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ABSTRACT: This paper presents results of laboratory compaction testing to determine the influence of particle size, size gradation and moisture content on compaction of crushed rock salt. Included is a theoretical analysis of the optimum size gradation. The objective is to evaluate the relative densities that can be achieved with tamping techniques. Initial results indicate that compaction increases with maximum particle size and compaction energy, and varies significantly with particle size gradation and water content.

1 INTRODUCTION

The United States Department of Energy is developing the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico to provide a facility for demonstrating the safe disposal of radioactive wastes. Design concepts for WIPP call for permanent sealing of shafts, following waste emplacement (Stormont, 1984; Nowak et al., 1990). Compacted crushed salt, consolidated to low permeability by creep closure of the surrounding rock, is the long-term barrier to seal the shafts (Nowak et al., 1990). If crushed salt could be compacted in place to sufficiently high density, salt seal emplacement could be simplified (Howard, 1988), and its performance could be enhanced.

The compacted crushed salt should have the maximum possible dry density. When the dry density is at its maximum, the hydraulic conductivity of the seal materials should be at its minimum. The higher the initial compacted density, the less time (i.e., shaft closure) is required to form (compact) an effective seal; thus, the greater will be the length of effective seal formed in the shafts during a given time span (Nowak and Stormont, 1987).

Under impact, geometrically systematic arrangements of proportioned crushed salt particles can form a seal with the highest possible density. The proper mixture of sizes of particles appears to give the best compaction (Fuller and Thompson, 1907). The porosity decreases as the particles deviate from uniform size distribution to proportional distribution, because the finer particles fill the voids between the larger grains. To achieve the highest compaction, particle size gradations have been designed, based on a Fuller-Thompson particle grading equation (Head, 1980).

The objective is to investigate compaction properties of crushed rock salt as a function of particle size, size gradation, compaction energy and moisture content, to determine the optimum size gradation for the highest compaction. Theoretical analysis of the optimum size gradation is discussed. Compaction is defined as the ratio of the density of the compacted sample to that of intact rock.

Visual observation of samples before and after compaction strongly suggests that breakage of larger particles occurs during compaction, but no systematic investigation of comminution during compaction has been made.

Laboratory compaction was conducted using a standard Proctor mold with a compaction energy of 5,400-16,200 kN·m/m³, two to six times the modified Proctor effort (ASTM D 1557). The crushed salt used for compaction has maximum particle size of 9.5, 19.1 or 38.1 mm.

2 PARTICLE GRADATION AND DENSITY

Particle size gradation affects sorting and porosity, which determines the permeability. When two different sizes of materials are uniformly mixed, the percentage of voids is less than the weighted average of the two (Fumas, 1929). The introduction of a set of smaller particles into a set of larger particles, the former small enough to fill pore spaces between the larger ones, can reduce porosity significantly. The proportionally sized particles have a lower permeability than uniformly distributed ones (Fraser, 1935; Graton and Fraser, 1935). When the larger particles become sufficiently numerous, they tend to nest together. If there are not enough smaller particles to fill the voids, often a
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layer of "cavities" with lower density will form. Usually, larger particles with uniform size distribution interlock and bridge, resisting deformation by sliding and rearrangement of particles. A larger compaction effort is required to reduce the volume of the voids in such a cavity layer. Poor compaction may be expected for the cavity layer, compared with particles with well-sorted proportional particle size distribution.

2.1 Mixing density of particles of different sizes

When smaller particles are introduced in between the larger particles, they do not increase the volume of the assembly as a whole until all the voids in between the larger particles are filled. It is postulated that if the crushed salt has a higher initial bulk density, a higher compaction can be achieved. Consider mixing \( n \) sets of different size particles with \( X(i) \) percent containing a certain fraction of voids, \( V(i) \), and solid volume of \( S(i) \), and with density \( G(i) \). For a mixture of varied size particles, the total density \( G_i \) of the mixture is given by:

\[
G_i = \frac{W}{V_i} = \left[ \sum_{i=1}^{n} \frac{X(i)V(i)}{G(i)} \left[1 - k(i) \right] - S(i - 1) \right] + \sum_{i=1}^{n} \frac{X(i)}{G(i)} \tag{1}
\]

where \( k(i) \) is the proportion of the voids that the smaller particles can not fill, \( k(i) = 0 \sim 1 \), \( W \) is the total weight of the sample, and \( V_i \) is the total volume after mixing, given by:

\[
V_i = W \sum_{i=1}^{n} \frac{X(i)V(i)}{G(i)} \left[1 - k(i) \right] - S(i - 1) \tag{2}
\]

\[
+ W \sum_{i=1}^{n} \frac{X(i)}{G(i)} \tag{2}
\]

The total unit volume of solids, \( S_i \), is:

\[
S_i = \sum_{i=1}^{n} \frac{X(i)}{G(i)} \left[1 - V(i) \right] \tag{3}
\]

If the pore space between larger particles can be filled completely by the smaller particles, then \( k(i) = 0 \). If the pore space is too small so that no smaller particles can fit in, then \( k(i)=1 \). The constant \( k(i) \) describes the fill of smaller particles into the voids between larger particles. \( k(i) \) is related to the critical diameter ratio (Fraser, 1935), the ratio of the diameter of the smaller particle to the larger particle. The critical diameter ratio describes the ratio of entrance for the smaller particles to just pass through the throats between larger particles.

The relation between the relative density and the distribution of particle sizes gives the justification for using proportional size gradation to achieve a higher compaction. Fig. 1 shows that the relative density varies with the proportion of two sets of particles with different sizes under zero compactive force. For an ideal mix of two sets of particles of different sizes, the relative density of the combination is 27-32% more than their average.

![Fig. 1 Calculated relative density of mixes with different proportions of two sets of salt particles with different sizes. Size set 2 has particles from 0.1 to 0.2 mm, set 4 from 0.2 to 0.3 mm, set 6 from 1.2 to 2.0 mm, and set 10 from 19.0 to 38.1 mm.](image)

2.2 Compaction of particles with a single size range

The bulk density of loose crushed rock salt varies from size to size for particles in a single size range (Table 1). The relative density increases with increasing particle size. The compaction of ranges of salt particles varies greatly with size (Table 1). Particles with a relatively uniform size distribution to which 2% water is added have low compaction, using a 44.5 N rammer. Particles that range from 19.0 to 38.1 mm result in the highest compaction (88.2%). The compaction decreases with increasing particle size for particles smaller than 0.3 mm, then increases with size up to 38.1 mm. It is more difficult to compact medium size particles. Measurements of bulk density and compaction of particles of a single size range indicate the volume occupied by solids and the potential for void reduction. Large particles leave larger voids in the sample. Small particles leave larger total void volume, but smaller individual voids. For best compaction, the void size and size distribution are important.

2.3 Particle Size Gradations

Particle size gradations designed to achieve the highest dry density of crushed salt at the lowest compactive effort, are obtained using the Fuller-Thompson equation (Head, 1980)
\[ p = 100 \left( \frac{d}{D_{\text{max}}} \right)^n \]  \hspace{1cm} (4)

where \( p \) is the weight percentage of the particles passing sieve aperture \( d \), \( D_{\text{max}} \) is the maximum particle size, and \( n \) is a material constant.

Table 1. Density of loose crushed rock salt and compaction of particles of single size ranges (2% water added for compaction only).

<table>
<thead>
<tr>
<th>Particle Size (mm)</th>
<th>Bulk Density (kg/m³)</th>
<th>Relative Density (%)</th>
<th>Compaction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.1</td>
<td>773.3</td>
<td>36.0</td>
<td>70.1</td>
</tr>
<tr>
<td>0.1-0.2</td>
<td>919.0</td>
<td>42.8</td>
<td>68.1</td>
</tr>
<tr>
<td>0.2-0.3</td>
<td>966.1</td>
<td>45.0</td>
<td>67.1</td>
</tr>
<tr>
<td>0.3-0.6</td>
<td>1031.3</td>
<td>48.0</td>
<td>68.6</td>
</tr>
<tr>
<td>0.6-1.2</td>
<td>1019.6</td>
<td>47.5</td>
<td>73.6</td>
</tr>
<tr>
<td>1.2-2.0</td>
<td>1047.7</td>
<td>48.8</td>
<td>76.2</td>
</tr>
<tr>
<td>2.0-4.8</td>
<td>1075.2</td>
<td>50.1</td>
<td>82.0</td>
</tr>
<tr>
<td>4.8-9.5</td>
<td>1081.0</td>
<td>50.3</td>
<td>85.0</td>
</tr>
<tr>
<td>9.5-19.1</td>
<td>1084.8</td>
<td>50.5</td>
<td>86.6</td>
</tr>
<tr>
<td>19.1-38.1</td>
<td>1136.1</td>
<td>52.9</td>
<td>88.2</td>
</tr>
</tbody>
</table>

The bulk density of salt particles with the Fuller-Thompson distribution varies greatly with the size gradation exponent, as well as with the maximum particle size in the mix (Fig. 2). The curves are calculated from Eq. (1), assuming all smaller particles can be filled into the voids between larger particles if such void spaces are available. When the size distribution exponent \( n \) is approximately 0.5, the mix has its maximum bulk density for all \( D_{\text{max}} \) examined. When \( n \) is larger than 0.5-0.55, the bulk density decreases with increasing size distribution exponent. The bulk density decreases rapidly with a decrease of the size distribution exponent below the optimum. This analytical result matches the compaction results discussed later.

3 CRUSHED ROCK SALT COMPACTION

3.1 Crushed rock salt used for compaction testing

The rock salt used for this study is prepared from one 91.4 cm diameter core from the WIPP site. Pieces of the core are crushed and sieved to size. On average, the WIPP salt consists of more than 95% NaCl, and less than 5% quartz, anhydrite, gypsum, magnetite, polyhalite and clays (Stein, 1985). Non-NaCl phases appear as either finely divided particles dispersed throughout the salt or as intergranular coatings (Stein, 1985). Particle shape varies with size (Kaufmann, 1960). The finer the salt particles the more they tend towards perfect cubic fragments, while larger particles are imperfect spheres (Kaufmann, 1960). The intact dry density of salt is 2.147 g/cm³. The density of individual particles may vary slightly, because the chemical composition of particles changes slightly (Kaufmann, 1960).

3.2 Particle size gradations and compaction testing

Ten particle gradations are used for compaction tests, obtained from Eq. (4) with size distribution exponents of 0.3, 0.45 or 0.6, and with maximum sizes from 9.5 to 38.1 mm. The particle gradations are classified into 3 groups in terms of maximum particle size (9.5, 19.1 and 38.1 mm), and 3 groups in terms of particle gradation exponent (0.3, 0.5 and 0.6), as shown in Figure 3 and Figs. 4 through 6. Not enough compaction tests have been performed for \( n = 0.45 \) to allow similar grouping of results.

Compaction tests have been conducted using a standard Proctor mold and two to six times the modified
Proctor effort (5,400-16,200 kN/m$^3$, ASTM D 1557-91). The compaction rammer weighs 24.5, 44.5 or 89 N, having a 5 cm diameter. 0.5-7% water has been added to the crushed salt during compaction.

![Graph](image1)

**Fig. 4:** Compactions as a function of maximum particle size and size gradation for samples with 1% water added.

![Graph](image2)

**Fig. 5:** Compactions as a function of maximum particle size and size gradation for samples with 2% water added.

### 3.3 Influence of largest particle size on compaction

The compaction increases with increasing maximum particle size (Figs. 4 through 6). The largest particle makes the densest sample. The larger particles have more volume of solid that does not need to be compacted. From Table 1, assemblies of larger particles have higher bulk density and can be compacted to higher density. Compaction increases 0.5-2% as the largest particles increase from 9.5 to 38.1 mm for crushed salt with 1-3% moisture content. Larger particles are broken into smaller pieces under the compaction effort. Therefore, more small particles are available to fill voids.

![Graph](image3)

**Fig. 6:** Compactions as a function of the maximum particle size and size gradation for samples with 3% water added.

### 3.4 Influence of Size Distribution Exponent $n$

Particle gradations with a size distribution exponent of 0.5 have the highest compaction for 1-3% water contents (Figs. 4 through 6). Gradations with size distribution exponent of 0.5 have higher initial density (Fig. 2). They have void sizes and particle size ratios which allow more readily for deformation by particle sliding and rearrangement under compaction. Samples with size distribution exponents 0.5 and 0.6 have more coarse particles. For samples with smaller particles ($D_{\text{max}} = 9.5$ mm), the size distribution for $n = 0.3$ has the lowest compaction with 1-2% water added, compared with those of size distribution exponents of 0.5 and 0.6. As the number of larger-sized particles increases, for samples with $D_{\text{max}}$ larger than 19 mm, the size distribution exponent of 0.6 results in the lowest compaction (Figs. 4 through 6). The compaction increases by 0.6-1.5% as the size distribution exponent increases from 0.3 to 0.6.

The compaction difference between particle gradation exponent of 0.3 and 0.6 for $D_{\text{max}} = 9.5$ mm decreases with increasing moisture content. Samples with size distributions of 0.3 have more fine particles, and larger surface area, and hence more water is needed to coat the particles. If the particles are not fully coated, a higher friction between particles may be expected during compaction. Greater friction reduces the ability of sliding and rearrangement of particles,
and therefore, reduction of the void volume is not as large as that of particles fully coated by water. When the moisture content increases, the particles with size distribution exponent of 0.3 have more compaction than those with size distribution exponent of 0.6.

Particles with size distribution exponent of 0.45 and maximum particle size of 9.5 mm have the lowest compaction for all moisture contents. This observation does not match the postulate based on the bulk density analysis (Fig. 2) that samples with size distribution exponent of 0.45 should be compacted more than those of 0.3.

3.5 Influence of Compaction Energy

Fig. 7 shows that compaction increases with increasing compaction energy, but levels off asymptotically. The crushed salt consists of $D_{\text{max}}=38.1$ mm with size distribution exponent of 0.5 and with 2% water added. When the compaction energy increases three times (from 5,400 to 16,200 kN-m/m$^3$), the compaction increases 3%.

Crushing of larger particles may be the major contribution to increased compaction under higher compactive effort. Crushing can result in considerable reduction of porosity at higher stress due to the production of fines, and to the increase in surface area which increases particle size range (Ingles and Grant, 1975). Destruction of the cohesion between grains leads to rearrangement and closer packing (Fraser, 1935).

Salt particles consist of halite crystals interlocked along grain boundaries, and individual crystals (Jeremic, 1994). Both contain weakness planes. Crushing takes place along weakness planes as the compactive stress exceeds the crushing strength. Crushing takes place when particles bridge, with few points of contact. As the compaction increases, particles come closer, point contacts increase and less crushing occurs. Therefore, compaction increases more slowly as the compactive effort increases beyond twice the standard compaction effort (Fig. 7).

![Graph showing compaction as a function of compaction energy](image)

Fig. 7: Compaction as a function of compaction energy, using an 89 N rammer for particles with gradation exponent of 0.5, 2% water added and with maximum particle size of 38.1 mm.

3.6 Compaction and Water Content

Fig. 8 shows compaction as a function of moisture content and particle size gradation. The compaction increases with increasing water content until the optimum water content is reached, and decreases with further water content increase.

Numerous authors (Head, 1980; Ingles and Grant, 1975) studied the influence of water content on soil compaction. Howard (1988) studied compaction of salt with varied water content at the laboratory scale. For dry particles, interparticle friction during compaction resists the reduction of void volume by compactive effort. At low moisture content, some salt particles are surrounded by a thin film of water, which tends to reduce the interparticle friction, keeps the particles apart and enhances the ability of particles to rearrange when compacted. If the moisture content increases further, the additional water enables the particles to be easily compacted together. Some of the air is displaced and the dry density is increased. The additional water, up to a certain amount, enables more air to be expelled during compaction. At that point, the particles become as...
closely packed as they can under the compaction effort. When the amount of water exceeds that required to achieve this condition, the excess water begins to push the particles apart, so that the dry density is reduced.

At saturation, the fine particles are more soluble than large ones. In solution in equilibrium with fine particles, the coarser particles grow at the expense of the finer ones, with intergrowth of adjacent grains (Kauffmann, 1960), which also increases the density. For crushed salt particles, the optimum water content increases with increasing size of larger particles (Fig. 8). The optimum water content increases from 3.3 to 4.8%, as the size distribution exponent $n$ increases from 0.3 to 0.6, and the largest particle size increases from 9.5 to 38.1 mm. In laboratory compaction testing, excess water bleeds down to the bottom of the mold and flows away. Larger particles hold less water, because of their smaller specific surface area. The smaller particles have larger specific surface area and can hold more water. The more water in the sample the lower the relative density is, when air is expelled from the voids.

The major contribution to increasing optimum water content with increasing larger particles may be the drainage that occurs during compaction. To the right of the optimum point, compaction is limited by the pore pressure of water opposing the compactive force (Ingles and Grant, 1975). Such restriction can be overcome by free drainage. To the left of the optimum point, frictional resistance opposes interparticle movement and hence compaction. At sufficiently high compactive forces, crushing of larger particles could result in a further compaction.

4 CONCLUSIONS

Particle size and gradation influence salt compaction significantly. Salt particles with proper size and size distribution can be compacted to a relative density of more than 90% using a standard Proctor mold, an 89 N rammer and twice the modified Proctor effort (5,400 kN·m/m³). Compactions of more than 92% can be obtained using four times the modified Proctor effort (10,800 kN·m/m³), and 93% using six times the modified Proctor effort (16,200 kN·m/m³). The optimum water content of the compaction increases with the largest particle size and with the larger particle content.

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