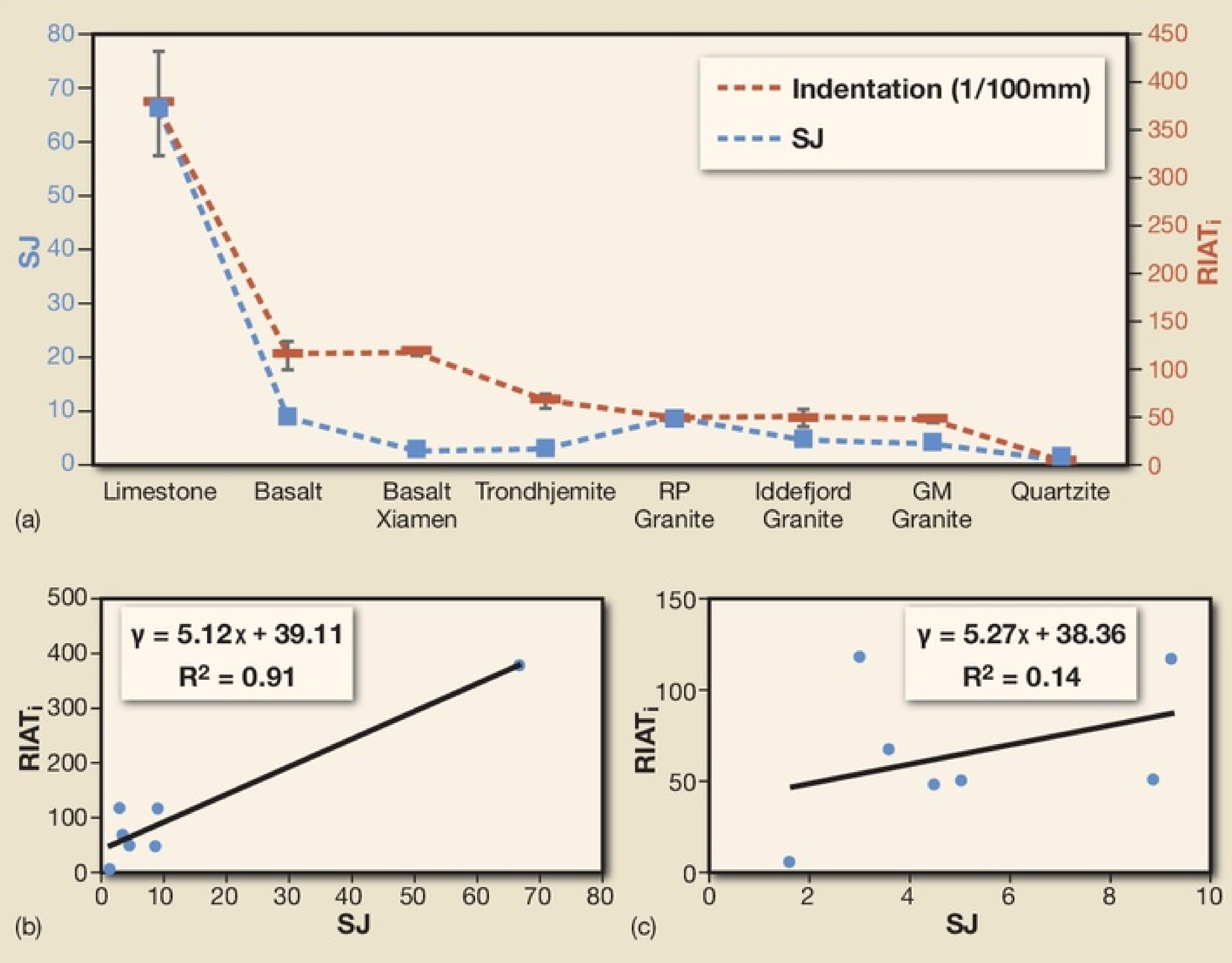
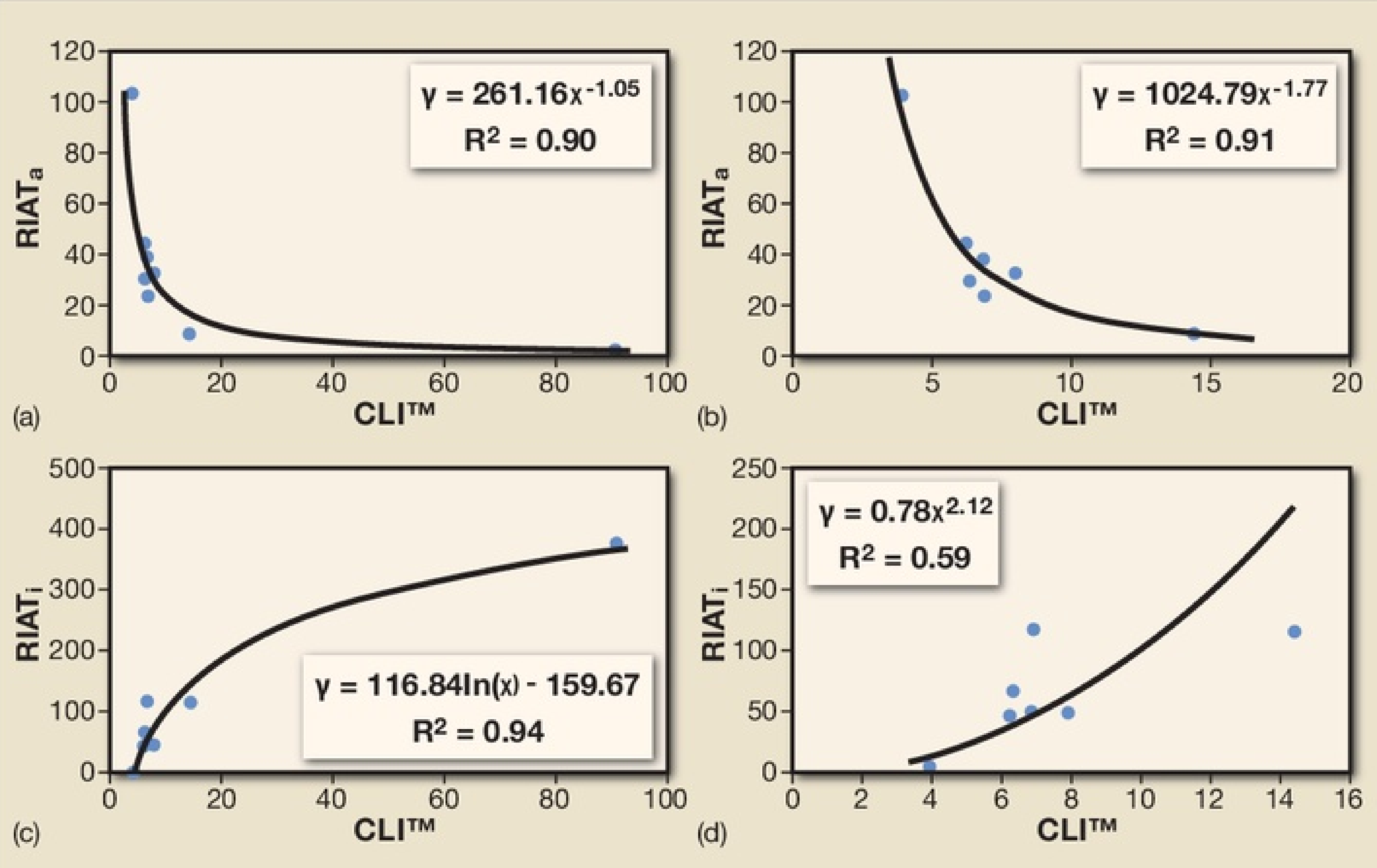


Figure 9: Relation charts of $RIAT_a$ with CLI™ (a) and (b), and $RIAT_i$ with CLI™ (c) and (d) for the rock types tested. Figures (b) and (d) are the corresponding correlations leaving out limestone (Macias et al., 2016).



Quartz equivalent content includes the entire mineral content's influence on the abrasiveness relative to quartz. Each mineral amount is multiplied with its relative Rosiwal abrasiveness to quartz. The individual Vickers hardness and the percentage of each mineral in the rock can be used to calculate a hardness number of the rock (Vickers Hardness Number Rock, VHNR) according to Bruland (1998).

There is also a correlation between the CLI™ and $RIAT_a$ for the tested rock types (Figure 9, a b). A somewhat weaker correlation is found between the CLI™ and $RIAT_i$, but it can still be regarded as good.

None of the other remaining conventional laboratory tests showed clear correlations with the RIAT indices.

The mineral composition of a rock type, essentially quartz and other abrasive minerals, may have considerable influence on ability of the rock to induce tool wear in the cutter rings.

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Table 4 shows the quartz, quartz

Table 4 Quartz content, equivalent quartz content and Vickers hardness number rock (VHNR) for the eight rock types (Macias et al., 2016).

Rock type	Quartz	Quartz equivalent	VHNR	VHNR (%)
Limestone	2%	4 %	144	14 %
Basalt	-	48 %	689	65 %
Basalt Xiamen	-	55 %	704	66 %
Trondhjemite	31%	66 %	801	76 %
RP granite	43%	75 %	868	82 %
Iddefjord granite	25%	65 %	785	74 %
GM granite	34%	69 %	825	78 %
Quartzite	100%	100 %	1060	100 %

Figure 10: Relation charts of $RIAT_a$ and $RIAT_i$ with quartz content (a) and (c) and equivalent quartz content (b) and (d) for the eight rock samples tested (Macias et al., 2016).

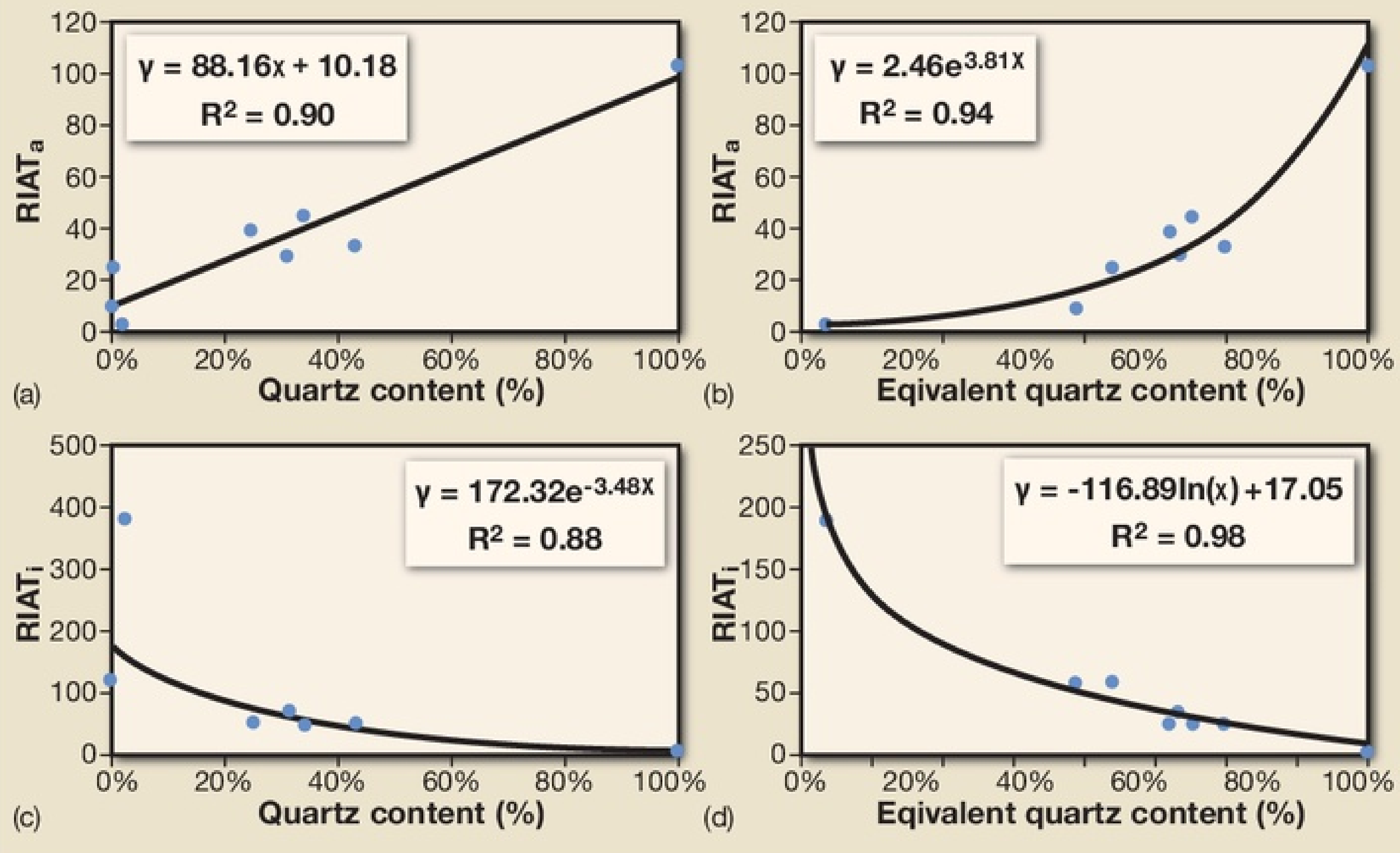
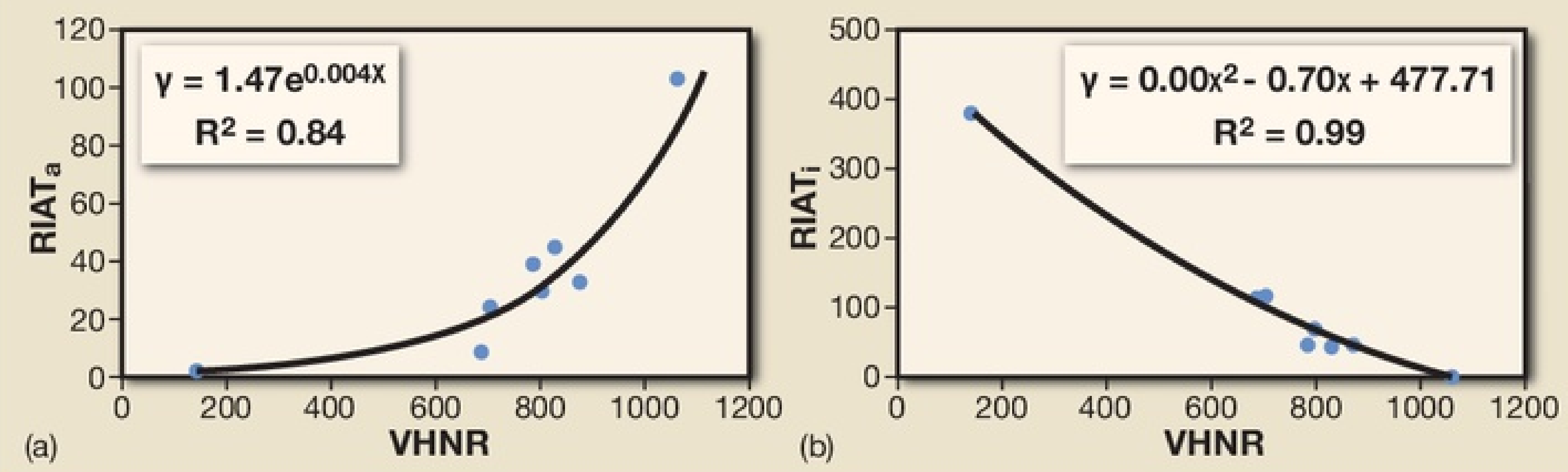


Figure 11: Relation charts of VHNR with (a) $RIAT_a$ and (b) $RIAT_i$ for the eight rock samples tested (Macias et al., 2016).



equivalent and VHNR for the used rock types.

Figure 10 presents the relationship between the RIAT indices with the quartz content (%) and equivalent quartz content (%).

Figure 11 shows the relationship between the VHNR and the RIAT indices ($RIAT_a$ and $RIAT_i$).

Clear correlations are found between the VHNR and $RIAT_a$ (Figure 11 (a)) and $RIAT_i$ (Figure 11(b)) for the tested rocks. More testing is however needed to confirm the relations, due to the scattering of the values.

Conclusions

The obtained initial results by the RIAT indicate a great ability to assess abrasive cutter wear for a wide abrasivity range of rocks, capable to evaluate rock abrasivity on TBM cutters as well as indentation in hard rock by rolling discs simultaneously.

The RIAT method improves the ability to enlarge the definition of the abrasivity for rock types with the highest capacity to produce cutter wear and the highest resistance to indentation which result in a higher cutter consumption.

The main advantages of the RIAT are:

- Wear caused by rolling contact.
- Testing of intact rock samples.
- Can be performed on relatively small samples.
- Straightforward procedure which allows testing of several samples in a cost effective way.
- Provides measurement of rock indentation resistance or rock surface hardness in addition to wear.
- Possibility to perform testing in wet conditions, with slurry or additives, and more.

Further work is being carried out in order to characterize abrasivity of a larger selection of rock types and evaluation of the capability of the test for cutter life prediction for hard rock TBMs.

REFERENCES

ASTM (2010). Standard test method for laboratory determination of abrasiveness of rock using the CERCHAR method. Designation: D7625-10.

Bruland, A. (1998). Hard Rock Tunnel Boring: vol. 8 Drillability Test Methods. Ph.D. Thesis. Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Dahl F., Bruland A., Jakobsen P.D., Nilsen B. and Grøv E. (2012). Classifications of properties influencing the drillability of rocks, based on the NTNU/SINTEF test method. Tunnelling and Underground Space Technology 28: 150-158.

ISRM International Society for Rock Mechanics. (1978). Suggested methods for the quantitative description of discontinuities in rock masses. – Commission on Standardization of Laboratory and Field Tests, Document No. 4, Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., 15: 319-368.

Macias (2016). Hard Rock Tunnel Boring: Performance predictions and cutter life assessments. Ph.D. Thesis. Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Macias, F.J., Dahl, F.E. and Bruland, A. (2015). New rock abrasivity test method by rolling disc. Proceedings of the 13th Congress on Rock Mechanics, ISRM Congress 2015 - In-novation in Applied and Theoretical Rock Mechanics, May 10-13, 2015, Palais des Congrès der Montréal, Canada, paper 634, 10 p., ISBN: 978-1-926872-25-4.

Macias, F.J., Dahl, F.E. and Bruland, A. (2016). New rock abrasivity test method for tool life assessments on hard rock tunnel boring: The Rolling Indentation Abrasion Test (RIAT). Rock Mechanics and Rock Engineering, Vol. 49, no. 5 (2016), pp 1679-1693.

Web Reference:
http://www.drillability.com. The suggested DRI™, BWI™, CLI™ Standard.