Measurements of humidity-enhanced salt creep in salt mines: Proving the Joffe effect

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Measurements of humidity-enhanced salt creep in salt mines: proving the Joffe effect

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ABSTRACT: Laboratory testing of salt rocks, particularly uniaxial creep testing, reveals a phenomenon of faster creep during periods of greater atmospheric humidity and corresponding reductions in creep rate when the atmosphere becomes drier—a so-called Joffe effect. The Joffe effect has been considered a laboratory testing phenomenon where cracking and dilation allow atmospheric humidity to penetrate the test specimen. Salt pillars in mines or the undisturbed salt around shafts, however, are shown to exhibit the Joffe effect in measurements described in this paper. The examples include a 30-year-long extensometer history in the Waste Isolation Pilot Plant (WIPP) shafts, 14-year-long room-closure rate (both vertical and horizontal) histories at WIPP, and examples of vertical room closures and pillar expansion in the Cayuga salt mine under both normal and restricted ventilation. In each example, the long salt-creep histories exhibit enhanced creep that is not attributable to influences such as temperature change or evolving rock damage.

1 INTRODUCTION

Laboratory testing of salt rocks, particularly uniaxial creep testing, reveals a phenomenon of faster creep during periods of greater atmospheric humidity and corresponding reductions in creep rate when the atmosphere becomes drier. Russian investigators (for example, Stavrogin et al. 1975) suggest that potash and salt test specimens exposed to an increase in humidity might experience increases in creep rate by a factor of 15 or more, but that the creep rate autonomously slows again when the humidity is reduced. A humidity-related effect on the ductility of freshly cleaved halite specimens was described by Joffe et al. (1924). Parker et al. (1958) go so far as to use the term "discovered" to describe Joffe's contribution to understanding (albeit, incorrectly) the moisture-related transition between brittle and ductile behavior for salt—hence the term "Joffe effect" to identify that humidity changes the mechanical behavior of salt even under constant load and temperature.

Humidity-enhanced creep of salt rocks (hereafter, either rightly or wrongly, called the Joffe effect) has typically been considered strictly a laboratory testing phenomenon because it is principally observed in small test specimens and particularly in uniaxial-creep test specimens, where microcracking and dilation is believed to allow atmospheric humidity to penetrate across the test specimen thickness. Horseman (1988) differentiates between the Joffee (sic) effect and moisture-enhanced creep. He describes the phenomenon of enhanced creep in the context of pressure solution and recrystallization contributing to creep deformation in small, moist salt specimens subject to severe stress and dilation. He further concludes that dilatancy and lack of confining stress are prerequisites to humidity-enhanced creep.

Several other salt-mechanics investigators (for example, Urai and Spiers (2007)) explain the role of liquid water (brine) surrounding test specimens and the effect of liquid water on creep rates and salt crystal recrystallization. Tests involving liquid water are consistent with humidity- or water-vapor-enhanced creep, but the amount of moisture involved and the intimacy between the salt and water is quite different in their tests compared to salt in a "dry" salt or potash mine.

If humidity-enhanced creep is strictly a laboratory testing phenomenon, the Joffe effect should not be observed in salt pillars in underground mines or undisturbed salt surrounding unlined shafts. Both of these examples of large salt volumes are also examples where the salt should be in a state of triaxial compression with suppressed dilatancy. Hence, based on the literature, a Joffe effect should not be observed in these in situ situations because atmospheric moisture cannot readily penetrate through such large, tight volumes of salt. At most, the humidity can only affect the salt near the surface (within 1.5 m or so) of pillars or shaft; that is, within what is called the disturbed rock zone (the DRZ) or the excavation damaged zone (EDZ).

Hunsche and Schultz (2001) interpret humidity-induced changes in salt creep rates as an enhancement of the dislocation mobility within salt crystals that controls the overall or macroscopic creep rate of rock salt. Because of intact rock salts' inherent impermeability, only after dilatant behavior (because of unfavorable stresses that cause microcracks to open) can water or water vapor migrate into the salt, and then only as deep into the salt as new porosity was generated and the permeability increased. This is why the same authors (Hunsche and Schulze (2003)) note that humidity-induced creep is greatest within the "damaged rock zone" and when the relative humidity is 75 percent (corresponding to the 3-phase-equilibrium of vapor pressure of brine and rock salt). In other words, rock salt that has never endured dilatancy-causing stresses remains inaccessible to water vapor, so in dry and undamaged rock salt, no humidity-induced creep enhancement occurs.

Examples are presented in this paper where salt-mine behavior (room closure, pillar shortening, and extensometer measurements) responds in a manner suggestive of a Joffe effect since deformation rates correlated to expected seasonal changes in mine-ventilation humidity. The examples include 30-year-long extensometer history in the Waste Isolation Pilot Plant (WIPP) shafts; 14-year-long room closure rate (both vertical and horizontal) histories at WIPP; and room closures, pillar expansion, and roof extensometers in the Cayuga salt mine under both normal and restricted ventilation. In each example, the long histories exhibit enhanced creep rates that correlate with humidity changes rather than other influences such as temperature change or evolving rock damage. The evidence is compelling that a Joffe effect contributes to seasonal deformation rates in salt and potash mines.

2 SALT MINE EXAMPLES

Field measurement examples are presented with the hypothesis that the Joffe effect alters salt-shaft and salt-pillar behaviors. Two examples are from arid New Mexico: one example is long-term extensometer measurements in the WIPP waste shaft and the other is vertical and horizontal room closure in the WIPP waste-transportation drift. The third set of examples includes long-term room-closure and pillar-expansion measurements in the Cayuga (New York) underground salt mine with relatively dry winters and humid summers.

For background, Figure 1 shows monthly average temperature and relative humidity for the cities of Carlsbad, New Mexico (near WIPP), and Ithaca, New York (near the Cayuga Mine). Carlsbad has more than a 20°C average temperature variation between its winter (4°C) and summer (27°C) with the lowest relative humidity in the spring (38 percent in April) and highest in the fall (55 percent in September). Ithaca is cooler than Carlsbad; its average winter and summer temperatures being –4°C and 21°C. Ithaca's average relative humidity is nearly constant at a low of 67 percent (April) and high of 75 percent (December/January).

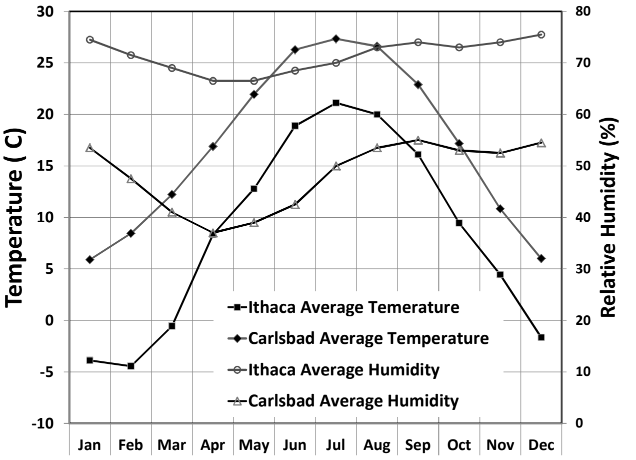


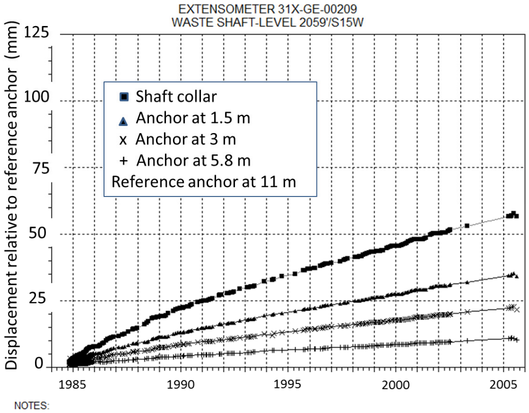
Figure 1. Monthly average temperature and relative humidity for Carlsbad, New Mexico, and Ithaca, New York.

The underground temperature and humidity in these facilities are not the same as aboveground; however, the trends in the underground environment will likely track the surface conditions. WIPP has a large volume of air moving through a relatively short ventilation route (about 2 km total); in contrast, Cayuga Mine has a similar volume of air but a long ventilation route (at least 15 km). WIPP's examples are on intake air (the shaft and 0.5 km from the shaft), and the Cayuga mine examples are also on intake air but several kilometers from the shaft.

2.1 *WIPP waste shaft*

The WIPP waste shaft was sunk in the early 1980s so it is about 30 years old. Borehole extensometers in the surrounding salt have measured the radial shaft closure at three elevations in the unlined portion of the shaft between the top of salt and the storage horizon. These extensometers are four-point extensometers anchored at the shaft wall (extensometer collar or about 0.1 m deep into the salt) with four borehole anchors at depths of 1.5, 3, 5.8, and 11 m into the salt. Van Sambeek (1993) presents technical details about the shaft extensometers and initial interpretation of their measurements.

Figure 2 shows a history plot of one of the nine extensometers in the waste shaft, which was excavated in 1984. This particular extensometer is at a depth of 628 m (2059 feet) and oriented at S15°W. The measured radial displacements are relative to an assumed zero displacement condition at the deepest (or reference) anchor located 11 m from the shaft wall.



NOTES:
1. Excavation date: June 1984.

Figure 2. Measured displacement for WIPP waste-shaft radial extensometer at 628-m (2059-foot) depth and oriented S15W.

Figure 3 shows a history plot of the extensometer rates (based on the measured displacements shown in Fig. 2) plotted according to the date-of-the-year (Julian date) for the 18-year period between 1984 and 2002. Superimposed on the displacement rate data are annual cyclical functions of the form: $R_0 + \left(R_1 \times \cos\left(\left(\text{day-base}\right)/182 \times \pi\right) + 1\right)$, where R_0 is the average annual displacement rate, R_1 is the seasonal rate variation, and "base" is the number of days of offset between January 1st (day 1) and the date of the peak rate.

The shaft wall (0.1-m depth) has the greatest displacement rate and seasonal variation and the shortest offset. The deepest anchor (5.8 m) has the smallest displacement rate and seasonal deviation and the longest offset.

Only a low volume of ventilation air is drawn down the waste shaft; still, the changes in the air cause seasonally varying displacement rates. Because both environmental factors peak in July or August, the enhanced displacement rate could be caused by either the temperature increase or the humidity increase, or both. The reverse situation exists for cooler temperature and lower humidity during the periods of slower displacement rates.

2.2 *WIPP underground room closure*

Room-closure rates in the WIPP underground also show a repeatable seasonality. A location in the E140 waste-route drift at S1775 was selected to illustrate the seasonality in the closure rate. This closure station has long-term measurements on six chords across the drift: three vertical and three horizontal. The closure rates are plotted in Figure 4 versus their corresponding date-of-the-year for each of the six chords. Each chord has an average closure rate for the entire year and a seasonal variation that increases during the summer and decreases during the winter. The average rate and variation for each chord are listed in Table 1.

For the three vertical chords, their winter closure rate (average annual rate minus the drier-months' variation) are nominally 2/3 their annual rate, and their summer closure rate (average annual rate plus the wetter-months' variation) are 4/3 their annual rate. The three horizontal chords all have similar annual rates (ranging from 38 to 42 mm/yr) and seasonal variations (9 to 10 mm/yr); their winter closure rate is 3/4 and their summer rate is 5/4 their average annual rate.

A seasonally influenced creep rate for the salt pillars is being measured since both the vertical and horizontal creep rates of pillars (as reflected by the room closure rates) are simultaneously affected. This is because at WIPP, vertical (roof-to-floor) closure is mostly the result of lateral pillar creep causing roof-beam buckling and floor heave. Thus the ratio between vertical and horizontal closure rate is constant, even though the two rates vary between dry and moist months. The constant ratio tentatively "proves" that the observed seasonality is caused by the Joffe effect's influence on the lateral pillar-creep rate. The recent closure rates at this station maintain average seasonal ratios of 3.2 and 3.3 for winter and summer, respectively. As point of interest, the 14-year cumulative vertical closure is three times the cumulative horizontal closure.

2.3 *Cayuga salt mine*

The Cayuga Salt Mine is located in western New York near Ithaca and mostly under Cayuga Lake. The mine is situated at the bottom of a thick sequence of bedded salts and shales at a depth of about 650 m. Currently, a yield-pillar panel design is used for mining; additional technical details for this style of mining are given by Petersen et al. (1993).

The first example is a long-term closure measurement over a 23-year period in a yield-pillar panel. The measured roof-to-floor closure is shown in Figure 5. During the period 1994 to 2003, monthly closure measurements were made. The monthly closure rates from those 9 years are shown in Figure 6 plotted according to date of the year. An obvious seasonality exists in the closure rate. Because of its long distance from the intake air shaft, this panel is buffered from temperature changes, so the seasonality is most likely caused by humidity changes.

A different yield-pillar panel has had room closure measurements with simultaneous temperature and humidity measurements. The results for a 5-year period are shown in Figure 7, which shows two types of closure behavior. When measurements started in 2006, the panel had been mined 5 years earlier and it was inactive but still ventilated. As shown, the temperature was nearly constant and the humidity varied with the seasons. The measured room-closure rate tracked the relative humidity.

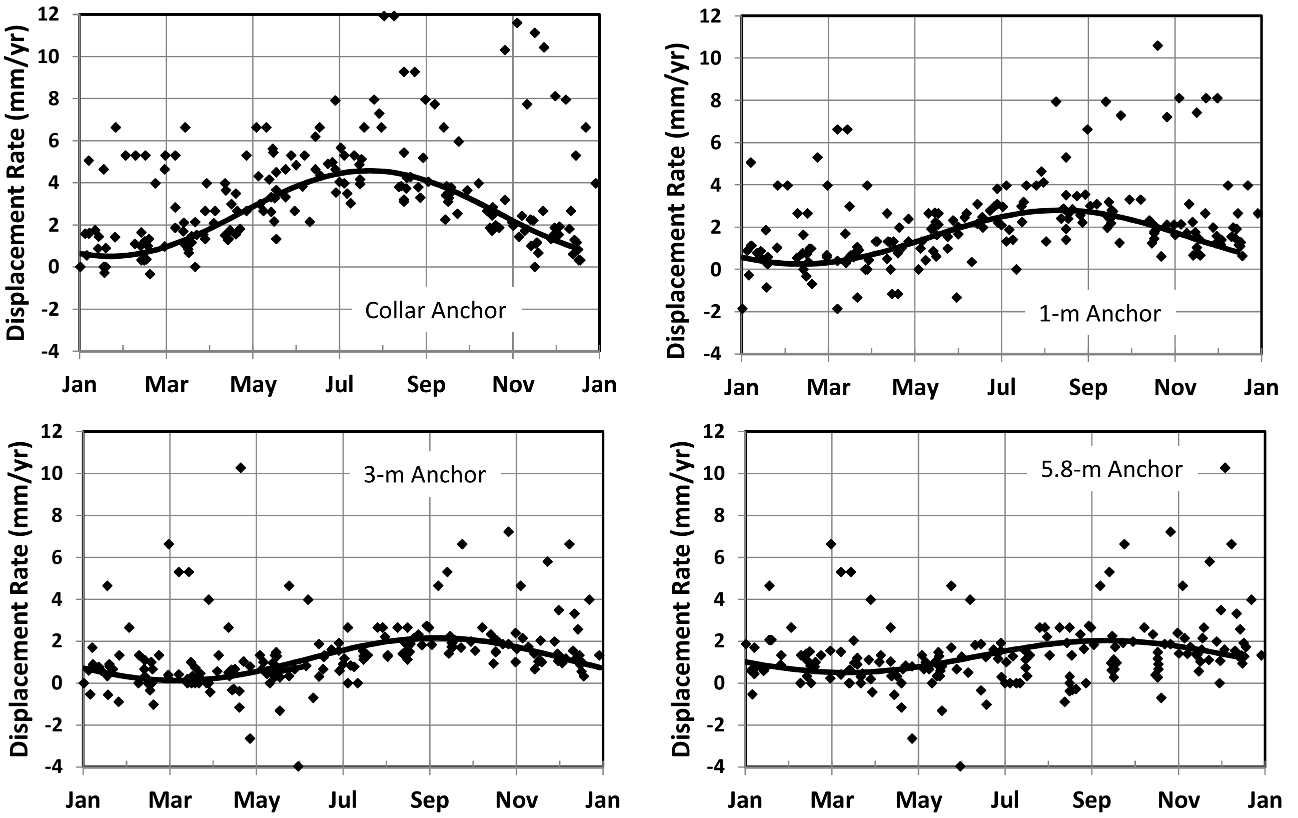


Figure 3. WIPP waste shaft extensometer displacement rates over an 18-year period for anchors at the collar, 1-, 3-, and 5.8-m deep relative to the deepest extensometer anchor at 11 m.

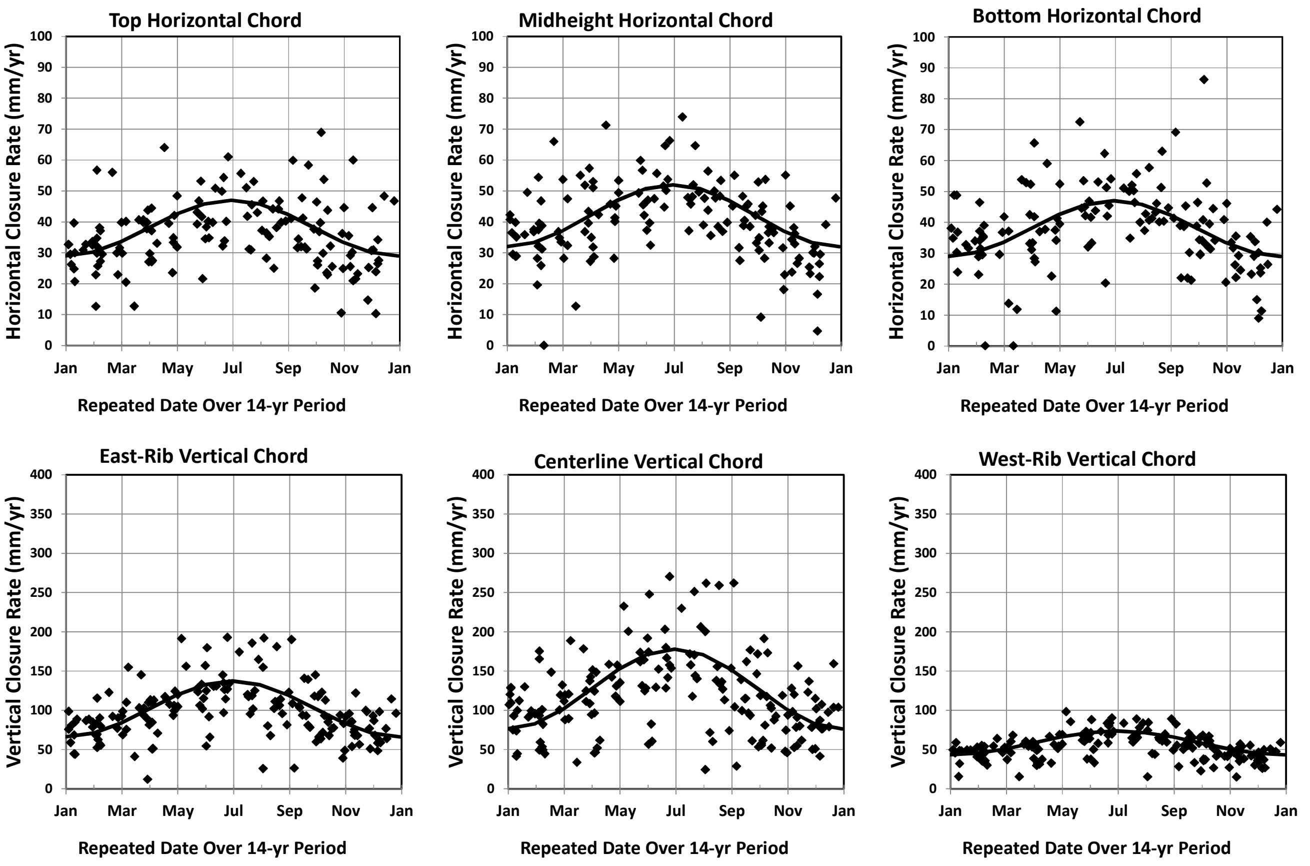


Figure 4. Seasonal closure rates at WIPP station E140 S1775 over a 14-year period for its three horizontal and three vertical chords. Solid cosine curve emphasizes repeatability in the seasonal trend. Note difference in scale for horizontal and vertical closure rates.

Table 1. WIPP closure-station E140-S1775 average annual closure rates and seasonal variation during 14-year period.

Chord	Direction	Location	Average annual rate (mm/yr)	Seasonal deviation (mm/yr)
L-H	Vertical	West Rib	59	15
A-G	Vertical	Centerline	127	51
B-F	Vertical	East Rib	102	36
C-K	Horizontal	Top	38	9
D-J	Horizontal	Midheight	42	10
E-I	Horizontal	Bottom	38	9

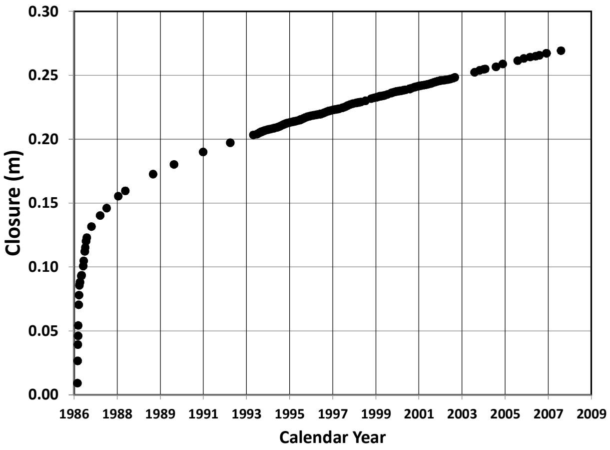


Figure 5. Long-term roof-to-floor closure measurement in a Cayuga Mine yield-pillar panel with an initial room height of about 3.5 m.

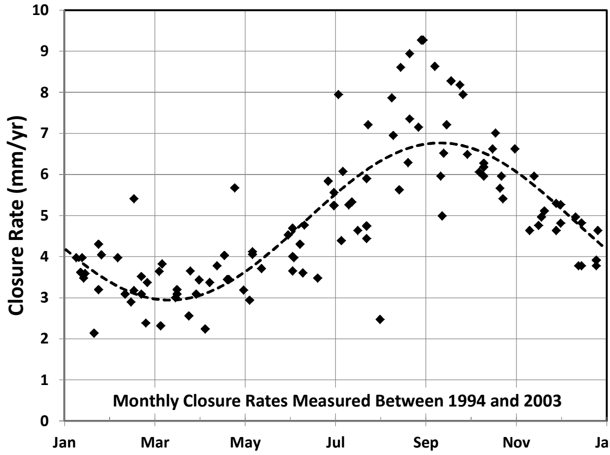


Figure 6. Closure rates for closure history shown in Figure 5 versus date of the monthly measurements from 1994 to 2003.

Beginning in March 2007, backfilling of the panel began using waste product from the underground mill (a mixture of rock particles and salt fines). The waste comes into the panel on a conveyor, is moistened to lessen dust and improve compaction, and then spread around using heavy diesel equipment. A combination of the seasonal humidity in the ventilation air, the water added, and water vapor in the diesel equipment exhaust pushed the humidity level in the panel above the previous maximum level of 60 percent. The relative humidity approached (but of course could not exceed) the nominal 75 percent critical humidity threshold for deliquescence of water vapor on salt (Kaufman, 1960). The annualized room-closure rate simultaneously increased with the greater humidity level. Moreover, since Figure 7 shows the temperature was nearly constant throughout this period (and there was no nearby mining), the closure rate changes are attributed to humidity changes.

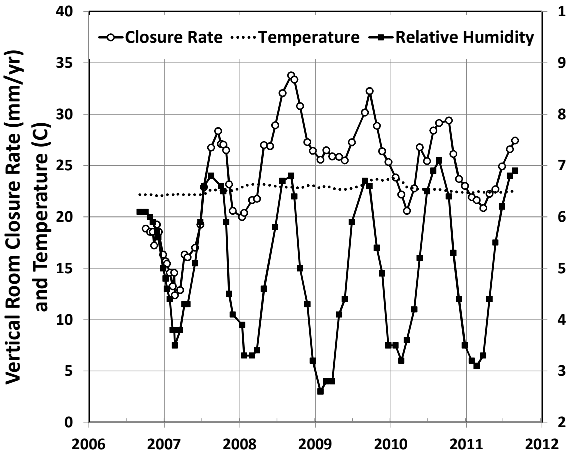


Figure 7. Room-closure rate, ambient temperature, and relative humidity at a long-term closure station in the Cayuga mine.

Figure 8 shows the information from Figure 7 replotted to show the correlation between the measured room-closure rate and the prevailing humidity. Five complete annual cycles are shown. The first cycle (mid-2006 to March 2007) occurred while the panel was inactive and quiet (before backfilling operations started). The later annual cycles (after March 2007) are during backfilling activities, and the room-closure rates are greater than their earlier values. The correlation trend is that closure during the humid months will be nominally 75 percent faster than during the drier months.

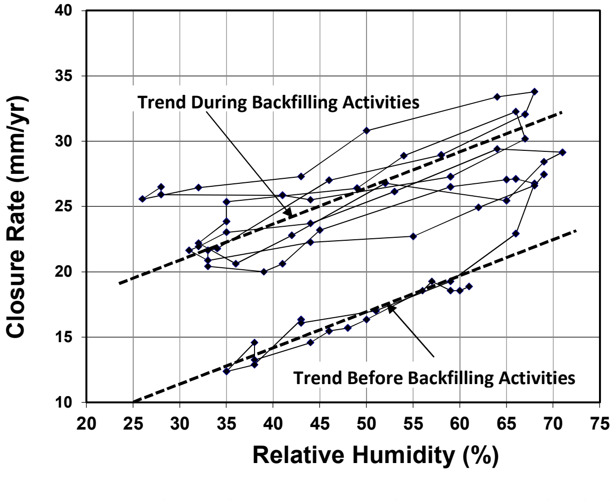


Figure 8. Correlation between room-closure rate and relative humidity at nearly constant temperature through five annual cycles.

A dedicated test was conducted in the Cayuga Mine specifically to determine if the increase in roof-to-floor closure rate could be attributed to swelling of the exposed shaley roof rock immediately (<0.3 m) above the room. Extensometers were installed both horizontally into the pillar and vertically into the roof. The extensometer-collar displacement rates and measured relative humidity are shown in Figure 9 covering a 2-year period. A correlation exists between the measured pillar-expansion rate and the relative humidity (although the data become sparse toward the end of the period). Key, however, is that the displacement rate of the roof extensometer showed no displacement, which proves no swelling of the shaley roof occurred. The conclusion is that the Joffe effect observed in the salt-pillar expansion in this measurement and presumably other roof-to-floor closure measurements elsewhere in the Cayuga Mine do not relate to swelling of clays in the roof rock.

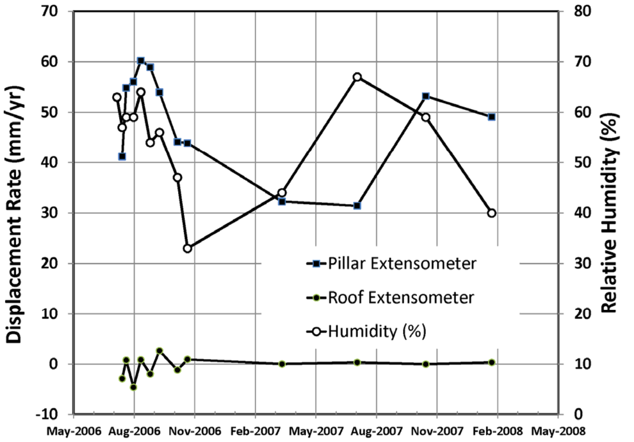


Figure 9. Comparison of displacement rates for a horizontal extensometer in salt pillar and a vertical extensometer in the clay-rich shaley roof rock over a 2-year period and a range in relative humidity.

3 CONCLUSION

Humidity-enhanced salt creep (rightly or wrongly called the Joffe effect) has historically been considered a phenomenon observed in laboratory tests on small test specimens that were probably in a state of dilation. The laboratory tests showing the most pronounced Joffe effect were unconfined and exposed to the atmospheric humidity changes, particularly greater humidity, although the phenomenon was reversible. In this paper, several examples were presented of long-term in-mine deformation measurements that also show an in situ change in rock-salt creep rates as the seasonal humidity changes, thus proving the Joffe effect occurs even on a large scale. Extensometer measurements in both salt pillars and salt around a shaft show that the Joffe effect influences salt even at depths of several meters which is, considerably deeper than the expected dilatant zone in the DRZ or EDZ. The influence of the humidity was observed over a range of humidity, not just at the greater levels. The humidity-enhanced creep was not significantly delayed, appearing to change simultaneously with the humidity change, although this aspect is difficult to judge from low-frequency measurements. These conclusions and our understanding of the Joffe effect would be better supported if deformation, temperature, and humidity are monitored simultaneously in future measurements.

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