DEVELOPMENT OF NEW LUNAR SOIL SIMULANTS IN JAPAN  H. Kanamori¹, K. Matsui², A. Miyahara³, and S. Aoki⁴, ¹Shimizu Corporation, Institute of Technology, 3-4-17, Etchujima, Koto-ku, Tokyo 135-8530 Japan, kanamori@shimz.co.jp, ²Japan Aerospace Exploration Agency (JAXA), Lunar Exploration Technology Office, 2-1-1, Sengen, Tsukuba, Ibaraki 305-8505 Japan, matsui.kai@jaxa.jp, ³Japan Aerospace Exploration Agency, Lunar Exploration technology Office, miyahara.akira@jaxa.jp, ⁴Shimizu Corporation, Institute of Technology, saoki@shimz.co.jp

Introduction: Studies for developing various systems, devices and tools to be applied for lunar exploration missions in the near future are becoming active these days. Most of these studies require lunar soil simulant to investigate influences of lunar environment and to find the best solution for designing systems to be operated on lunar surface. The lunar soil simulants, such as MLS-1, JSC-1, and FJS-1 have been developed and used for these purposes up to this point, but they are almost out of stock now.

The FJS-1 was developed in Japan in 1995. This material was produced by crushing basaltic lava obtained from Mt. Fuji area, and well simulates bulk mechanical properties and approximates chemical composition of Apollo samples in lunar mare region. However, it contains very small amount of glasses, which may affect the chemical behaviors in ISRU processes. In addition to this, our next mission to the Moon could be performed in or near lunar highland region. Under these circumstances, we decided to develop new simulants.

Goals: Goals of our new simulants are as follows;
1. The simulants meet the regional needs, not only simulating mare soils but also highland soils.
2. The simulants are used for various purposes, not only mechanical studies but also chemical process studies.
3. The simulants are used internationally as one of the standard simulants.
4. The simulants are quickly supplied to investigators with reasonable amount and price.

Criteria for the Selection of Raw Materials: The most important process of developing simulants is the selection of raw materials. In this process, we put following criteria.
1. The materials, which approximate bulk chemical composition of lunar mare or highland soils. These materials are used as base (root) material of the simulants.
2. The materials, which contain pure minerals. They are used as additives of the simulants.
3. The materials, which are available to produce enough amounts of simulants.

Selected Raw Materials: Various possible materials were surveyed, and some of the samples were evaluated by fluorescent X-ray spectrometer analyses followed by the FeO determination (ISO 9035) tests, EPMA modal analyses, and particle density tests. So far, we have selected following materials as possible raw materials of new simulants.

As base materials:
- Bytownite (Minnesota)
- Albite (Norway)
- Labradorite (Madagascar)
- Anorthosite (Stillwater complex)
- Basalt (Hawaii)
- Basalt (Izu-Oshima, Japan)
- FJS-1 (Basalt / Mt. Fuji, Japan)
- Gabbro (Kohyama, Yamaguchi, Japan)
- Bytownite (Mexico)

As additives:
- Forsterite (Arizona)
- Forsterite (South California)
- Forsterite (Horoman, Hokkaido, Japan)
- Forsterite (Pakistan)
- Bronzite (California)
- Enstatite (Norway)
- Ilmenite (Australia)

Some of the samples are shown in Figure-1.
Evaluation of Raw Materials: The selected raw materials were further evaluated by comparing chemical contents of SiO$_2$, TiO$_2$, Al$_2$O$_3$, MgO, CaO, Na$_2$O, and K$_2$O in the raw materials with those in Apollo samples. The factor R was calculated as a deviation of the material from Apollo samples [1]. The smaller R indicates better simulation.

\[ R = \sqrt{\frac{\sum_{i=1}^{7} (Li - Ci)^2}{7}} \]

where, Li: Content of #i component in the Apollo sample, Ci: Content of #i component in a raw material.

Recommended Raw Materials: If a single material represents the simulant, following materials were recommended based on the factor R.

Apollo-11: Basalt (Hawaii), R=4.705
Apollo-12: Basalt (Hawaii), R=2.826
Apollo-14: Anorthosite (Stillwater), R=1.951
Apollo-15: Anorthosite (Stillwater), R=2.907
Apollo-16: Bytownite (Minnesota), R=3.941
Apollo-17: Gabbro (Kohyama), R=3.400

If the simulant is produced by mixing different raw materials, a better simulant can be obtained from the viewpoint of chemical compositions as shown in Table-1.

Table-1: Recommended Mixture of Raw Materials

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Mix Proportion (%)</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo-11</td>
<td>1 18 81</td>
<td>1.336</td>
</tr>
<tr>
<td>Apollo-12</td>
<td>10 81</td>
<td>1.591</td>
</tr>
<tr>
<td>Apollo-14</td>
<td>5 76 19</td>
<td>0.737</td>
</tr>
<tr>
<td>Apollo-14</td>
<td>9 6 85</td>
<td>1.220</td>
</tr>
<tr>
<td>Apollo-16</td>
<td>87 5 8</td>
<td>2.728</td>
</tr>
<tr>
<td>Apollo-17</td>
<td>4 12 84</td>
<td>1.616</td>
</tr>
</tbody>
</table>

Future Works: New lunar soil simulants are now being produced from the raw materials obtained in this study. Simulating properties in the first stage will be the same as the FJS-1, i.e. bulk mechanical properties such as density, particle size distribution, and shearing strength. In the next stage, we will try to simulate agglutinates and grain level properties.

Conclusions: An analytical study on the raw materials for the new lunar soil simulant was conducted, and possible materials were selected on the basis of chemical compositions and modal abundances. The bulk mechanical model will be available soon, while the agglutinate models will be developed in the next year.