Column Experiments to Assess Consolidation Behaviour at Different Initial Irrigation Rates in Copper Heap Leaching

Ángel D. Briseño Arellano, GeoSystems Analysis, Inc., USA
Tzung-mow Yao, GeoSystems Analysis, Inc., USA
Michael Milczarek, GeoSystems Analysis, Inc., USA
Mark Brusseau, University of Arizona, USA

Abstract

It is common practice to initiate irrigation in heap leach facilities at low rates, followed by a gradual ramp-up to the final target irrigation rate. This presumably improves the leach ore permeability and the metal recovery. However, no detailed study has been performed to understand the processes that may lead to better recovery using this technique. Large diameter column tests were performed with crushed and agglomerated copper heap leach ore to study solution flow and ore consolidation behaviour under three different initial irrigation schemes: baseline, slow ramp-up and fast ramp-up. The columns were monitored with moisture sensors, a neutron probe, and tensiometers. In addition, tracer tests were performed to evaluate flow uniformity. The baseline test used the full target irrigation rate from the beginning. In the baseline test, the leach ore experienced significant agglomeration structure collapse, localized ponding, consolidation, and preferential flow to depths of 30 cm. The slow ramp-up test exhibited minimal ore consolidation, no ponding, and reduced preferential flow. The faster ramp-up test showed some ore consolidation, but no ponding and intermediate preferential flow. Water content appears to be a determining factor in the agglomeration structure collapse; however, other factors such as pore size variation, bulk density (depth of heap), and pore solution velocity may also contribute. Consolidation tests can be performed to evaluate the ideal ramp-up schedule for specific heap leach ores.

Introduction

Heap leaching is a process to extract metals via irrigation with chemical solutions of rocks that are piled in heaps. The method has been used for centuries to recover precious and base metals from low grade ores. In recent years, its use has been expanded, due to favourable costs compared to the high cost and environmental impact of ore milling and smelting. Numerous studies have investigated heap leach ore processing and irrigation methods, focusing on the unsaturated hydrology nature of this method (Decker, 1996; Orr, 2002; Galla, 2007; Guzman et al., 2013; Milczarek et al., 2013; Silver, 2013; Robertson, 2017). However, there is much improvement that can be made in the recovery process.

Leach ore hydraulic properties can play a significant role for metal recovery besides the ore grade. In particular, the presence of low permeability ores or the presence of preferential flow in the heap results in poor leachate distribution, leaving unleached or incompletely leached rock under normal irrigation cycles (Rucker et al., 2009). Many heap leach operations initiate solution irrigation at slow rates, ramping-up until a final target irrigation rate is achieved. This has been shown in some cases to improve the metal recovery; however, a limited number of detailed studies have addressed the flow mechanisms that cause increased leaching efficiency (Vries, 2013; Fernando et al., 2018). The purpose of this study is to investigate the flow mechanisms of this initial phase in the leaching process through a series of instrumented large-scale laboratory column experiments.

Methods

Heap leach ores from two copper mines were mixed, obtaining a particle size distribution that was expected to have a lower range of acceptable hydraulic properties according to the criteria described by Milczarek et al. (2013). The resulting ore blend was agglomerated with raffinate (leaching solution) at a gravimetric water content (GWC) of 0.06 g/g and concentrated sulfuric acid at 6 kg H_2SO_4/ton of ore. After agglomeration, the samples had a curing period of between 1 and 2 weeks. The agglomerated and cured ore was used for all tests in this study, except for the particle size distribution (PSD, ASTM D6913), which was performed on subsamples of air-dried ore.

Saturated hydraulic conductivity (K_{sat}) tests were carried out on 15-cm-diameter dual-wall cores using the long column method as described by Milczarek et al. (2013). This method simulates the confining pressures that the leach ore experiences at different depths in the pad and assists in determining the maximum heights of heaps in minimize permeability constraints. In this study, wall pressures were increased to simulate heap depths between 0 and approximately 20 m.

Large columns (150 cm tall × 53.8 cm in diameter, 341 L) were packed with agglomerated and cured leach ore at target dry bulk densities of 1.5 g/cm^3. The column tests consisted of irrigating the columns with raffinate at a constant application rate of 9.1 L/h/m^2 (38 mL/min), through a single drip emitter at the center of the column, with different initial irrigation schedules, as shown in Table 1. Test 1 was the baseline, with constant irrigation at the target application rate. Slow ramp-up was applied in Test 2, whereas fast ramp-up was used for Test 3. Similar to heap leach operational practices, ramp-up irrigation rates were achieved by turning the pumps on and off. For example, for a rate of 1/16th of the target irrigation rate, the columns were irrigated at the target rate for 0.5 hour and stopped for 7.5 hours, in 8 hour cycles (Table 1).

Table 1: On and off irrigation periods for each of the simulated irrigation rates, and schedule for ramp-up periods on all tests

Fraction of the target irrigation rate	Application (irrigation) rate ($L/m^2/hr$)	Time on (hr)	Time off (hr)	Duration of each irrigation phase (hr)		
				Test 1	Test 2	Test 3
1/16th	0.57	0.5	7.5	–	48	–
1/8th	1.14	0.5	3.5	–	48	–
1/8th	1.14	1	7	–	–	25
1/16th	0.57	1	15	–	16	–
1/16th	0.57	0.5	7.5	–	–	23
1/8th	1.14	1	7	–	–	24
¼	2.28	1	3	–	24	24
½	4.56	1	1	–	24	–
½	4.56	4	4	–	24	24
1	9.12	Continuous	–	382	432	408
Total test duration (hr)				382	616	528

Heap leach solution was applied using calibrated high precision flow pumps; inflow rates were checked by measuring changes in the inflow reservoirs over time. Due to limited solution supply, heap leach solution was recycled throughout the tests; inflow reservoirs were refilled once or twice every day using the outflow solution. The column outflow rates were measured by obtaining the volume accumulated in the outflow reservoirs twice daily.

Moisture content was measured with nine capacitance soil moisture sensors (ECH_2O-10HS, Decagon, Pullman, WA) installed every 15 cm, through the center of the column. Sensor readings were cross-checked with GWC (oven dry weights) measurements before and after the tests. Soil moisture sensors were calibrated using the same ore material and the leaching solution as the column tests. Calibration was performed in a box by adding leaching solution in 0.03 volumetric water content (VWC) increments to the ore uniformly until reaching saturation. Raw readings were recorded and correlated to the known moisture content. Soil moisture calibration equations were adjusted for the solution density (1.17 g/cm^3), and solution high salts content (20% by wt).

Moisture content sensors were paired with micro-tensiometers (GeoSystems Analysis, Tucson, AZ). Data from the sensors was collected with a Campbell Scientific CR10X data logger, at 5-minute intervals (CSI, Logan, UT).

Surficial ore collapse was assessed by measuring the depth difference from the original packed surface inside the column. In Test 1 the column center and three other outer locations were monitored. Depths from a reference height were measured approximately every hour for the first six6 hours, and more were taken while the test continued. For Tests 2 and 3, depths were tracked in a more comprehensive manner. Ten locations were monitored across the column area: five along the West-East axis and five along the South-North axis.

To assess preferential flow, Dye Blue FD&C 1 was injected at a concentration of 1 g/L at the end of the test when full target irrigation was achieved. After approximately two pore volumes, the irrigation was terminated.

The columns were drained by gravity and unpacked by removing 10 cm of material in each step and taking photographs to capture the dye distribution at each 10 cm depth. Ore samples were taken for GWC testing every 20 cm vertically at the: center; each cardinal direction at the edge of the column; and another four samples between the center and the edge.

In Test 2, bulk density samples were also taken with 10 cm diameter by 10 cm high PVC cores at each location, in order to verify the bulk density estimates. In Test 3, bulk density samples were taken every 20 cm vertically at the center and at the four positions on the edge of the column.

Results and discussion

Saturated hydraulic conductivity (K_{sat})

Results from the dual wall K_{sat} test showed the agglomerated leach ore increased bulk density from 1.5 g/cm^3 with no loading pressure (top of the heap) to 2.0 g/cm^3 with 18.7 m of equivalent loading pressure; K_{sat} values ranged from 1.99×10^{-1} cm/s to 2.2×10^{-3} cm/s over the same heap heights (Figure 1). A K_{sat} value > 100× the target irrigation rate is considered good ore permeability (Milczarek et al, 2013), consequently at heap heights greater than 5 m, the K_{sat} is below the ore permeability threshold (2.53×10^{-2} cm/s) and the leach ore is likely to have permeability constraints at depth within the heap.

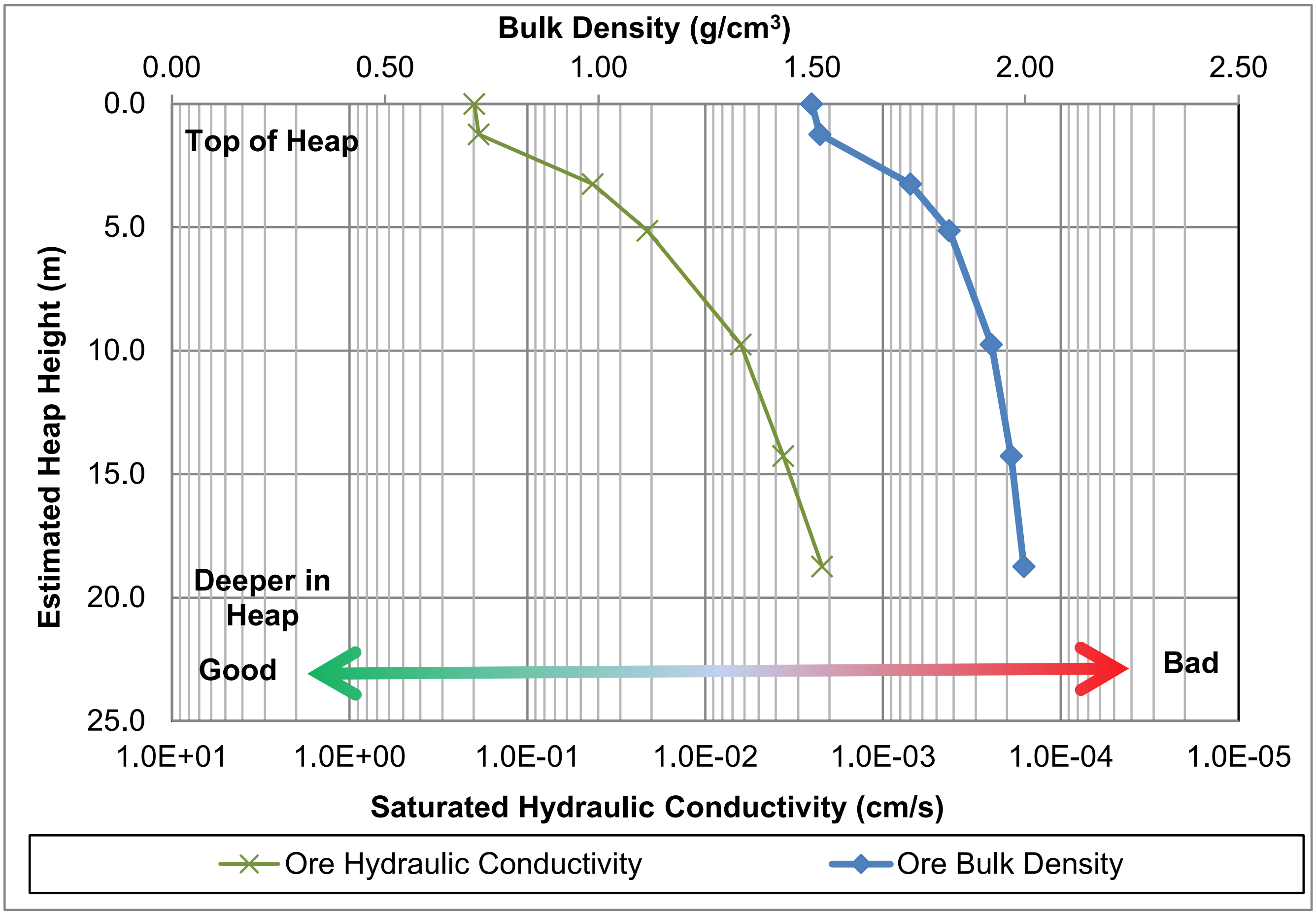

Figure 1: Leach ore saturated hydraulic conductivity at depth

Column tests

Consolidation/ore collapse

Figure 2 shows the change in depth at the ore surface for the three tests with total applied solution in litres (L) on the X-axis. Test 1 showed the most slumping, followed by Test 3 and Test 2. Test 1 also showed ponding of solution and the fastest ore collapse, settling to a final depth at approximately 38 hours, or 69 L of applied solution. Test 2 settled to an approximate final depth at 326 hours (430 L), and Test 3 at 260 hours (375 L) without ponding. Tests 1 and 3 showed greater ore settlement in the center versus the outer part of the column, whereas Test 2 showed even settlement.

For this reason, there is only one settlement curve for Test 2. These results indicate significantly greater ore collapse occurred with the faster ramp-up schedules compared to the slow ramp-up Test 2 which appeared to preserve the agglomeration structure.

Figure 3 shows the density profiles in all tests as linear regression from the bulk density samples collected at 20 cm intervals from the top to the bottom of the columns. Test 1 showed the highest bulk densities in the center and outer portions of the column: 1.6g/cm^3 at the top (10 cm deep) and 2.20 g/cm^3 at the bottom. Test 2 showed the lowest bulk densities, from 1.50 to 1.68 g/cm^3 and Test 3 showed bulk densities from 1.50 g/cm^3 to 1.88 g/cm^3 at the bottom.

The observed consolidation in Test 1 at depths greater than 40 cm (> 1.8 g/cm^3) is equivalent to depths greater than 5 meters measured in the consolidation K_{sat} test, which also indicates a 10× or greater loss of ore permeability below 40 cm.

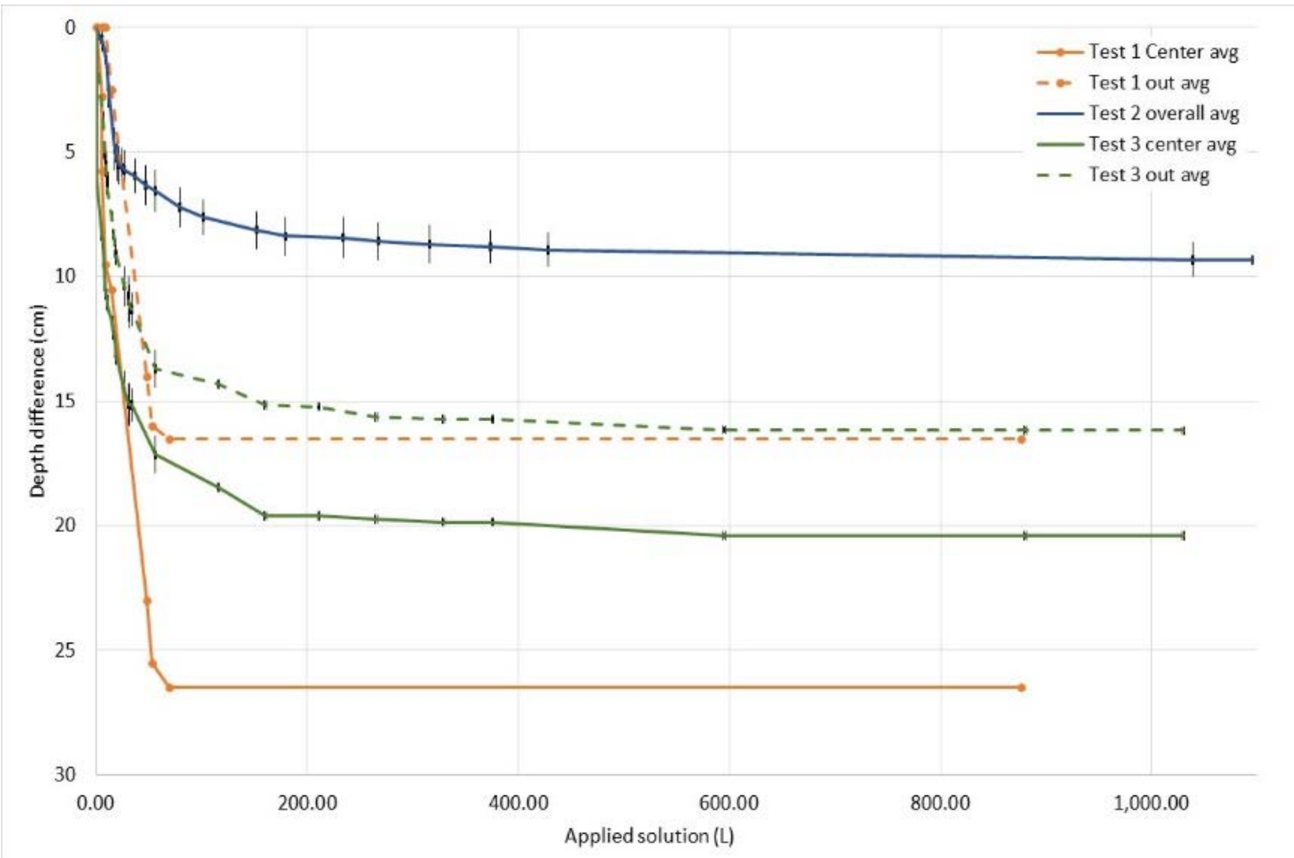

Figure 2: Slumping from original surface in Tests 1, 2, and 3 vs. time as applied solution

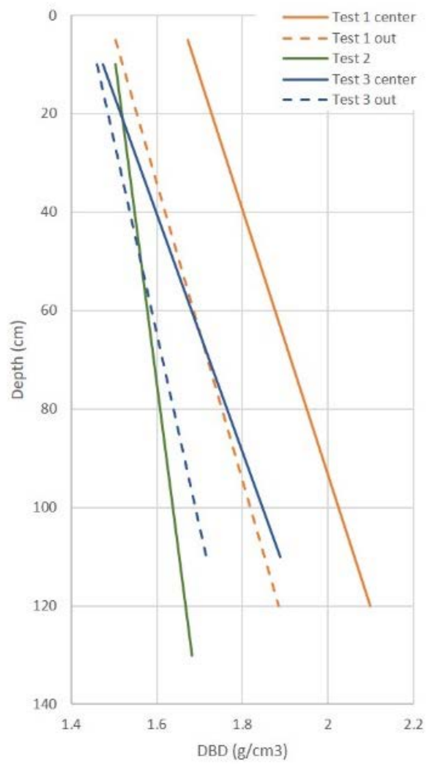

Figure 3: Estimated final bulk densities in Tests 1, 2, and 3

Moisture content

Initial VWC values from the nine moisture content sensors indicated a range of 0.085 to 0.111 with an average of 0.100 g/cm^3, in Test 1. Figure 4 shows the wetting front progression in the Test 1 (baseline) column. The wetting front progressed faster in the first 45 cm than in the rest of the column, where the solution velocity was relatively constant, most likely due to spreading of solution away from the dripper. Observed step-shaped curves, such as sensors at depths 15, 30, 75, and 135 cm are interpreted to be the result of the ore collapse that occurred in the column. Significant variations can be seen in the moisture content data at 45, 75, and 90 cm in the first 150 hours.

The wetting and drainage behaviour from the Test 2 slow ramp-up period is shown in Figure 5. Exfiltration from the column did not occur until after the flow rate was changed to 1/8th of the target rate, more than 48 hours after the irrigation started (Test 1 was irrigated for 382 hours). Smooth water content curves were observed in Test 2 compared to Test 1. Moisture content values slowly increased with every irrigation pulse, whereas drainage from sensors deeper than 30 cm deep were greater than the 15 cm sensor most likely due to less consolidation and ore collapse at these depths. Overall, the VWC (average sensor data) was approximately 0.02 g/cm^3 lower than in Test 1.

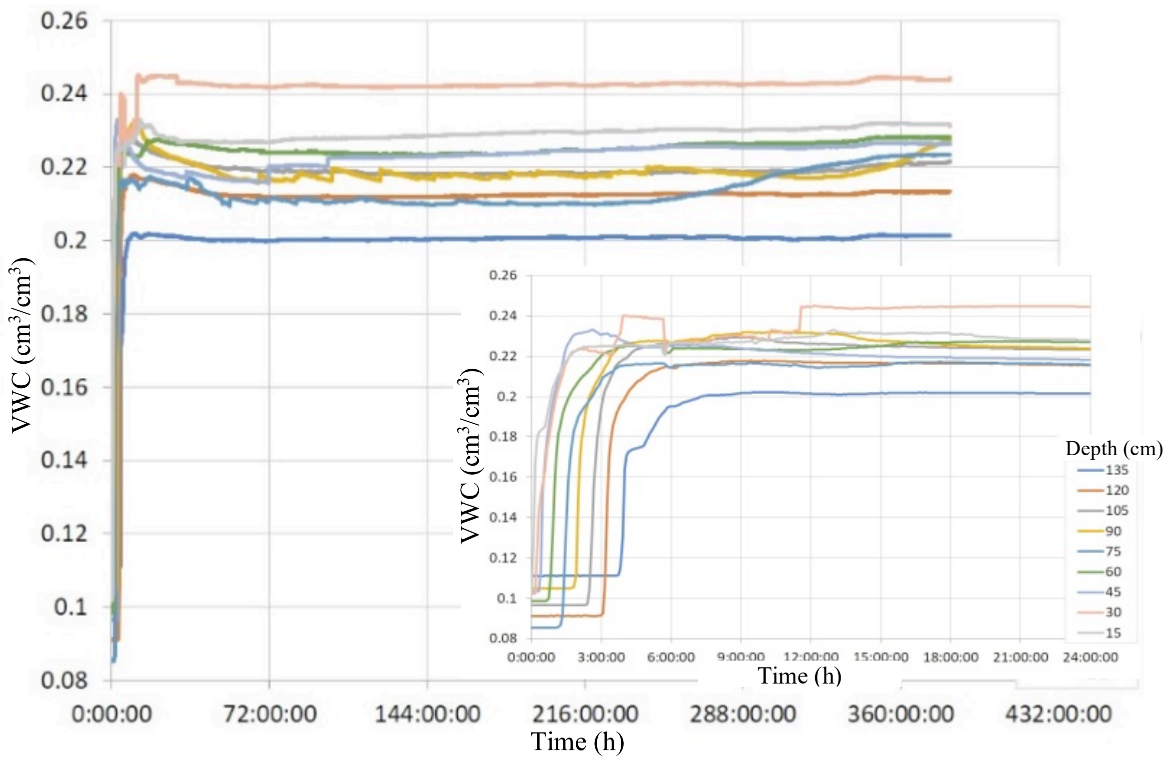

Figure 4: Volumetric water content at nine depths vs. time in Test 1

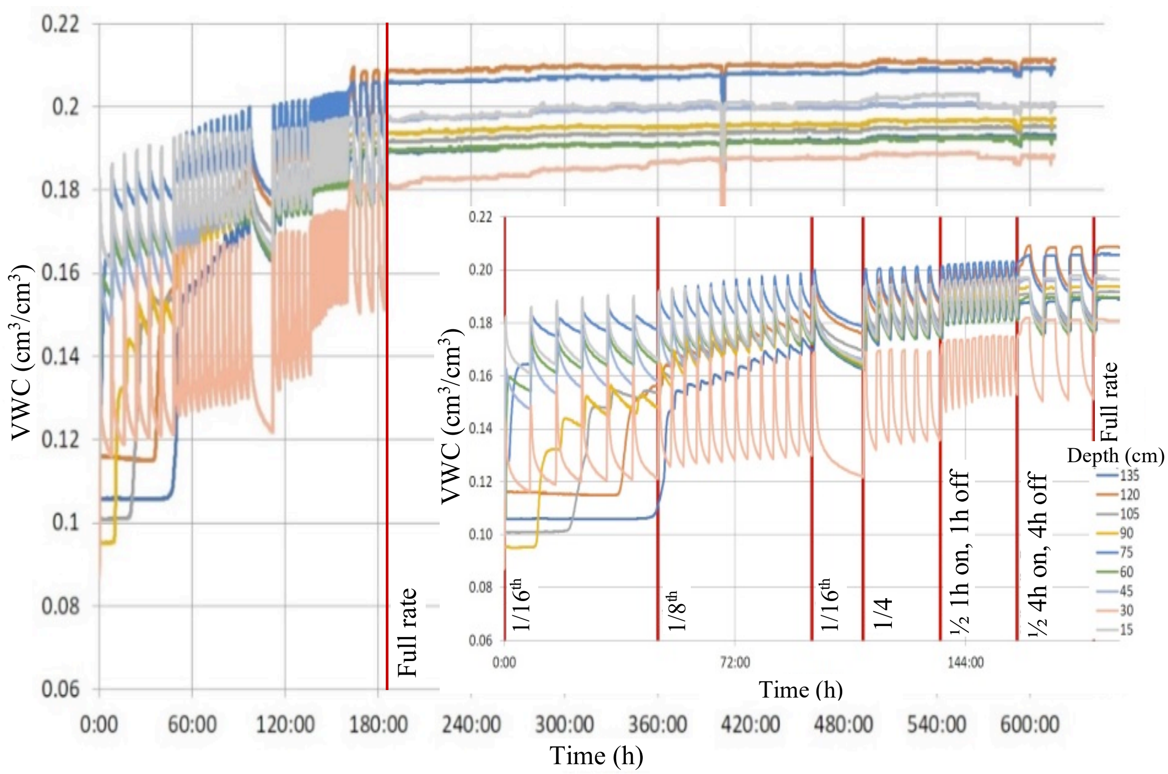

Figure 5: Volumetric water content at nine depths vs. time in Test 2

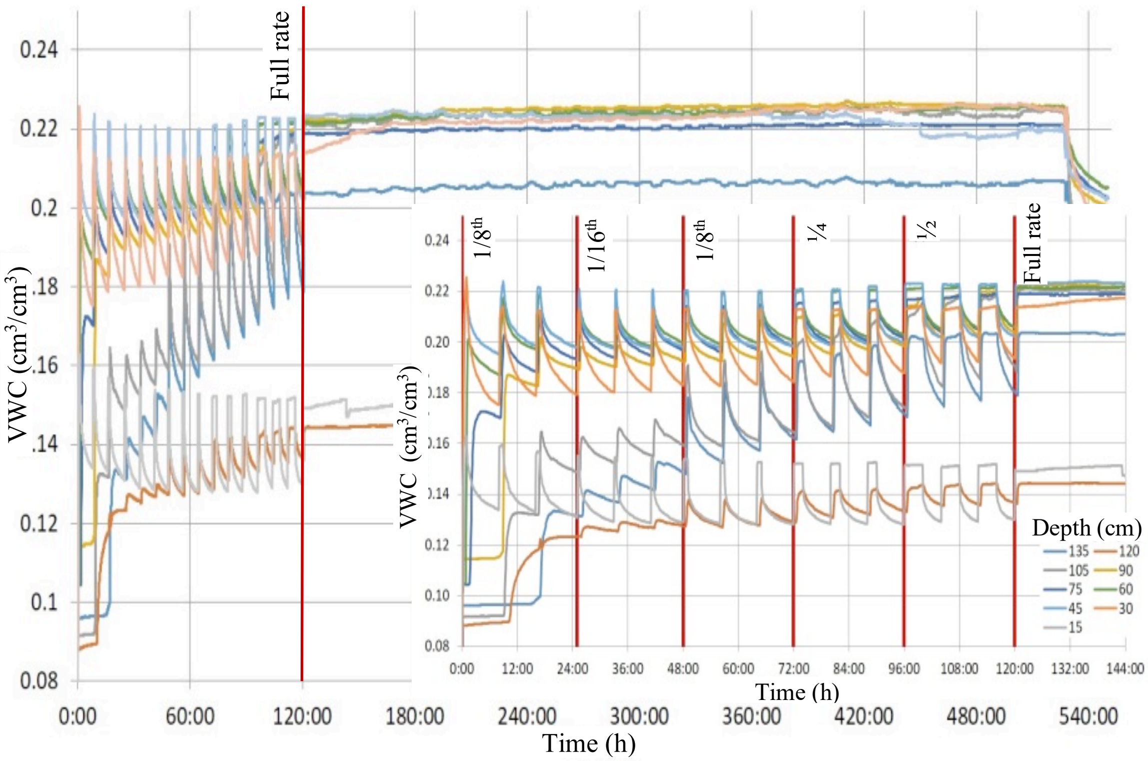

Figure 6: Volumetric water content at 9 depths vs. time in Test 3, from moisture sensors

Test 3, which started with a higher irrigation rate (1/8th target irrigation) than Test 2, resulted in higher moisture contents over time (Figure 6). The exceptions are sensors 105 and 135 cm, which had lower moisture from the start. After significant slumping was detected in Test 3 after the first day of irrigation, a 1/16th rate was used to assess if reducing the rate would assist in stopping the ore collapse. This was not the case, so at 48 hours, the 1/8th irrigation rate was used again. Sensors at depths 15 and 120 cm showed lower VWCs throughout the test, possibly due to solution bypass (see Dye tracer test results). Although intermediate ore collapse was observed in this Test 3, compared to Tests 1 and 2, the VWC was stable.

Dye tracer test

Figure 7 shows the ore and dye staining from solution contact at different depths. Due to the short period of dye tracer application (two unsaturated pore volumes) the amount of dye was insufficient to fully penetrate the entire column and thus dye tracer staining is indicative of the predominant flow paths within each column. Due to limited ore availability, no sorption coefficients or retardation factors were measured for the dye. However, prior research has reported sorption of Blue FD&C 1 by various porous media (Flury and Flühler, 1995; Perillo et al., 1998; Germán-Heins and Flury, 2000; Koestel et al., 2008). The estimated volume of influence (dyed volume/solution volume) are 60.03, 50.93, and 67.06 L in Tests 1, 2, and 3, respectively.

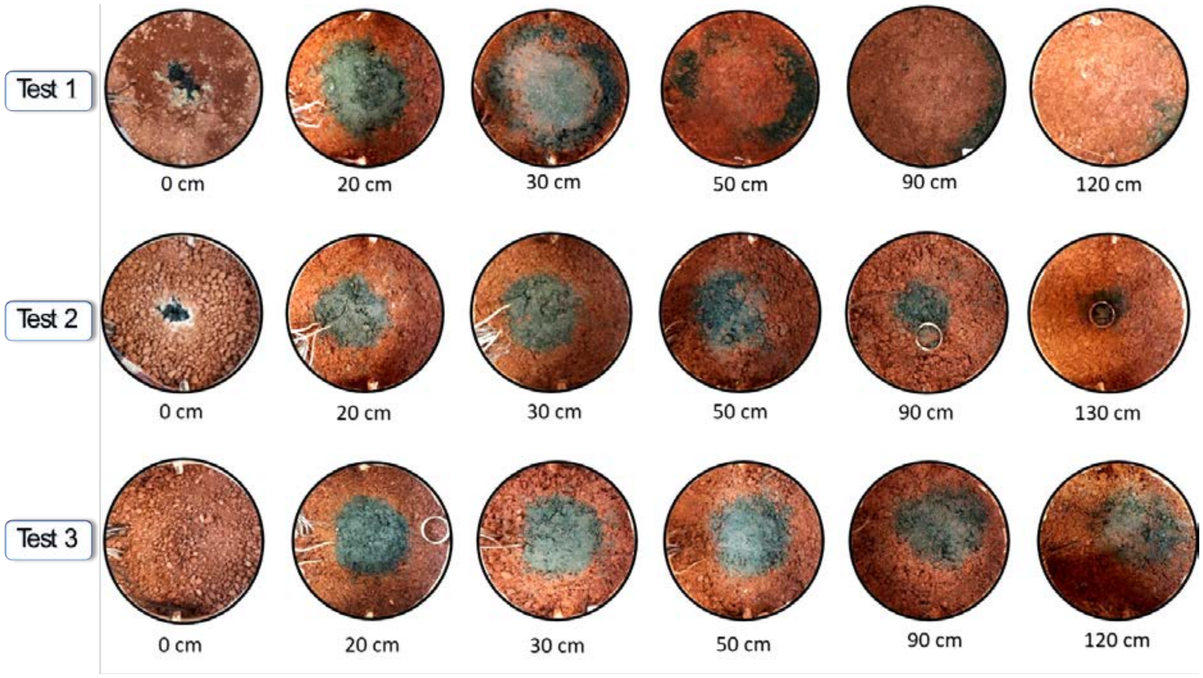

Figure 7: Ore images at different depths after the dye test

Test 1 showed two dye patterns. The surface of the column shows a small centroid directly under the emitter. By 20 cm, the dye spread through the center of the column and spreading increased by 30 cm with notable staining towards the outside of the column. By 50 cm, staining is only observed around the outer portions of the column until only a small portion or ore was dyed at 120 cm depth. This indicates that below 30 cm, solution flowed around the collapsed center of the column into the outer pore space with higher hydraulic conductivities. Nevertheless, limited, and slower flow may still have occurred in the center of the column, as seen from moisture content data slowly increasing at the final stage of Test 1 (Figure 4).

Test 2 showed more uniform staining patterns. With the exception of the deepest moisture sensor in Test 2, there is correlation with the measured VWCs in all tests with the dyed areas, i.e., the smaller the dyed area, the lower the moisture content. Although ore settlement in Test 3 was intermediate to Tests 1 and 2, the dyed areas show that the ore collapse in the center of the Test 3 column was not enough to reduce the ore permeability to cause diversion of flow to preferential pathways around the outside of the column. Dye staining remained in the center, but showed more lateral spreading, as seen by the slightly larger dyed areas compared to Test 2. This indicates that the partial collapse of the agglomerate structure may have promoted more spreading of solution in Test 3 versus Tests 1 and 2.

Mass balance

The mass balance results indicate that in Test 1, storage increased quickly to greater than 30 L during the initial wetting period, and then it decreased between 100 to 200 of solution applied (Figure 8). Although additional slumping was not observed during this time, the redistribution of solution draining from the collapsed ore space to higher conductivity pore spaces may have been the cause of this loss in storage. After 200 L, storage stabilized and slightly increased from 25 to 27 L. Storage in Test 2 increased slowly during ramp-up and had a sudden increase when the full irrigation rate was applied. It experienced a second increase after tracer injection started and then decreased slowly until the end of the test. Storage in Test 3 increased up to 21 L during the initial ramp-up and increased slowly up to 27 L. Overall, Test 2 showed the greatest solution retention between the three columns.

Conceptual model of leach ore initial irrigation

Rapid wetting of leach ore and subsequent ore collapse is most likely due to a combination of physical forces. Solution flux rates near the drip emitter are very high compared to the target rate of 9.1 $L/m^2/hr$; a 5 cm^2 area below the dripper is subject to 2,000× the target irrigation rate. As solution then flows under gravity into agglomerated leach ore, it rapidly increases saturation and weakens the capillary and direct contact forces that keep particles together.

Rapid saturation may also loosen fine particles from the agglomerated surface and break down the structure, in addition to chemical decrepitation which breaks down larger particles. The resultant ore collapse should be localized under the emitter and result solution flow bypass (Figure 9). High localized flux rates should decrease with depth as the wetting front advances and capillary forces pull the solution into smaller pores both laterally and downward. These processes are further discussed in Yao et al. (2022, in these proceedings).

The results of these column studies indicate that initial irrigation at the target flux rates resulted in ore collapse and solution bypass below 30 cm depth. The ramp-up irrigation column results indicate that during the off-irrigation period, drainage can be expected to occur initially from larger pores and then from smaller pores spreading laterally and slowing down and redistributing the wetting front. When irrigation is reinitiated, the underlying leach ore is more uniformly wetted and better able to conduct solution due to higher hydraulic conductivity than in the initial irrigation phase. This process was repeated at 8 hour intervals for the initial ramp-up step and then subsequently with lower off period intervals. Since the on periods were maintained at 0.5 hours of irrigation, the shorter drainage periods result in less time for redistribution. However, if the column or leach ore profile is initially wetted during the initial ramp-up phase, additional solution distribution is likely to occur more uniformly.

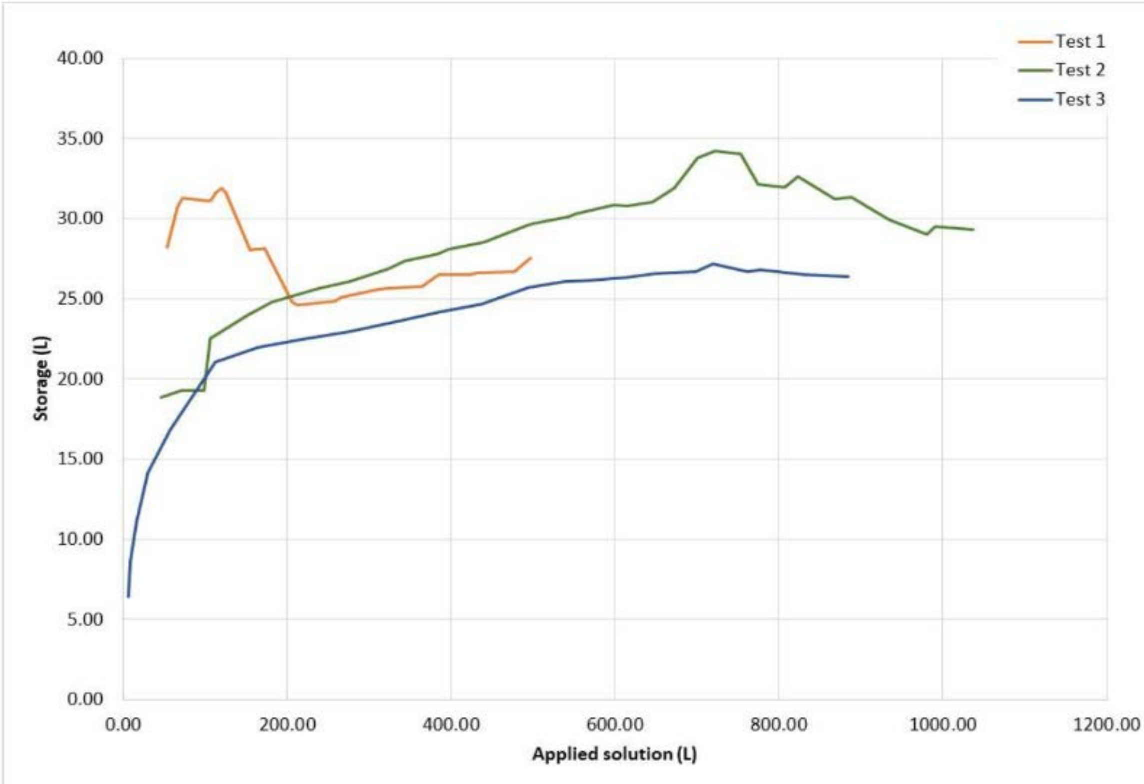

Figure 8: Solution storage over time in Tests 1, 2, and 3

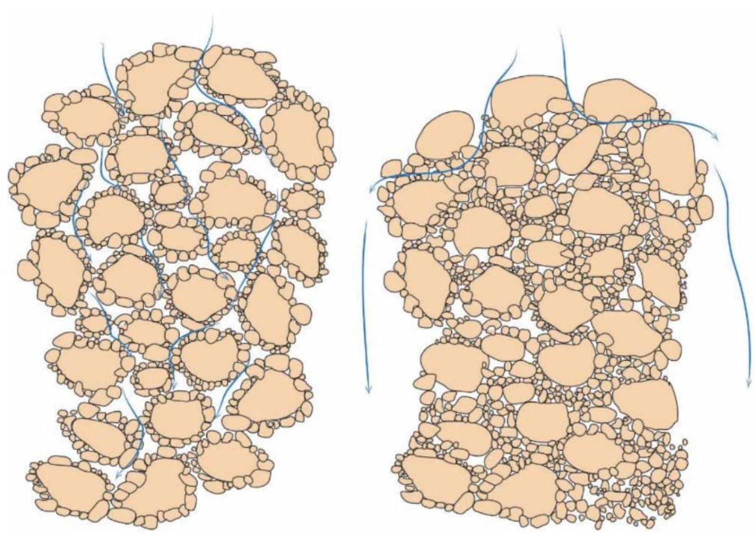

Figure 9: Conceptual process of redistribution of particles after agglomeration break-up. Left: Before irrigation. Right: During and after initial irrigation and wetting

Conclusions

A large copper leach ore sample was agglomerated and tested for hydraulic and physical property parameters. Three large column tests were performed to assess the effect of different initial irrigation schemes on ore consolidation and solution distribution. The baseline test (Test 1) irrigated the column at a target irrigation rate of 9.1 L/m^2/hr, which showed significant ore collapse, ponding at the surface, and preferential flow. Test 1 showed a rapid increase in solution storage and then decline after ore collapse; overall solution storage retention was smaller in this test than in the ramp-up tests, which indicates lower solution contact with the ore. Although Test 1 showed larger dyed areas in the upper 30 cm of the column, significant dye channeling was observed in the lower half of the column. The dye staining indicated solution bypass occurred around a collapse zone in the center of the column.

The slowest ramp-up test (Test 2) showed minor ore settlement, and the highest solution retention. Dye tracer results indicated flow was present through the central portion and not diverted as in Test 1. The higher storage retention is most likely due to improved moisture redistribution during the off-irrigation periods. The fast ramp-up test (Test 3) showed intermediate slumping between the baseline Test 1 and slow ramp-up Test 2; however, the degree of collapse was not as extreme, and solution flow remained in the central portion of the column. Given that solution to ore contact is important for leaching, the Test 1 and Test 2 column results indicate good conditions for copper recovery.

The results of this study indicate that initial irrigation conditions can significantly affect the solution distribution and consolidation of agglomerated copper leach ore at the near surface. To maintain desirable conditions for agglomerated ore heap leaching, irrigation ramp-up schedules should be evaluated and incorporated into copper heap leach system design.

Acknowledgements

We would like to thank BHP and Freeport McMoRan, Inc. for providing the crushed heap leach ore samples for the experimental work.

References

ASTM. 2004. Hydraulic conductivity with flexwall permeameter. In *Annual Book of ASTM Standards,* pp. 1045–1067.

ASTM. 2017. Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter 1. ASTM International, West Conshohocken, Pa, August, 1–24. https://doi.org/10.1520/D5084-16A.1

Decker, D.L. 1996. The determination of the hydraulic flow and solute transport parameters for several heap leach materials. University of Nevada Reno. doi: 10.16953/deusbed.74839.

Fernando, W.A.M., I.M.S.K. Ilankoon, M.N. Chong and T.H. Syed. 2018. Effects of intermittent liquid addition on heap hydrodynamics. *Miner. Eng.* 124: 108–115. Available at: https://doi.org/10.1016/j.mineng.2018.05.016