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Improved Roofbolting Methodologies: Reducing Hydraulic Fracture of Strata

David William Evans
Dywidag Systems International

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IMPROVED ROOFBOLTING METHODOLOGIES: REDUCING HYDRAULIC FRACTURE OF STRATA

David William Evans

ABSTRACT: Induced hydraulic fracture of strata during roof bolt installation is a potentially prevalent, but masked phenomenon within the underground coal industry. Previously reported resin testing programs (McTyre *et al.,* 2014) examined the relationship between resin mixing effectiveness and varying bore hole diameter. The methodology employed within this earlier test program facilitated a further critical area of research – the measurement of back pressures generated within the bore hole during standard rock bolt installation practices. Experimental data has indicated that fluid resin can be pressurised to levels where it exceeds the compressive strength of the strata, inducing hydraulic fracture within the immediate area of the bolting horizon. The routine cycle of roof bolting serves to propagate this effect, progressively fracturing and delaminating the roof during mine advancement. This masked phenomenon can lead to a perception of difficult ground conditions - mining efficiencies and costs are therefore affected, with increased need for additional support subsequently required to re-stabilise the inadvertently damaged roof.

Further analysis of the parameters associated with resin bolt installation has now been conducted, assisting in the development of an empirical relationship between bore hole pressure, bore hole diameter and bolt insertion times. This relationship has been analysed for 15:1 ratio resins and 2:1 ratio resins, within 28 mm and 30 mm boreholes. Further to this, load transfer performance has been comparatively assessed for both 28 mm and 30 mm boreholes, suggesting that for 2:1 resins, acceptable resin mixing and load transfer can be obtained within a 30 mm bore hole. The combination of 2:1 resins, utilised within a 30 mm bore hole, may well provide the optimal solution to reduce the risk of hydraulic fracture in weaker strata during resin bolt installation.

INTRODUCTION

A number of industry papers have previously investigated areas of concern associated with the performance of cartridge style resins in roof bolting, predominantly focussing on the effects of plastic film gloving, inadequate resin mixing and the pressurisation of resin within the bore hole. These three effects have a critical influence on the load transfer of the steel bolt element, through the cured resin and into the surrounding strata.

Gloving occurs due to the plastic film of the resin cartridge partially encasing or wrapping around the steel roof bolt element – a known phenomenon over many years (Pettibone, 1987). The plastic film creates regions of discontinuity between the bolt, cured resin and borehole, reducing effective load transfer into the strata. Experiments conducted into the effects of bolt ends fully encased by plastic film (Pastars and MacGregor, 2005) revealed that load transfer can be reduced by 85 to 90% in worst-case occurrences. It is also known that the aggregate filler size used within the resin can assist in shredding and breaking up the plastic film – this effect was observed in a previous study on resin mixing effectiveness (McTyer *et al.,* 2014).

Beyond the immediate impact of gloving discontinuities, is the issue of poor resin component mixing – where sections of resin remain unmixed and uncured after bolt installation is complete. The film casing of a resin cartridge has two internal compartments, each respectively holding the 'mastic' and 'catalyst' components. Note that the referred ratios for resin cartridges are simply the volumetric ratio of mastic to catalyst. When the mastic and catalyst are mixed in the correct ratio, the resin will cure and harden. However, it has been reported that for some resin cartridge designs, the catalyst compartment is dimensionally too small to be fully ruptured by the rotation of the bolt in the borehole (Campbell and Mould, 2003). Laboratory trials within a 28.5 mm borehole indicated that under initial insertion of the bolt, the resin cartridge expands and the catalyst compartment is pushed against the wall of the borehole. In this instance, the geometrical configuration can permit the ribbed bolt profile to pass through without fully rupturing and dispersing the catalyst through the resin mix, causing significant areas of uncured resin. While the cartridge and bolt are not fully defined within the 2003 paper, given the date of publication and

Dywidag Systems International, Australia, E-mail:david.evans@dywidag.com.au

the New Zealand origins of the experimentation, it can be assumed that the bolts were an M24 left hand anchor bar and that the resin cartridges were a 24 mm diameter 15:1 mastic to catalyst ratio.

Pressurisation of fluid resin within boreholes has also been an area of investigation. Earlier research focussed on the relationship between resin pressurisation and gloving, with theorisation that the plastic film cartridge may radially expand under the initial thrust of the bolt, then rupture and slip over the bolt end – hence the derivation of the term 'gloving'. Resin pressurisation was also associated with the loss of resin volumes into strata voids, reducing resin encapsulation of the bolt and weakening of the corresponding load transfer. (Giraldo *et al.,* 2006) proposes a mathematical model for the burst pressure associated with rupture of resin cartridges. However, as seen from the derived pressure verses displacement curves, while the point of cartridge rupture provides an initial pressure increase, it is certainly not associated with the peak pressures that are measured on full bolt insertion. Pressures observed by Giraldo, for different bolting systems, ranged from 3,500 psi (*24.13 MPa*) up to 7,000 psi (*48.26 MPa*). It was also observed that bolting systems with greater annulus around the bolt, as well as slower installation speeds, produced lower insertion pressures. While pressures of this magnitude have been measured, the exact modes that lead to the generation of such elevated pressures have not been fully explored.

THE DEVELOPMENT OF AN EMPIRICAL MODEL

The determination of internal borehole pressures due to resin flow presents a highly complex fluid mechanics model, involving numerous parameters. These parameters can be compiled under three main groupings, being the *fluid characteristics* of the resin, the *dimensional geometry* of the resin, borehole and bolt, as well as the *rate of insertion* of the bolt. These parameters are outlined below:

- Fluid characteristics of the resin
  - Dynamic Viscosity (N.sec.m^{-2})
  - Density (kg.m^{-3})
- Dimensional geometry – resin, borehole and bolt
  - Resin cartridge diameter (m)
  - Resin cartridge length (m)
  - Bore hole diameter (m)
  - Bolt core diameter (m)
  - Bolt rib profile (various dimensions) – height, width, flank angles, radial profile, pitch spacing (m, degrees)
  - Relative surface roughness of the borehole (dimensionless)
- Rate of insertion of bolt
  - Bolt insertion velocity (m.s-1)
  - Bolt rotational speed (rad.s-1)

Two points are worthwhile noting in regards to these parameters. The first is that for a mining resin, viscosity is only a notional concept. The resin is actually a suspension of solids in liquids – it is not a uniform, homogenous fluid. Further to this, resin cartridges are of course a two component system – a chemical reaction transforms the properties of the resin during bolt installation. Therefore, a true measurement of viscosity is actually indeterminate. Similarly, the measurement of true density values is also difficult.

The second key point relates to bolt insertion velocity. It is the velocity of the bolt through the resin that generates the flow of the liquid and the corresponding back pressures in the bore hole. The insertion force (N) of the bolt will of course influence the bolt velocity – a greater thrust force will insert the bolt faster – however it is the velocity of the rockbolt that determines the velocity of the resin flow and associated borehole pressures. This is schematically shown below in Figure 1.

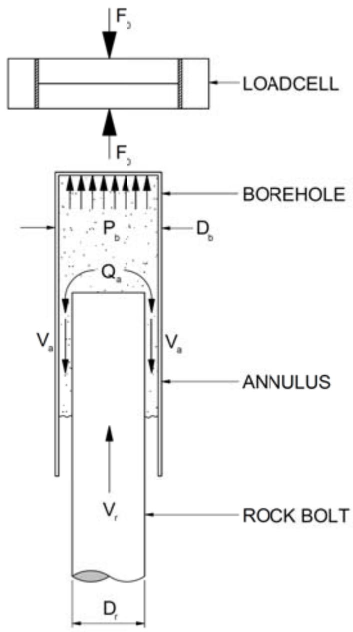

Figure 1: Representation of resin flow within borehole due to advancement of rock bolt

In Figure 1 the following values have been used:

V_r = Insertion velocity of rockbolt ($m.s^{-1}$)

P_b = Borehole internal fluid pressure (Pa)

Q_a = Flow rate of fluid in annulus ($m^3.s^{-1}$)

V_a = Fluid velocity in annulus ($m.s^{-1}$)

D_b = Borehole diameter (m)

D_r = Rockbolt core diameter (m)

F_o = Output force (N)

Further complicating the analysis of borehole pressures is the fact that the resin flow is highly turbulent – due to speed, rotation and geometry. For applications of internal incompressible viscous flow, it is known that "In turbulent flow the pressure drop cannot be evaluated analytically, but this can be achieved by experimental results and dimensional analysis to correlate the experimental data" (Fox and McDonald, 1985).

For bolt insertion through resin, in order to develop a working empirical model that makes sense of experimental data, the added complexity of minor or indeterminate parameters must be initially set aside. Only parameters that are determinate and have a major influence on back pressure have been selected for use. For the purposes of this initial mathematical model, the bolt rib dimensions, relative roughness and rotational speed are not included as explicitly defined parameters – even though their influences will be captured within the experimental data sets. Also, note that the experiments and associated data are exclusively grouped by resin type. This is due to the fact that resin viscosity and density cannot be truly measured and therefore cannot be explicitly defined within the empirical model. The influences of plastic remnants from the film cartridge are also not specifically accounted for – however, these would only serve to further restrict flow and increase annulus pressure.

The fundamental premise of the empirical model is that the back pressure of the liquid resin in the borehole (Pa) is predominantly a function of the velocity of the liquid resin ($m.s^{-1}$) through the annulus created between the bolt and the borehole. From a fluid mechanics perspective, this is a logical relationship – as the bolt progressively advances, the static volume of the liquid resin must rapidly accelerate and flow through the comparatively small cross sectional area of the annulus – hence the velocity of the resin through the annulus becomes high. Further to this, note that pressure losses for sudden constrictions in fluid flow are based on the square of the fluid velocity divided by two (Fox and McDonald, 1985, 367).

So, the basic empirical model becomes:

$$P_b = f\ (V_a^2 / 2) \qquad (1)$$

Where: P_b = Borehole internal pressure ($kg.m^{-1}.s^{-2}$)
V_a = Fluid velocity in annulus ($m.s^{-1}$)
f = functional correlation between pressure and resin fluid velocity

Excluding minor and indeterminate parameters, the thesis is that this empirical relationship holds true at the point of peak pressure and annulus velocity – when measured at full bolt insertion. At the peak of insertion and specific to individual resin types, a ratio can then be assumed between peak pressure and velocity - and the equation becomes:

$$P_b = R_{pv} \left(V_a^2 / 2 \right) \quad (2)$$

Where: R_{pv} = pressure-velocity ratio, *at peak pressure* ($kg.m^{-3}$)

EXPERIMENTAL METHODOLOGY

The experimental method utilised for this report was documented in an earlier publication (McTyre *et al.,* 2014). This involved internally sleeving the borehole utilising a PVC pipe of specific diameter, contained within and structurally supported by an external, heavy walled steel pipe to prevent swelling of the inner PVC pipe. The PVC pipe was capped at the top end to prevent resin loss and constrained at each end to prevent internal slipping and rotation. The internal PVC pipe could be readily removed after each installation test was completed, permitting quick changeover and multiple tests to be conducted. The PVC pipe could also be easily cut open and peeled away, to fully view and inspect the entire resin annulus. Various pipe combinations could be utilised to simulate both a 28 mm and a 30 mm borehole. This sleeving method was further supported with calibrated instrumentation on the drill rig, including a toroidal load cell, linear displacement transducer and tachometer. For every bolt installation, a data logger was utilised to capture force (kN), displacement (mm) and rotational speed (rpm) against time (sec) to a resolution of 0.1 sec per data event. Figure 2 outlines the experimental arrangement.

Experimental results – pressure / flow relationships

Utilising this experimental method, a series of bolt installations were conducted and average data sets were compiled. Two resin types were investigated - a 2:1 resin and a 15:1 resin. Two bore holes were also investigated, 28 mm and 30 mm. A single bolt type was used across all installations, being standard left hand anchor bar with a nominal core diameter of 21.7 mm. The bolt steel grade was HSAC840, commonly available on the Australian market. The following installation graphs shown in Figures 3 to 6 provide the experimental data derived from this test program – each graph represents the average data set from multiple tests for each experimental combination.

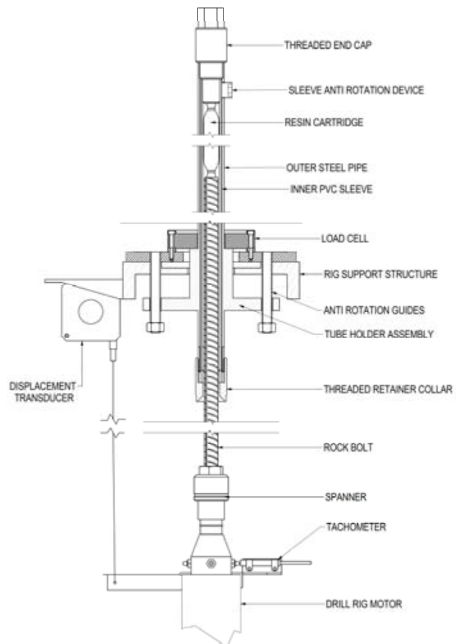

Figure 2: The 'Borehole Sleeving' experimental method, including instrumentation features

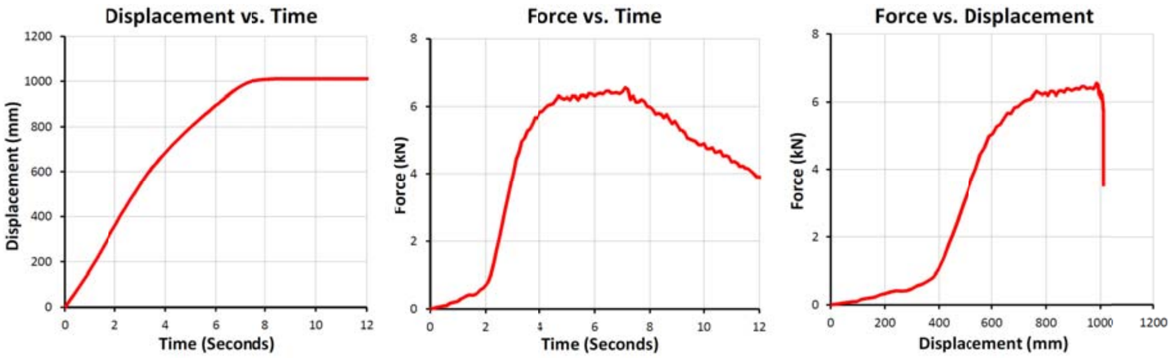

Figure 3: Installation graphs for 15:1 resins, 1000 mm long, into a 28 mm borehole. Data shown is the average curve for 20 tests

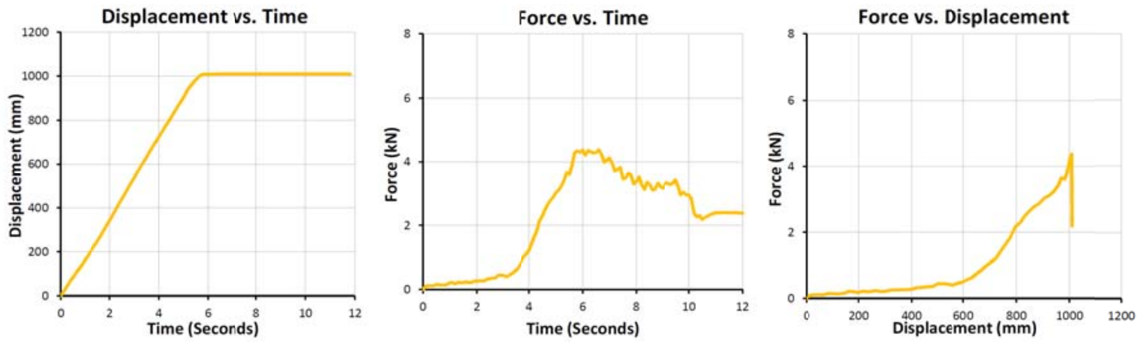

Figure 4: Installation graphs for 15:1 resins, 1000 mm long, into a 30 mm borehole. Data shown is the average curve for five tests

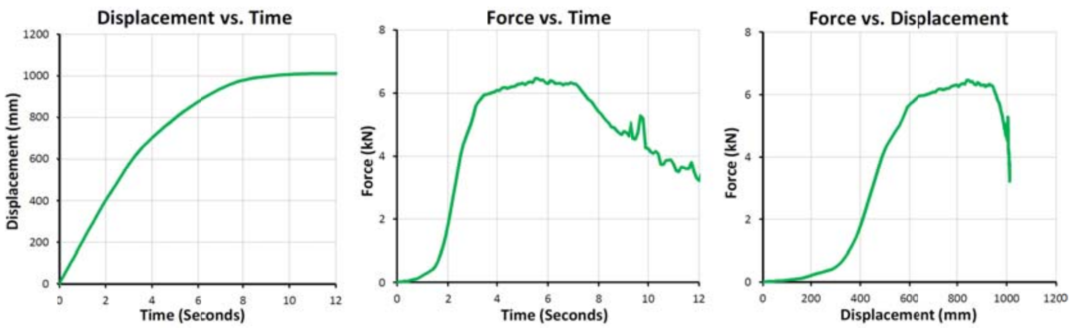

Figure 5: Installation graphs for 2:1 resins, 1000 mm long, into a 28 mm borehole. Data shown is the average curve for 20 tests.

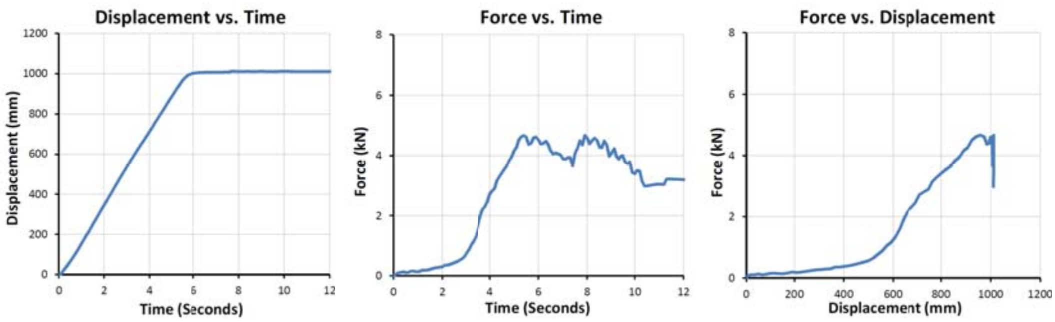

Figure 6: Installation graphs for 2:1 resins, 1000 mm long, into a 30 mm borehole. Data shown is the average curve for ten tests.

For each experiment, the average insertion time was determined - this was used to calculate the flow rate of resin through the annulus. The total resin volume is of course known, simply by measurement of the cartridge dimensions. Upon full insertion of the bolt into the resin, the flow rate into the annulus, Q_a, is then the total resin volume divided by the full insertion time. The peak velocity of resin in the annulus, upon full bolt insertion, is therefore the flow rate divided by the annulus area. This is expressed in the following equations:

$$Qa = vc / tf \qquad \text{and} \qquad Va = Qa / Aa \tag{3}$$

Where: Q_a = volumetric flow rate of resin into annulus ($m^3.s^{-1}$)
v_c = volume of Resin Cartridge (m^3)
t_f = time for full insertion through the resin cartridge (s)
V_a = velocity of resin within the annulus ($m.s^{-1}$)
A_a = annulus area (m^2)

Referring to Figure 1, the internal pressure of the bore hole is determined by the measured output force, divided by the area of the borehole, calculated simply as:

$$Pb = Fo / Ab \tag{4}$$

Where: P_b = Borehole Internal Pressure ($kg.m^{-1}.s^{-2}$)
F_o = Output Force (N)
A_b = borehole area (m^2)

Utilising the experimental methodology as described and the mathematical relationships defined above, data sets were compiled for each experimental combination, provided in Table 1 - this permitted calculation of the Peak Pressure-Velocity Ratio, R_{pv}.

Table 1: Calculation of Peak Pressure-Velocity Ratio (R_{pv}), based on the various experimental data sets

Resin Type	**15:1 Resin, 1000 mm Long**		**2:1 Resin, 1000 mm Long**	
Borehole Diameter (mm)	28	30	28	30
Bolt Type / Core Diameter (mm)	AT / 21.7	AT / 21.7	AT / 21.7	AT / 21.7
Cartridge Diameter (mm)	23.7	23.7	23.4	23.4
Cartridge Volume (mm^3)	441,208	441,208	430,108	430,108
Annulus Area (mm^2)	245.95	337.07	245.95	337.07
Bolt Full Insertion Time (s)	7.5	5.7	9	5.7
Effective Resin Flow Rate ($mm^3.s^{-1}$)	58,828	77,405	47,790	75,458
Annulus Flow Velocity ($mm.s^{-1}$)	239	230	194	224
Peak Load (N)	6,600	4,300	6,500	4,700
Peak Pressure (Pa)	10.717×10^6	6.082×10^6	10.555×10^6	6.648×10^6
Peak Pressure-Velocity Ratio ($kg.m^{-3}$)	3.747×10^8	2.307×10^8	5.591×10^8	2.653×10^8

Derivation of peak pressure installation curves

Given that the Peak Pressure-Velocity Ratio is determined for each experimental data set, this relationship can now be used to mathematically determine the Peak Pressure for varying flow velocities within the annulus. The annulus flow velocity correlates to bolt insertion velocity and bolt insertion time, pushing through 1000 mm of resin. Note that these empirical relationships are only assumed for each individual resin type and length – the R_{pv} value is assumed to be different for different resin types and fluid characteristics. The following charts of predicted peak pressure in Figures 7 and 8 have been determined by individual resin type and borehole size. Also, the R_{pv} value for the 27 mm borehole is a linear extrapolation, based on the R_{pv} values determined from the 28 mm and 30 mm data sets.

The peak pressure charts clearly indicate the nature of the relationship between bolt insertion velocity, borehole size and peak pressure. An important observation is that the pressures derived within this empirical model are of a similar magnitude to the borehole pressures measured by Giraldo, *et al.*, (2006). The empirical model also shows that increasing the borehole size and reducing the insertion velocity substantially reduces the peak pressure. Further to this, it can also be noted that the 2:1 pressure curves are slightly more elevated compared to the equivalent 15:1 curves – this outcome in the empirical relationship notionally captures the fact that the 2:1 resins are slightly 'thicker' or more 'viscous' compared to the 15:1 resins.

Further experimentation – load transfer for 30 mm boreholes

The inherent concern is that, with increasing borehole annulus size, the load transfer performance to the strata is assumed to reduce. In order to assess this potential difficulty, load transfer tests were conducted within a pre-cast concrete block, using a series of drilled holes 300 mm deep, both 28 mm and 30 mm in diameter. The boreholes were blown clear of debris with compressed air after drilling, internally inspected with a bore camera and dimensionally measured prior to bolt installation. Each resin and bolt combination were installed using recommended manufacturers spin times to ensure correct mixing and then left for a 24 hr period before pull testing commenced. Each installed bolt was of the same profile type (AT grade) and approximately 600 mm in length, in order to pass continuously through the hollow bore cylinder jack body. This avoided the use of couplers, eliminating displacement errors during initial loading and take-up of the system. The hollow bore jack and pressure gauge had current 3rd party calibration for force against hydraulic pressure. Displacements were measured using a dial gauge indicator mounted on a heavy steel block. 20 tests were conducted in total – 10 tests for 15:1 resin in a 28 borehole and 10 tests for 2:1 resin in a 30 mm borehole. Figures 9a and 9b show the setup for the pull test experimentation.

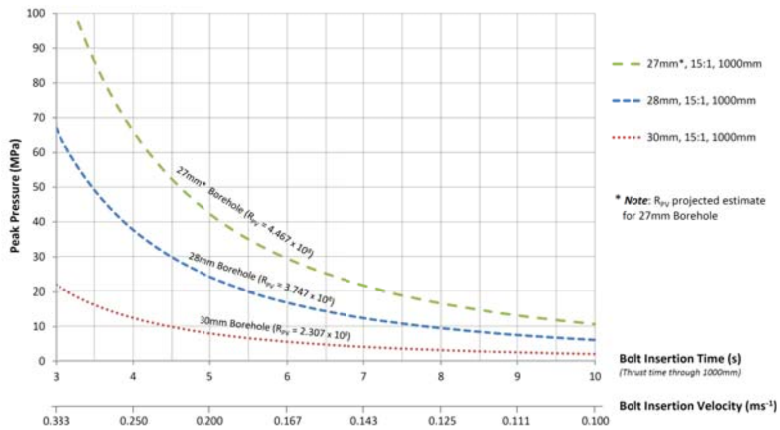

Figure 7: Predicted peak pressures for 15:1 ratio x 1000 mm long resin cartridges, against bolt insertion velocity – for 27 mm, 28 mm and 30 mm boreholes

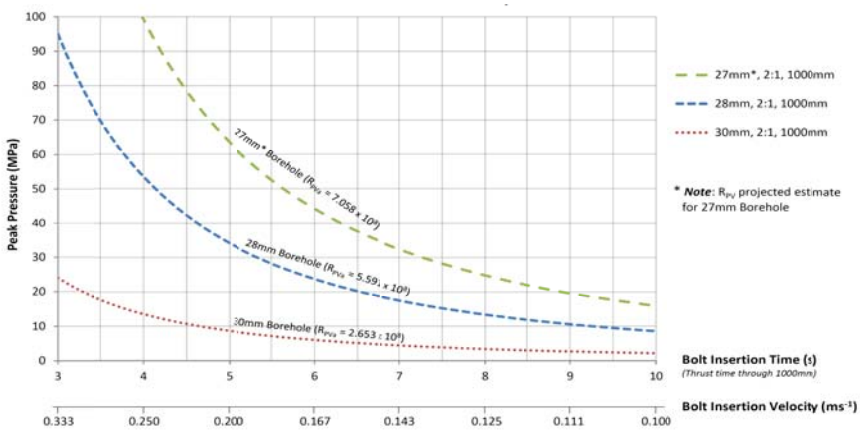

Figure 8: Predicted peak pressures for 2:1 ratio x 1000 mm long resin cartridges, against bolt insertion velocity – for 27 mm, 28 mm and 30 mm boreholes

Figures 9a and 9b: Pull test experimental setup – 300 mm embedment, 28 mm and 30 mm hole diameters

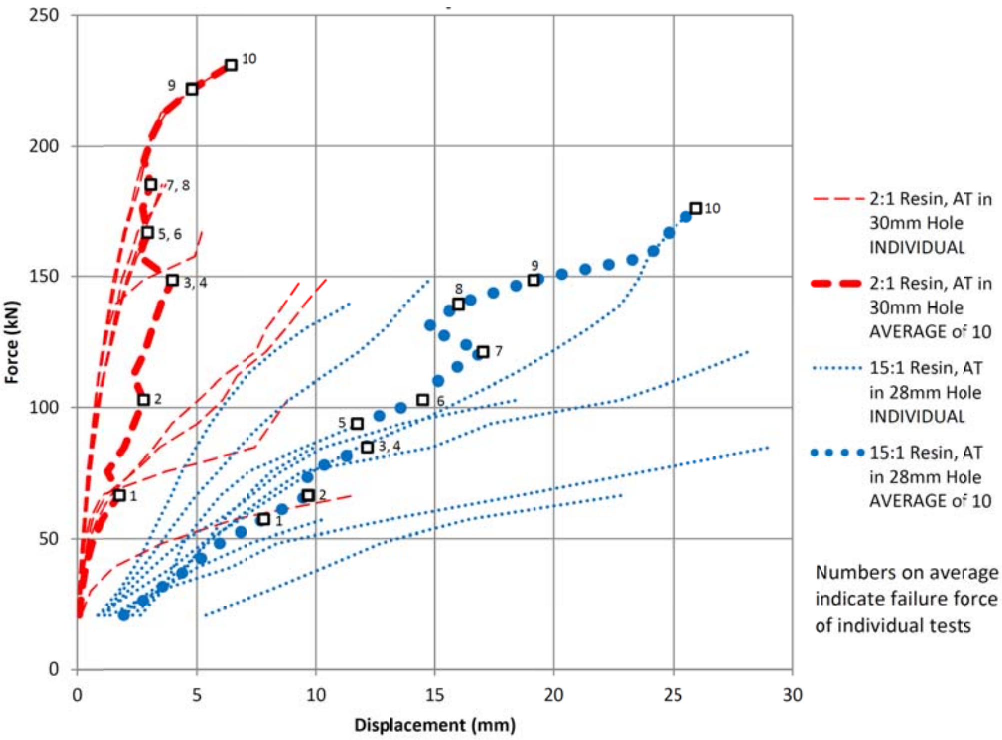

Figure 10: Pull test results for 300 mm embedment tests – 15:1 resins in 28 mm boreholes, 2:1 resins in 30 mm boreholes

The results from the pull tests are given below in Figure 10. The major curves indicate the progressive average of the ten tests, while the minor data curves show each individual test result. Note that the numbers indicated on the averaged curves show the peak load position of each individual test result. Based on the averaged curves, the 2:1 resins within 30 mm boreholes show a stiffer result compared to the 15:1 resins within 28 mm boreholes. The peak load transfer results are also higher for the 2:1 resins.

CONCLUSION

Plastic gloving and poor resin mixing are known concerns with 15:1 ratio resin cartridges – particularly in boreholes greater than 28 mm in diameter. However, for boreholes smaller than 28 mm, resin pressurisation during bolt installation can be elevated to levels that induce hydraulic fracture and delamination of weaker strata. At elevated insertion pressures, resin volumes are also lost into strata voids and bolt encapsulation is subsequently affected. The derivation of an empirical relationship between borehole size, bolt insertion velocity and peak borehole pressure is useful in determining the risk of hydraulic fracture of strata and resin loss during bolt installation - this risk is seen to substantially reduce with the utilisation of boreholes 30 mm in diameter. Further to this, 2:1 resins are observed to mix well within a 30 mm borehole, providing load transfer results that appear to exceed that of 15:1 resins within a 28 mm borehole. Taking all factors into account, the combination of 2:1 resins, utilised within a 30 mm bore hole, may well provide the optimal resin bolting solution - reducing the risk of hydraulic fracture and resin loss in weaker strata, while maintaining adequate load transfer performance

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