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The effect of nut shell addition on the permeability of a crushed gold ore

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Abstract: In this study, variations in permeability of a gold ore by nut shell addition was studied. Ore particle size, nut shell size and volume fraction in the ore were the parameters investigated. Permeability is an important issue in heap leach operations considering the processing duration. Particularly below 6 mm particle size permeability is greatly hampered. Turkey is the leading country in the world in hazelnut production. Therefore, considerable amounts of nut shell are obtained as a by-product. Incerase in the permeability of a finely crushed ore will obviously enable an increase in the leaching efficiency. The finer the particle size the more the liberation of gold is yet the permeability is lower. Therefore, this study focuses on the possibility of improving the permeability of ore heaps with nut shell addition. Optimum amount of nut shell which should be added to the ore was found to be 5% by volume. It was found that the permeability of ore crushed below 2.36 mm considerably increased by the addition of nut shell below 18 mm.

Keywords: *permeability, nut shell, heap leaching, gold leaching, leach efficiency*

1. Introduction

Permeability is an important issue in heap leach operations particularly at fine particle sizes. Ore permeability has long been recognized as a critical factor in heap leaching performance. Poor permeability results in a decrease in metal recoveries and prolonged leaching time (Milczarek et al., 2013). According to Breitenbach (2005), uniform permeability of heap is one of the key elements for successful heap leach operations. Breitenbach (2005) also mentioned that heap zones with low permeability resulted in unleached ore trapped, which can be explained by the low flow rate of solution.

Most heap leach operations recognize the need to agglomerate the ore to improve the percolation rate distribution and minimize channeling in the heap (Miller, 2003). As pointed out in Kawatra (2006) study, poor permeability is one of the main problems in grained ores. Fine particles form impermeable layers within the ore bed as shown in Fig. 1 (a). Ideally, the ore bed should be constructed as shown in Fig. 1 (b), which demonstrates the spaces between the particles creating a more permeable ore bed allowing for solution to flow freely.

Fine particle migration and ore segregation will result in dead zones in the heap and this will reduce permeability. Ore permeability can be improved by binding fine particles into coarser agglomerates which provides a more uniform distribution of particle sizes (Lastra and Chase, 1984; McClelland, 1986; Milczarek et al., 2013). In the study of Vethosodsakda (2012), agglomeration is denoted as pretreatment step in many gold and copper heap leach processes. In the same study of Vethosoksakda (2012), permeability tests were carried out to evaluate the quality of agglomerates and increased permeability of agglomerates that results in reduced leaching time. Relationship between particle size and permeability has been studied by many geologists and soil scienctists. However, it has been found out that not only particle size but also the moisture content affect permeability.Larger void spaces are available at 6 and 8% agglomerate moisture contents and having larger void spaces

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was reported as an improvement in the permeability (Vethosoksakda, 2012). Lewandowski and Kawatra (2009) claimed that gold ore agglomerates are stable because of the use of cement, while agglomeration of base metal ores with sulfuric acid or other binders will be frequently unstable because of the ongoing chemical decrepitation during leaching process (Milczarek et al., 2013).

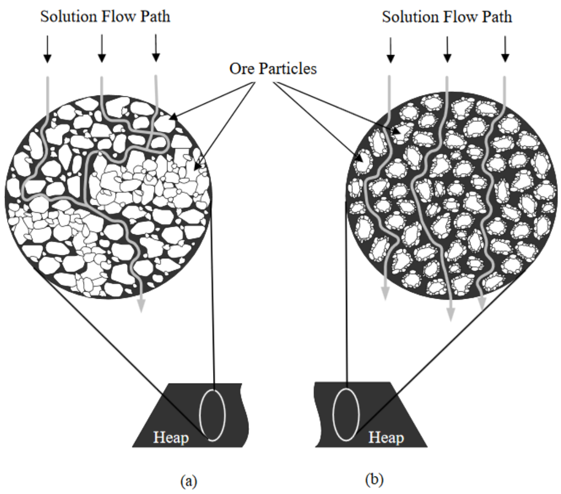

Fig. 1. Ore bed distribution: (a) actual, (b) ideal

According to Bouffard (2005), the wide range of particle size in the heap, the segregation of these sizes during stacking and irrigation, and the ore mineralogy are the ultimate reasons for low permeabilities. Permeabilities of some materials have been given as follows: very fine sand has a permeability of 10^{-5} cm/s, while impervious soils made up of clays have the worst permeability ranging from 10^{-7} to 10^{-9} cm/s, organic and inorganic silts, mixture of sands, silts and clays have a very low permeability of 10^{-6} cm/s (Bouffard, 2005). For a binder to be considered useful in a copper leaching heap, it should have the properties of "acid resistance", "economical" and "non-hazardous and non-toxic to bacteria" as mentioned by Kawatra et al. (2006). In terms of organic binders; agar, gelation, gums, sodium carboxymethylcellulose and starch have been tested in various leaching operations as tabulated in Kawatra et al. (2006) study.

Uhrie et al. (2003) found that the permeability of an ore decreased with increasing clay content. This was also reported and supported as the "variation in water permeability with salinity and clay content" in the study of CoreLab (1983) which is shown in Fig. 2. Kinard and Schweizer (1987) claimed that the permeability is inversely proportional to the bulk density, in more detail they found out the permeability changed between 10^{-4} and 4×10^{-7} cm/s while bulk density ranged from 1.19 to 1.43 t/m^3 respectively.

Inter-lift liners have been used on copper heap leach pads mainly in South America in the mid 1990s for more economical metal recovery reasons (Breitenbach, 2005) in order to reduce acid consumption (Smith, 1996) and to increase recovery kinetics (Echeverria et al., 2015). Schematic representation of a heap leach with inter-lift liner system is provided in Fig. 3. Echeverria et al., (2015) also observed that the higher the permeability of the ore, the higher the percentage of infiltration that occurs at each level. Lower percolation in higher heap heights can be reasoned by the decreased permeability (Echeverria et al., 2015).

According to Milczarek et al. (2013), primary factors that influence leach ore permeability include ore rock behavior after blasting and crushing processes, ore lift height (heap height) and lixiviant irrigation rate. Not only these primary factors influence the leach ore permeability but also generation of fines significantly affects ore permeability. Ore consolidation may cause minor reduction in ore permeability or it may significantly decrease the permeability (Milczarek et al., 2013). Permeability, or in other words hydraulic conductivity, also changes with heap height for different ore types i.e. soft ore or durable ore ("soft ores" cannot be stacked very high and "durable ores" can tolerate variable ore production and leach cycle time). This was demonstrated by Lupo and Dolezal (2010) as shown in Fig. 4.

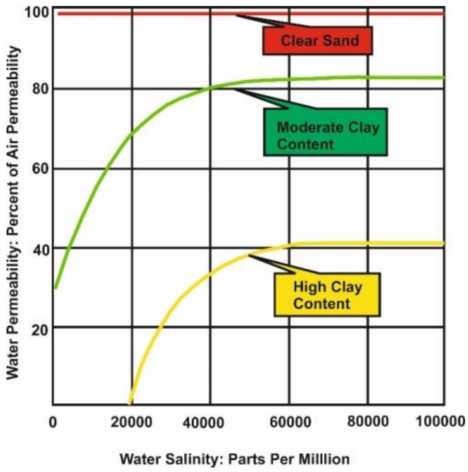

Fig. 2. Water permeability (percent of air permeability) vs. water salinity (part per million) with respect to clay content (CoreLab, 1983)

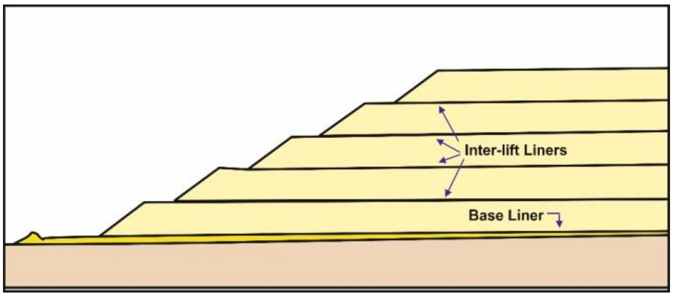

Fig. 3. Schematic representation of a heap leach with inter-lift liner system (adapted from the study of Echeverria et al., 2015)

The greater the permeability of a bed of rock or soil, the greater is the ability of the bed to transfer the leach solution without flooding. The solution flow rates in heap leaching applications are so small that the fluid can be assumed to obey Darcy's law (Bouffard 2015):

$$k = QL/At\ \Delta h,$$

where k is the hydraulic conductivity, Q is the quantity of water discharged, L is the sample height, A - cross-sectional area of specimen, t is the total time of discharge and Δh is the difference in head on manometers.

The objective of this study is to improve the permeability of gold ore by blending it with organic by-products such as nut shells. Effects of particle size distribution and volume percentage of nut shells on permeability were investigated. Turkey has abundant sources of nut shells that is why they may offer a cost-effective solution to increase the ore permeability

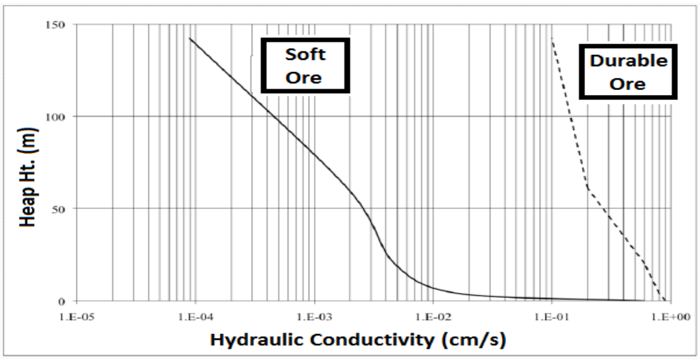

Fig. 4. Hydraulic conductivity changes with heap height and ore type (adapted from Lupo and Dolezal, 2010, presentation)

2. Experimental method

Permeability experiments were carried in an experimental setup as presented in Fig. 5.

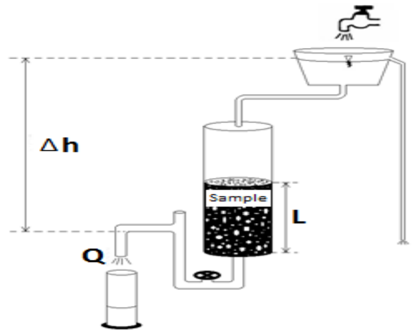

Fig. 5. Experiment setup for permeability experiments

A new permeability test rig was designed similar to the setup seen in Fig. 5 as shown in Fig. 6.

Fig. 6. Permeability test set up used in this investigation

In this experimental setup, hydraulic load (Δh) was kept constant in all tests and the water flow (Q) through the ore was measured with respect to time (t). Experiments were carried out complying with the ASTM standards (D2434).

The experimental parameters studied included volumetric ratio of the nut shell in the ore, particle size of the nut shells and particle size of the ore. Prior to tests, particle size distribution of the ore samples were determined using 25, 18, 10, 6.70, 4.75, 2.36, 1.00, 0.50, 0.212 and 0.150 mm sieves. Results of the size distribution of original ore is given in Table 1.

Table 1. Particle size distribution of the ore sample

Particle size (mm)	**Weight (%)**	**Cumulative undersize (%)**
+25	0.00	100
-25+18	0.45	100
-18+10	12.94	99.55
-10+6.70	8.63	86.61
-6.70+4.75	13.76	77.98
-4.75+2.36	18.50	64.22
-2.36+1.00	19.00	45.72
-1.00+0.50	4.08	26.72
-0.50+0.212	6.70	22.64
-0.212+0.150	1.82	15.94
-0.150	14.12	14.12
Total	**100**	

One set of tests were carried out using the as received ore from the heap operation. Two other size groups were prepared by crushing, below 10 and 2.36 mm. In addition to original ore size distribution analysis, particle size distribution of the -2.36 mm and -10 mm was provided as in the Table 2 and Table 3 respectively.

Table 2. Particle size distribution of the -2.36 mm ore sample

Particle Size (mm)	**Weight (%)**	**Cumulative undersize (%)**
+2.36	0.00	100
-2.36+1.70	13.20	100
-1.7+1.00	38.84	86.80
-1.00+0.50	13.95	47.97
-0.50+0.30	7.56	34.01
-0.30+0.150	9.93	26.46
-0.150+0.075	6.67	16.52
-0.075+0.038	8.64	9.85
-0.038	1.21	1.21
Total	**100**	

Table 3. Particle size distribution of the -10 mm ore sample

Particle Size (mm)	**Weight (%)**	**Cumulative undersize (%)**
+10.00	0.00	100
-10.00+6.70	10.80	100
-6.70+4.75	6.28	89.20
-4.75+3.36	12.12	82.92
-3.36+2.36	6.00	70.80
-2.36+1.67	9.28	64.80
-1.67+1.00	20.00	55.52
-1.00+0.50	7.72	35.52
-0.50+0.150	17.12	27.80
-0.150	10.68	10.68
Total	**100**	

As long as the permeability remains constant, a decrease in the ore particle size is expected to increase the leach efficiency as a result of increased liberation. Nut shells used in the tests were prepared either by screening into different fractions or by crushing. Nut shell size fractions employed in the tests were -18, -10, -3.36, -2.00 and -3.36+0.6mm. Volume percentages of nut shell in ore-nut shell mixtures were changed between 0 and 15% with an increment of 2.5%.

The main problem faced during the experiments is making a homogenous mixture of the ore and nut shell. However this was achieved by wet conditioning of the nut shell beforehand. This wet conditioning of the nut shell by leach solution provided the less absorbance of gold through the nut shells. In terms of laboratory conditions, this was easy and agglomeration of particles was ensured by wet conditioning of ore. In terms of plant operations; limestone, nut-shell and ore can be mixed within a specific ratio with the help of conveyors and silos. In gold ore processing plants, already the gold ore is mixed with limestone in terms of heap leach operations in order to have lower levels of pH, and nut shells can be mixed homogenously in between. The usage of nut shell would provide better permeable zones within the body of heap and channeling would be less probable.

3. Results and discussion

Permeability tests were carried out at 3 different size groups of ore. Referring to Table 1, 99.55% of the ore is seen to be under the size of 18 mm. One set of tests were carried out using the "as received" ore from the heap operation. Two other size groups were prepared by crushing, below 10 and 2.36 mm. It is known that as the particle size gets finer permeability decreases, however, metal recovery may increase. The permeability of three test samples was measured and the results are presented in Fig. 7.

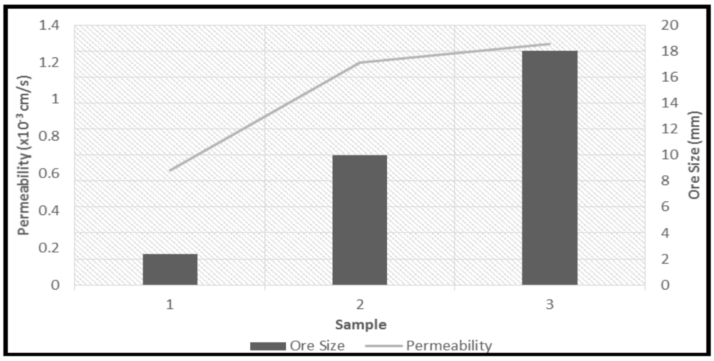

Fig. 7. Bed permeability with respect to ore particle size (-2.36 mm, -10 mm and -18 mm)

As seen in Fig. 7, permeability increases with an increase in size of ore with no nut shell addition. Permeability of the "as received" ore is 1.3x10^{-3} cm/s while the permeability of -2.36mm ore reduces to 0.62x10^{-3} cm/s. It is possible that the decrease in the permeability of the ore at finer particles sizes may be compensated by the addition of some sort of materials promoting percolation degree. In this respect, nut shell having different particle sizes was blended with the ore at varying volumetric ratios.

The effects of nut shell addition to the ore on the permeability rate were shown in Figs. 8-13.

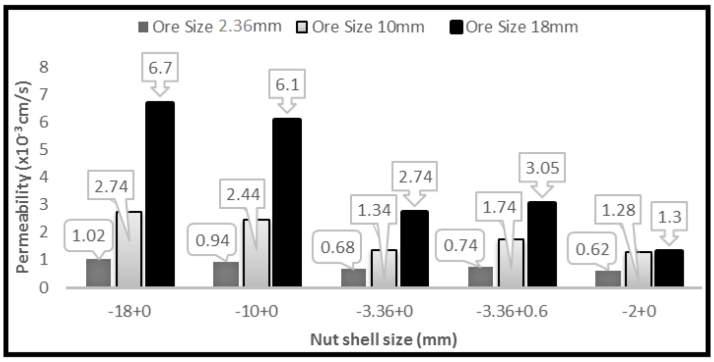

Fig. 8. Permeability vs nut shell size at nut shell percentage of 2.5%

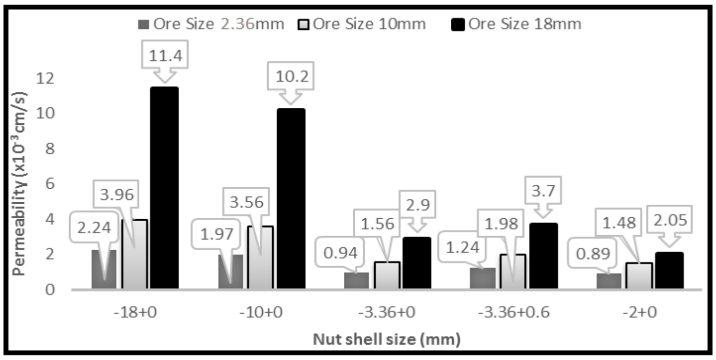

Fig. 9. Permeability vs nut shell size at nut shell percentage of 5%

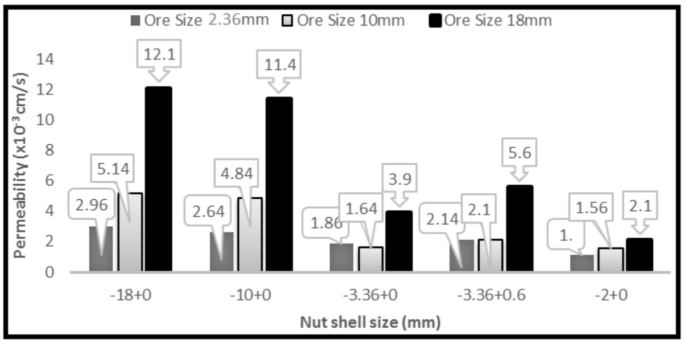

Fig. 10. Permeability vs nut shell size at nut shell percentage of 7.5%

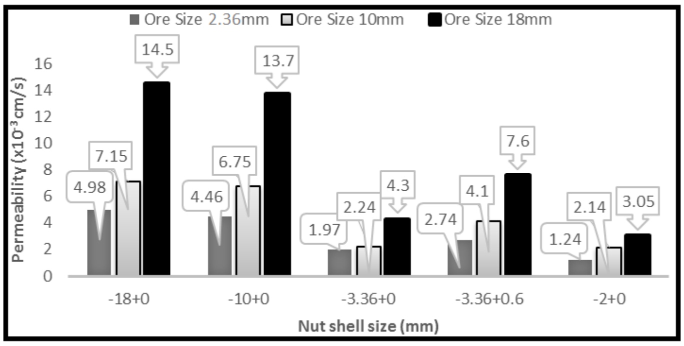

Fig. 11. Permeability vs nut shell size at nut shell percentage of 10%

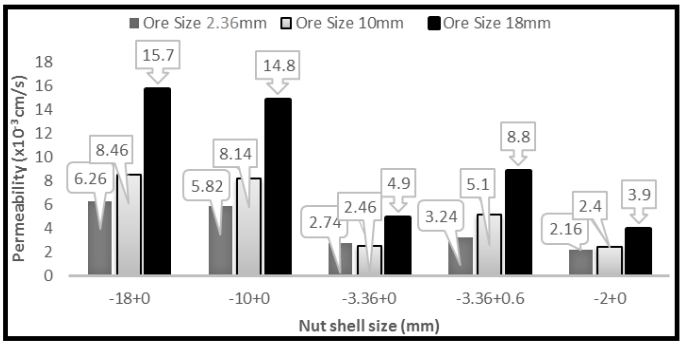

Fig. 12. Permeability vs nut shell size at nut shell percentage of 12.5%

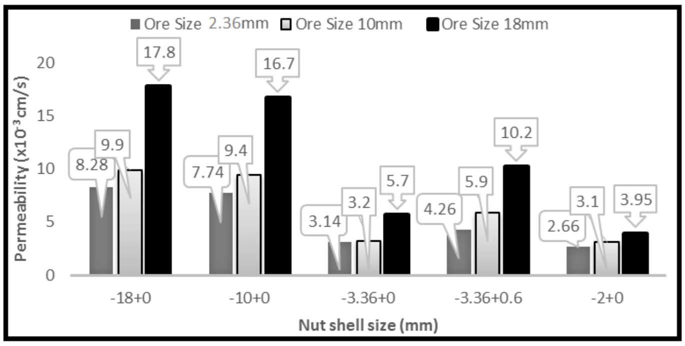

Fig. 13. Permeability vs nut shell size at nut shell percentage of 15%

As it is seen from the Figs. 8-13, permeability decreases as the nut shell size gets finer. In -3.36 mm nut shell size the effect of removing -0.6 mm size fraction was tested on the permeability change. In all figures it is apparent that removing -0.6 mm nut shell fraction has markedly increased the permeability values. Results obtained suggested that if the ore is crushed below 2.36 mm, the addition of 5% nut shell by volume of size less than 18 or 10 mm would be sufficient to obtain adequate percolation rate. Adding nut shell in higher volume percentages above 7.5% will provide better permeability, however, it may not be feasible to use such high amounts.

Milczarek et al. (2013) also claimed that pore size distribution significantly contributes to permeability. According to their experimental studies, one specific sample has the highest bulk density (highest load of the heap) and it has intermediate performance in terms of permeability. This is because of the pore size distribution of the ore according to Milczarek et al. (2013). Not only bulk density and pore size distribution of the ore could be related to lower permeabilities, but also PSD (Paricle Size Distribution) and PSD indicator (relates the proportion of large particles > # 4 mesh) is well correlated to ore permability. This is because it is the good representation of material gradation (Milczarek et al., 2013). In order to better understand the effect of PSD, previous test work by the authors (data not published) give a brief information of the range of PSD for the unacceptable and acceptable permeabilities. Milczarek et al. (2013) also showed that post-test ore samples with PSD indicator values lower than 2.0 show unacceptable permeability and values greater than 3.0 show acceptable permeability for heap leaching; while ore samples values between 2 and 3 can show either good or poor permeability. Higher permeabilities obtained for larger PSD of ore and ore-nut shell mixture supports the previous findings of Milczarek et al. (2013).

Literature findings of the above-cited researchers are a good validation of the affecting parameters on ore permeability. In the context of this study construction of a heap with ore and nutshells is a good alternative solution to the problem of low permeability.

4. Conclusions

The results of experiments suggested that addition of 5% by volume nut shell would be adequate to obtain much better permeability values even if the ore was crushed below 2.36 mm. In the case of coarser ore feeds, the exposure of gold containing particles would not increase, however, improved permeability with the addition of nut shell would lead to decreased leach durations. Some concerns arise when using nut shells as organic material for leach operations which may be absorbing the gold ore in the body of organic structure. Although this is true to some extent, organic body of nut shell absorbs some of the gold in its body, however it is being saturated with leach solution and then desorption of gold ore from the body of nut shell is starting. At the end, some insignificant amount of gold is accumulated in nut shell body which can be ignored comparing to the permeability increase and because of that, the net cumulative gold recovery should increase. That is why, when using an organic material in order to increase the permeability, increase in permeability and decrease in total gold recovery because of absorbed gold in the organic structure should be considered together and should be optimized. Other concern is the composting or denaturing of nut shells inside the heap. However, composting or denaturing of nutshells will not start during the period of 90-120 days of leaching. After this period of time, either heap is regenerated or heap is moved to some other place because the leaching of ore is already terminated in that period of time. In fact, composting of nut shell inside the heap would help in reclamation of the heap since it will contain more organic matter.

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