

Material Inspectability Assessment Related to Lunar Construction Technology Development

Eric Z. Tucker
Langley Research Center, Hampton, Virginia

Joseph N. Zalameda
Langley Research Center, Hampton, Virginia

William C. Wilson
Langley Research Center, Hampton, Virginia

Peter L. Takunju
Langley Research Center, Hampton, Virginia

Michael R. Fiske
Marshall Space Flight Center, Huntsville, Alabama

Reza Zoughi
Iowa State University, Ames, Iowa

Vy Pham
Iowa State University, Ames, Iowa

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

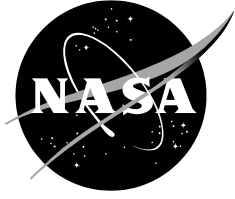
- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- Help desk contact information: <https://www.sti.nasa.gov/sti-contact-form/> and select the "General" help request type.



Material Inspectability Assessment Related to Lunar Construction Technology Development

Eric Z. Tucker
Langley Research Center, Hampton, Virginia

Joseph N. Zalameda
Langley Research Center, Hampton, Virginia

William C. Wilson
Langley Research Center, Hampton, Virginia

Peter L. Takunju
Langley Research Center, Hampton, Virginia

Michael R. Fiske
Marshall Space Flight Center, Huntsville, Alabama

Reza Zoughi
Iowa State University, Ames, Iowa

Vy Pham
Iowa State University, Ames, Iowa

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

July 2024

The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Available from:

NASA STI Program / Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

Acronym List

TM	technical memorandum
ISRU	in-situ resource utilization
NDE	nondestructive evaluation
X-ray CT	x-ray computed tomography
SWaP	size, weight, and power
3-D	3-dimensional
THz	terahertz
PCA	principal component analysis
SNR	signal-to-noise ratio
fs	femtosecond
2-D	2-dimensional
SAR	synthetic aperture radar
SIRIUS	Structural Integrity Inspection and Visualization System
SBIR	Small Business Innovation Research
TPS	thermal protection system

Abstract

For the building of lunar structures on the Moon using lunar regolith-based construction materials, ensuring their structural integrity and employing methods optimal for such tasks is crucial. In this technical memorandum (TM) the detectability of simulated void defects in a cementitious-based lunar construction material is compared between different nondestructive evaluation (NDE) methods, especially methods which have potential to be developed into space qualified instruments. Primarily, simulated voids, introduced during fabrication as foam spheres, were used for this evaluation. Furthermore, smaller, unintended void defects were used to assess the detectability. The results highlights trade-offs between the NDE methods in terms of detection limit, correct size indication, penetration depth, and potential for reduction in size, weight, and power (SWaP).

1. INTRODUCTION

In-situ resource utilization (ISRU) can have a significant impact on constructing various structures to support efforts to sustain a planned, long-term human presence on the moon and other planetary bodies.[1,2] As much as possible, construction technologies are being developed to utilize the regolith present on such planetary bodies and to minimize the amount of material that needs to be launched from Earth to these locations.

First, since actual lunar regolith is of limited supply here on earth, extensive efforts have been undertaken to develop lunar regolith simulants, which normally have been used to help develop these construction technologies.[2,3] Among the lunar simulants that have been developed, LHS-1 is one type which was designed to simulate lunar highlands regolith.[4] OB1-A is another lunar simulant intended to simulate the physical-mechanical properties of the lunar highlands regolith, which consists of a mixture of Shawmere anorthosite and fayalitic olivine slag glass.[5] However, neither of these simulants, or any other simulants, are available in large quantities, making characterization difficult.

Prior reports have demonstrated various technologies to consolidate different lunar simulants into materials that can potentially be used for various non-terrestrial structures and construction applications.[1,2,4] Different processes and types of construction materials may be needed to satisfy the requirements of different applications, but also the extreme conditions of the lunar environment and other planetary body environments need to be considered.[2] One such lunar construction material processes involves sintering, which is the fusion of solid powder material upon heating where the material is bonded but not fully melted.[1,3] One advantage of this type of process is only heat is required and no additional material needs to be added, like binders. Various heat sources can be utilized and have been proposed to sinter lunar regolith such as solar concentrators, lasers, microwave sources, resistive heaters, etc.[6]

Another such lunar construction material process involves producing lunar regolith cements, and concretes made from them, with regolith as the aggregate.[2,7,8] The composition of lunar regolith has been found to be relatively similar to various types of terrestrial cement materials, especially terrestrial fly ash, so much effort has been concentrated towards developing cementitious construction processes using lunar regolith.[2,8,9] However, the reduced pressure and extreme temperatures swings on the Moon complicate utilization of conventional, water-based processes to make concrete from lunar regolith. It is expected that a reduced pressure environment will lead to more porosity and lower strength construction materials. For example, it was previously found that when testing a calcium sulfo-aluminate binder and lunar simulant mixture in a water-based process at reduced pressures, lower strength construction materials

were produced.[7] Still, cementitious processes designed to operate in a vacuum environment and concretes with waterless binders (sulfur, for example), are being developed to mitigate this issue.[9,10] Even though much of the cementitious material can be made from unprocessed regolith, it is advantageous to have the capability to extract the other necessary materials from lunar regolith, especially the binder for these cementitious-based construction methods, or these materials need to be brought from Earth, so work is ongoing to develop these additional ISRU processes as well. Work is also ongoing to develop other binders, geopolymers, and deployable environmental enclosures to control the pressure exerted during the material formation process. Successful deployment of a cementitious-based process will depend on the development of these ISRU processes and materials.

Since the nondestructive evaluation (NDE) of these lunar construction materials will be critical for gaining insight into the strength of these materials by identifying the amount and types of defects present, in this work we explore the inspectability of cementitious-based lunar construction materials by various NDE methods. Specifically, the aim of this work was to evaluate how well various NDE methods were able to detect void defects in a cementitious-based lunar construction material compared to X-ray computed tomography (X-ray CT) as a baseline, but also discuss the potential advantages of the technologies to have relatively lower size, weight, and power (SWaP) requirements for eventual deployment in a lunar environment. X-ray CT was utilized for the baseline measurements for comparison to the other methods because it has a resolution and sensitivity which can provide for accurate pore dimensions and locations. Further, for concrete samples, X-ray CT has been developed to a point where it is considered a widespread, routine analysis method for these materials, which is not as much the case with the other methods in this work.[11]

2. MATERIALS AND METHODS

Two cementitious samples were created with intentional, simulated voids to test the inspectability of cementitious-based lunar construction material by various NDE methods. These cementitious samples were made by mixing 30% calcium sulfo-aluminate binder and 70% Deltion OB1-A Lunar highlands simulant, then adding water. The samples were cast into a 4" x 4" x 14" mold to form a sample of the same dimensions. Round foam inserts of specific sizes were inserted into the mold during fabrication to make specific sized simulated voids where Fig. 1 shows a schematic of the diameters and intended locations from the side of the sample labeled "top". These sized simulated voids were chosen for this analysis because their sizes facilitated easier distinction from the numerous, smaller unintentional voids, which enabled a clearer comparison of void detectability for the different methods. The final weight of both samples was approximately 17 lbs. Fig. 2 shows photographs of the two samples (sample A and B). Unfortunately, sample B fractured along the position of the voids, so was of limited use. Sample A did not fracture and was used for all the measurements described in this report. For consistency, most measurements were performed from the "top" surface of the sample, but other orientations were measured as indicated.

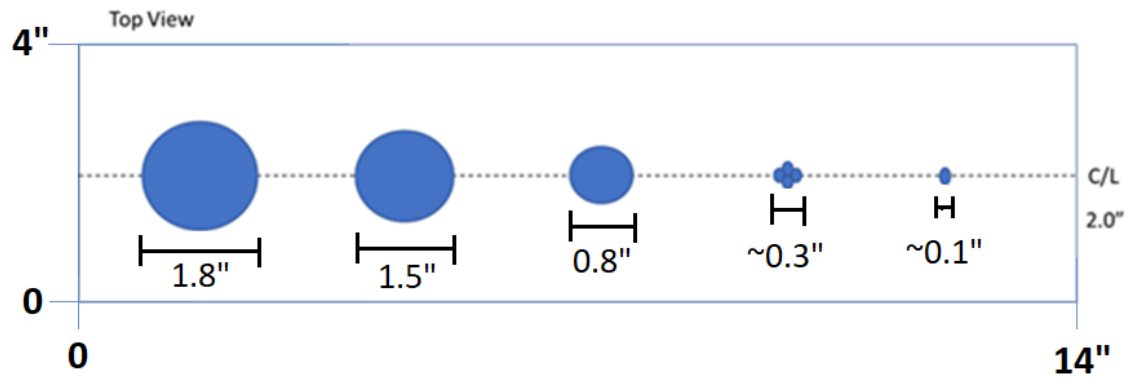


Figure 1. Schematic showing the intended location and diameter of the voids in both cementitious samples from the "top" side of the samples. Dimensions in units of inches are shown.

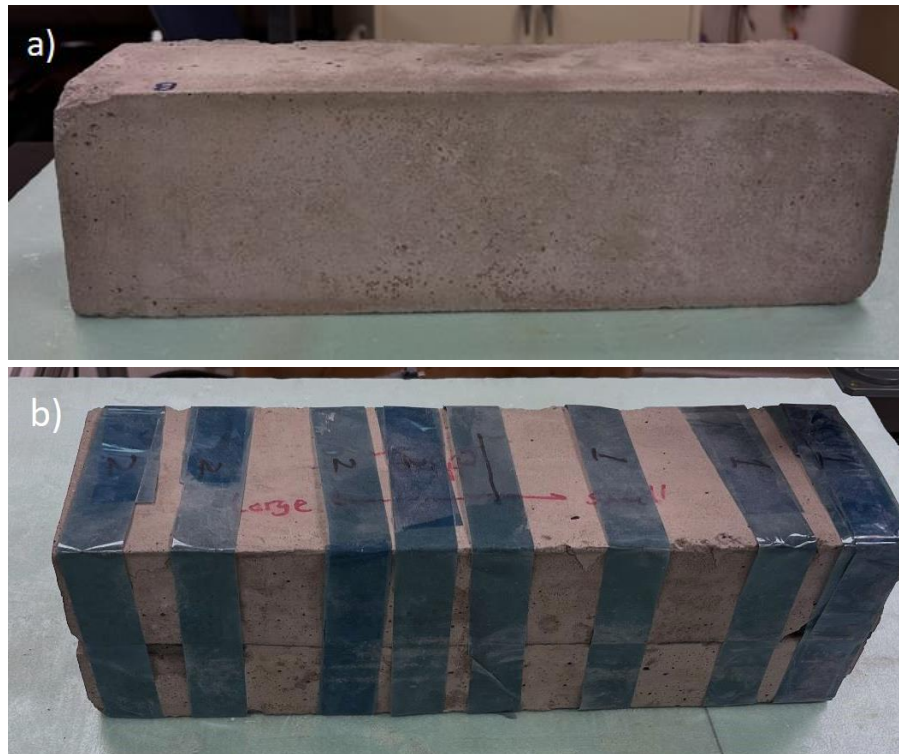


Figure 2. Photograph of (a) sample A, which is the cementitious sample that did not fracture and was the primary focus of this work and (b) sample B, which fractured, and was of limited use for this work. Tape was used to hold the two fractured pieces together.

X-ray CT measurements of sample A were done using a model HMXST225 Micro-CT system (X-Tek LLC) at 200 kV and 180 μA ^a. Voxel sizes were approximately 82 μm . Fig. 3 shows two slices from a 3-dimensional (3-D) X-ray CT data volume for this sample showing four voids. The orientation of the sample in both images in Fig. 3 is the same as how the sample was measured with the other inspection methods, which was from the “top” surface of the sample, except where indicated. The voids labeled #1-3 in Fig. 3(a) correspond to the largest three intentional voids that were placed within the sample, which was confirmed by determining the size and location of the voids from the images. However, the data showed that these voids deviated from their intended positions, which was due to difficulties placing the foam inserts in their intended positions and the inserts likely migrating around the sample prior to the mixture being fully cured. Fig. 3(b) shows another relatively larger void, void #4, along with the same three largest voids from Fig. 3(a). An additional void of similar size, void #5, was also detected at a different depth (bottom left image of Fig. 8). The size and location of void #4 and #5 does not match what was expected for any of the intentional voids, so the origin of those voids is unclear. Further, the status and location of the two smallest intentional voids that were placed within the sample is unclear. Regardless, Table 1 shows the diameter of the five largest voids detected. From the images the depth of the voids from the “top” surface of the sample could also be determined, which is also shown in Table 1. Here, the separation between voids along the long axis of the sample were determined as well to help in verifying the identity of features in the other inspection method images. Briefly, void #1 (the largest void seen in Fig. 3) is approximately 3.15 in. from void #2 (next largest void) while void #2 is roughly 2.30 in. from void #3 (3rd largest void). Void #4 is at nearly the same position along the long axis of the sample as void #3. As mentioned above, the intention was to utilize the X-ray CT measurements as a baseline from which to explore how well these defects could be detected using other novel NDE inspection methods.

^a Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the test hardware. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government nor does it imply that the specified equipment is the best available

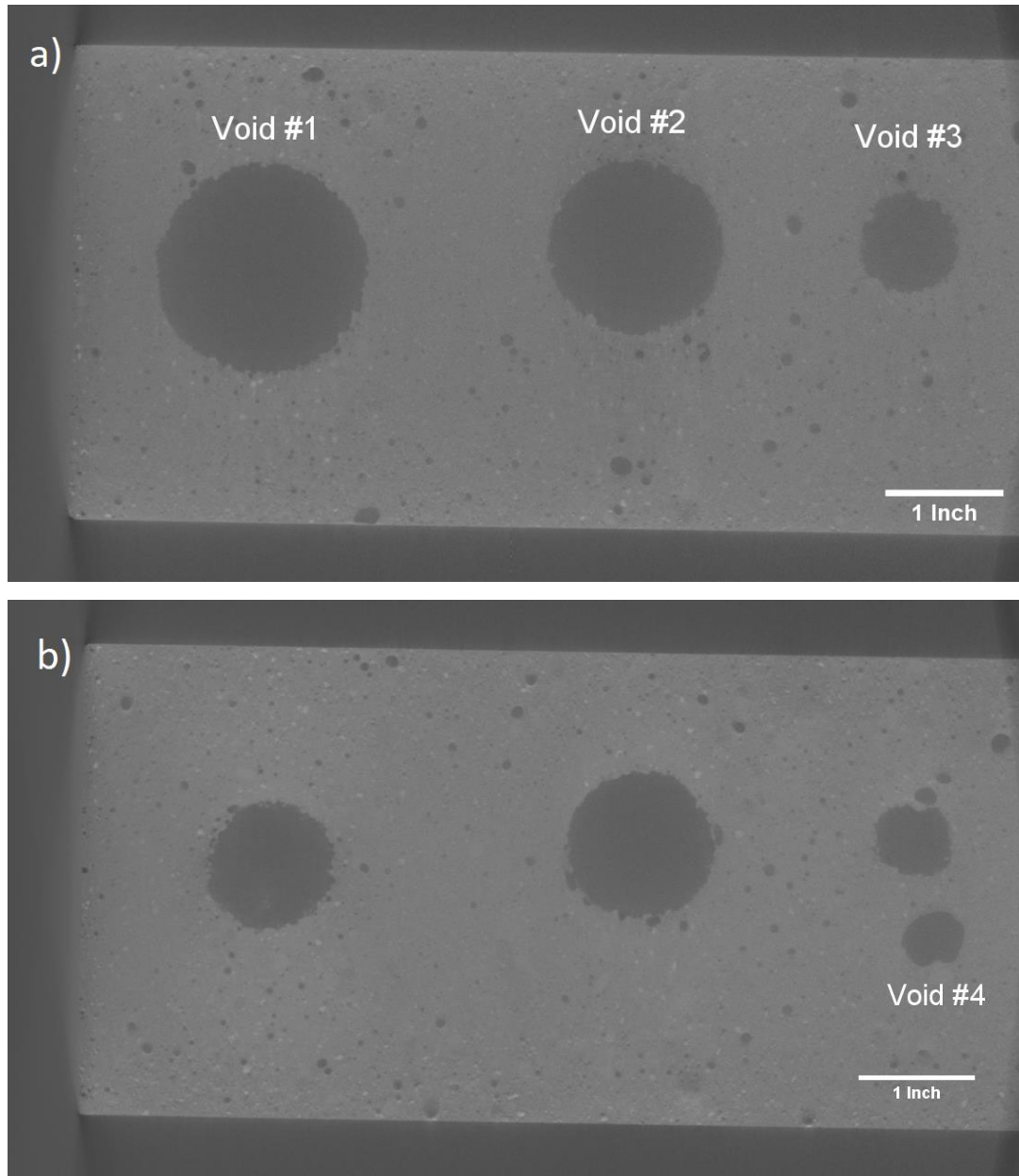


Figure 3. X-ray CT images of sample A at different depths from the “top” surface of sample showing (a) three of the largest intentional voids #'s 1-3 and (b) same three voids, along with void #4. (a) is a slice of the 3-D data volume at a depth of approximately 26.5 mm from the “top” surface of the sample while (b) is a slice at a depth of approximately 17 mm from that same surface.

Table 1. Table of depths from the “top” surface of the cementitious sample A to the top of various void defects, which was determined from X-ray CT. Also, shown is the measured diameter of the voids.

Defect	Measured Depth (mm)	Measured Diameter (Inches)
Void #1	11	1.8
Void #2	8	1.5
Void #3	13.5	0.8
Void #4	12.5	0.45-0.5
Void #5	2.5	0.45-0.5

In this study various novel NDE methods were utilized and compared against the X-ray CT baseline measurements, especially methods with potential to be developed into systems that could be operated in a lunar setting, including backscatter x-ray imaging, terahertz (THz) imaging, microwave imaging, and single-sided thermography.

Single-sided thermography inspection was employed to measure defects using the setup shown in the picture in Fig. 4. Defects are detected due to obstruction of the heat flow, which is monitored by an infrared camera. Here, two quartz heat lamps, 1000 watts each, were positioned on the same side as an infrared camera. To perform the thermal inspection, the quartz lamps heated the sample surface by illumination for roughly 70 seconds. Upon exposure with these sources, the surface temperature increased to approximately 65 °C. The rate of cool down and thermal response is measured after the quartz lamps are turned off using an infrared camera operating in the 3-5 micron mid-wave infrared band. The frame rate was 60 Hz and 88,922 frames were acquired for a total inspection time of 1,482 seconds. The thermal inspection image was produced by using a principal component analysis (PCA) technique.[12] This algorithm is based on decomposition of the thermal data into its principal components or eigenvectors. Singular value decomposition is a routine used to find the singular values and corresponding eigenvectors of a matrix. Since thermal NDE signals are slowly decaying waveforms, the predominant variations of the entire data set are usually contained in the first several eigenvectors, and thus account for most of the data variance of interest. A time window processing scheme was used for calculating the final inspection image where the thermal images corresponding to 417-750 seconds were used. The first eigenvector was selected for calculating the final inspection image.

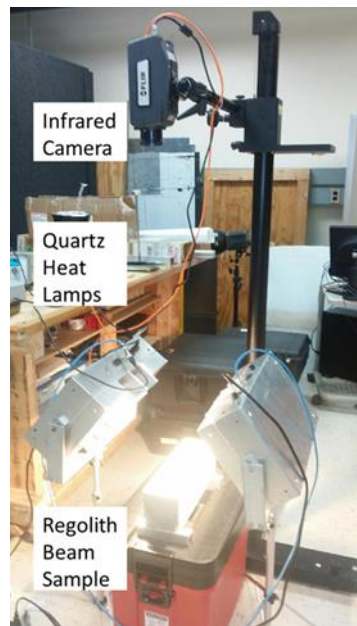


Figure 4. Photograph of the single-sided thermal inspection setup with quartz lamp heaters and infrared camera positioned on the same side.

The T-ray 5210 THz imaging system (Luna Innovation) is a time-domain, pulsed THz imaging system that illuminates a sample with THz radiation primarily between 0.05 to 4 THz, although the detector has optimal signal-to-noise ratios (SNR) up to 1 THz.[13,14] The diagram in Fig. 5 show the important parts of this system that allow for the generation and detection of THz radiation. The THz radiation is generated and detected using a pulsed laser having an 80 MHz repetition rate and 100 femtosecond (fs) pulse width. More specifically, THz radiation is produced by applying an electrical bias across a small antenna and exciting it with the laser, which causes the antenna to conduct and generate THz radiation having a pulse width of 200-300 fs. Detection is done with a similar device having a small antenna that becomes conductive when excited with the laser pulse. When THz radiation impinges upon this device, a small transient current is generated, which is proportional to the amount of incoming THz radiation. In this work the instrument was operated in reflection mode where the data can be displayed as A, B, and C-scan images, similar to ultrasound inspection. For example, the time-domain signals could be converted to 2-dimensional (2-D) images sensitive to certain depths into the sample. Previously, similar THz systems have been used to detect voids and bonding quality in a variety of materials and systems, including spray on foam insulation, insulating tiles on space vehicles, and radomes.[13,15]

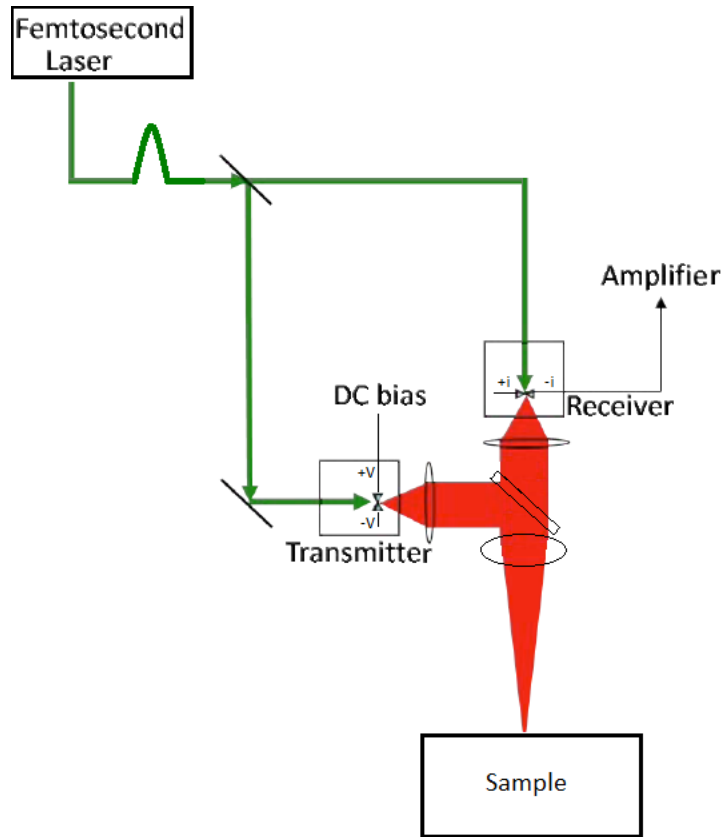


Figure 5. Schematic showing key components of the commercial THz system.

Initial NDE microwave band images were collected using a microwave imaging system that operates in the Ka-band (26.5-40 GHz), which is described in detail in previous work.[16] Briefly, in this multistatic setup, arrays of open-ended waveguide antennas irradiate the sample in the near-field and another set of arrays receive the scattered radiation from the same side of the sample. Once the sample is scanned, this data is processed via a synthetic aperture radar (SAR) algorithm to obtain sub-wavelength resolution, 3-D images of nonconductive materials. Later, similar measurements at two bands of lower frequencies, Ku (12.4-18 GHz) and X-band (8.2-12.4 GHz), were performed with a bistatic setup of two open-ended waveguide probes (Fig. 6). Here, the separation between the waveguides was roughly 44.6 mm. As with the multistatic Ka-band system, a SAR algorithm is used to generate sub-wavelength resolution 3-D images at these frequency bands as well. The depth resolution was ~16 mm at X-band (8.42-12.4 GHz) and ~12 mm at Ku-band (12.4-18 GHz).

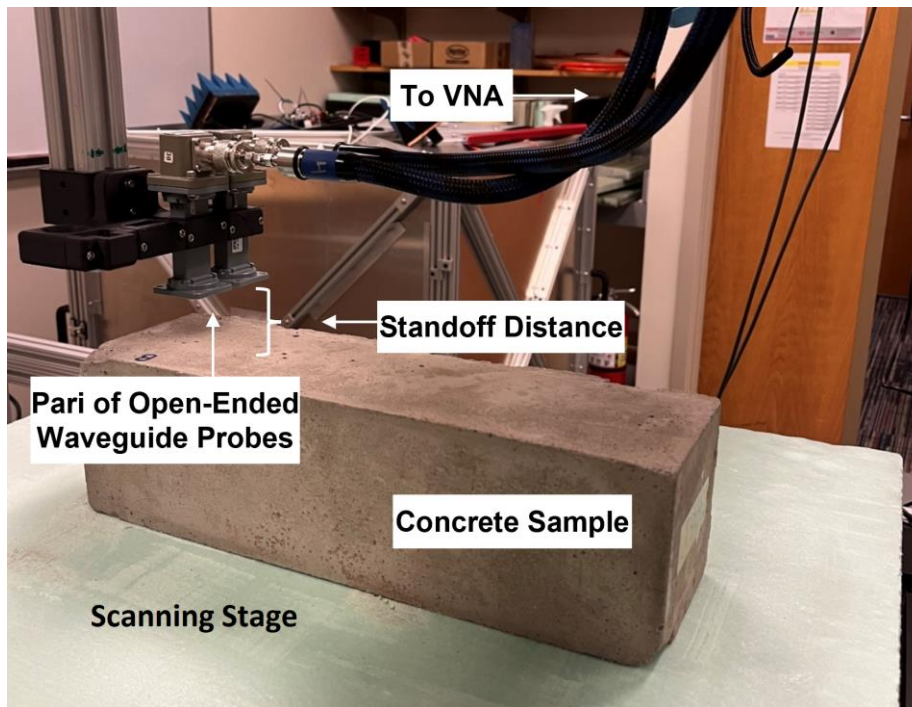


Figure 6. Photograph of lower frequency microwave imaging setup showing bistatic configuration and a pair of open-ended waveguides.

The Structural Integrity Inspection and Visualization System (SIRIUS) backscatter x-ray system (Physical Optics Corporation) is a single-sided benchtop system, which was obtained from an Small Business Innovation Research (SBIR) program phase II project and measures Compton scattering of x-rays from samples to generate images similar to what is observed with X-ray CT.[17,18] The instrument is described in more detail elsewhere.[17] Briefly, a series of 2-D images of the sample are collected, each being a 45° cross section of the sample, which forms the basis of a 3-D reconstructed image of the object. The source-detector assembly moves beneath the sample under test, with highly collimated fan-beam X-rays emanating from the source at 45° and backscattered X-rays detected by the detector. Consecutive slices of the sample are interrogated, and the scan results sent to the computer for volumetric (3-D) reconstruction of the interior of the sample. This instrument has a smaller footprint compared to conventional X-ray CT instruments and has a spatial resolution of 1 mm^3 . Previously, this instrument has been used to examine thermal protection system (TPS) ceramic, composite materials, and other space craft materials and structures. In previous measurements of TPS layers, simulated micrometeoroid damage was easily observed.[19]

During the measurement of the cementitious sample, sample A, using the backscatter system the “top” surface was oriented so it was facing towards the source, consistent with how it was oriented with the other methods. The sample was too large to be scanned in one set of images as the source is only capable to scan a limited area of the sample, so the sample had to be repositioned several different ways to image the whole sample. The photograph in Fig. 7 shows how the sample was oriented on the instrument when scanning one region.



Figure 7. Photograph of sample A being oriented on the backscatter x-ray system.

3. INSPECTION RESULTS OF CEMENTITIOUS SAMPLE

3.1 Thermography:

Initially, cementitious sample A was measured using the single-side pulsed thermography setup described above. Fig. 8(a) is a photograph of the side of the sample measured for reference, which was the “top” surface of the sample, while the Fig. 8(b) is the PCA processed thermal inspection image, which was produced following the details mentioned in the previous section. Here, the same three largest voids that were observed in both X-ray CT images above (Fig. 3) can be seen, which are shown with black arrow annotations in the figure. From the same orientation of the sample compared to how it was measured here, the depths as well as the sizes from X-ray CT (Table 1) are consistent with the intensity differences of these features in the thermography results. For example, void #2 is located at a shallower depth and has greater signal intensity as compared to the other voids as shown in Fig. 8. Void #2 appears larger due to in-plane heat flow given the time window selected for processing.

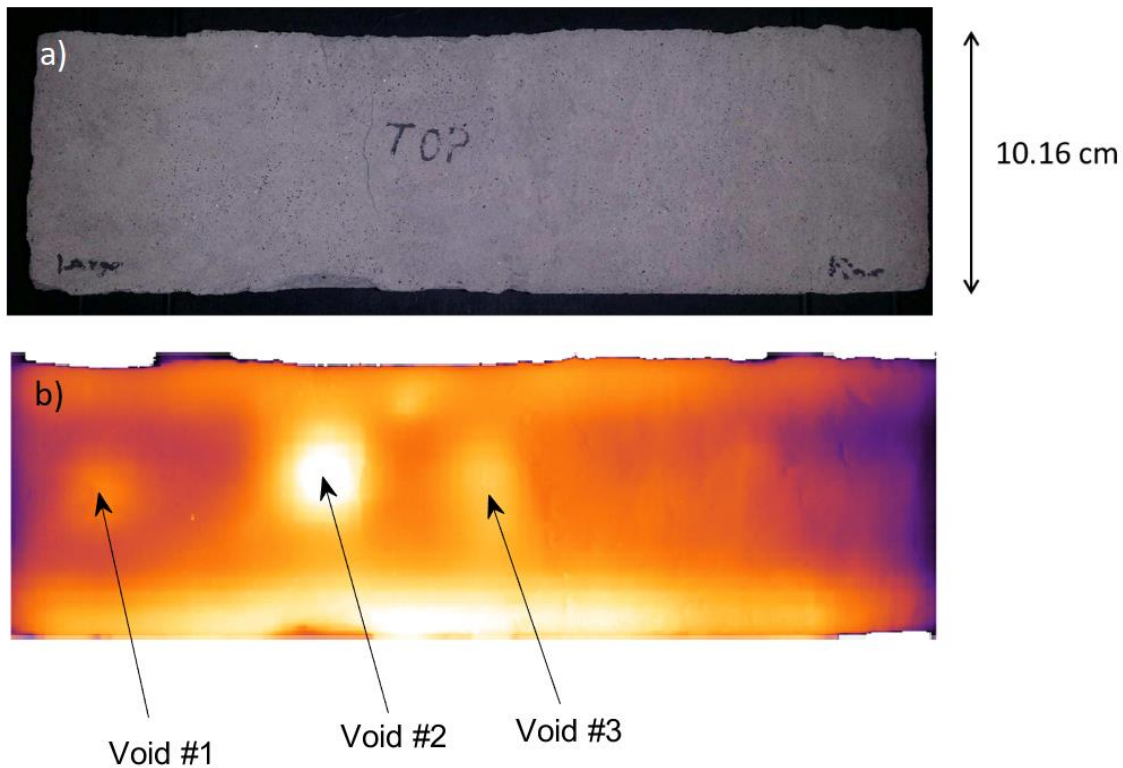


Figure 8. PCA processed thermal inspection image (bottom) from the same orientation as the photograph of the sample (top) with arrows pointing to the locations of the 3 largest voids.

Additional voids are also observed in the single-sided thermography results (Fig. 8(b) and top image in Fig. 9). The signal around the location corresponding to void #3 is non-circular in shape and elongated which, according to the X-ray CT results (bottom of Fig. 3 and bottom right of Fig. 9), is partly due to another smaller void defect, void #4, that is located below void #3 in these images. The thermography results show another defect towards the top of the of the image, which was confirmed to be void #5 from the X-ray CT results with a depth of approximately 2.5 mm (bottom left of Fig. 9). The diameters of void #4 and #5 have similar values of roughly 0.45-0.5 in., which does not match the size of any of the remaining intentional, simulated voids, so it is unclear where either void originated from.

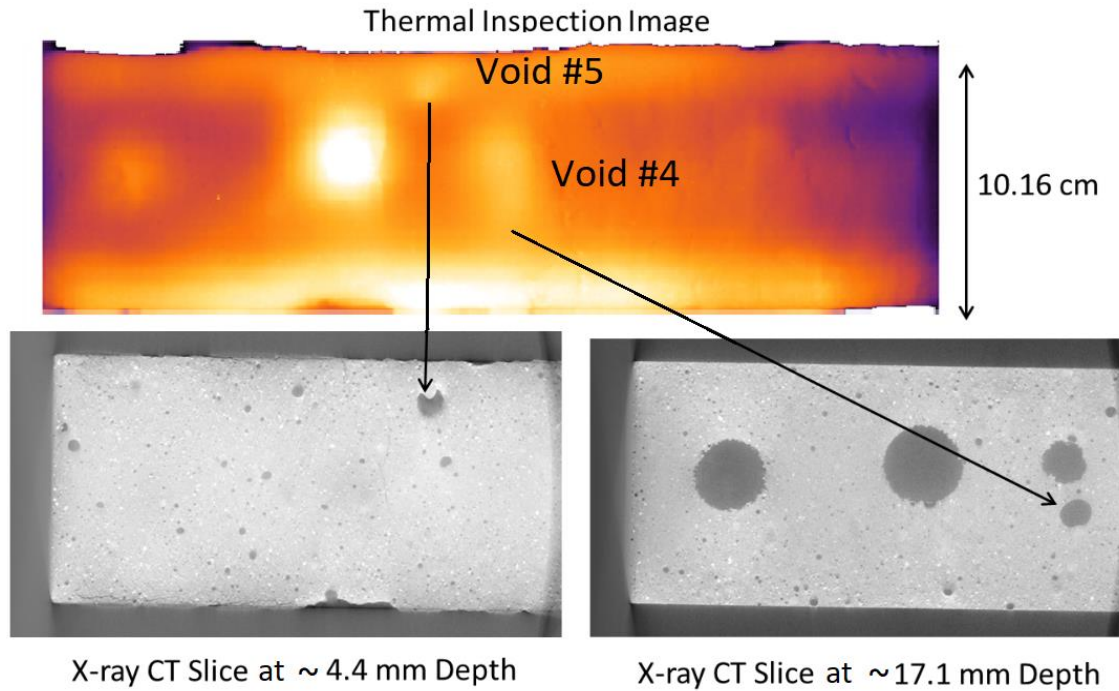


Figure 9. Comparison of the same PCA processed thermal inspection image (top) from Fig. 8(b) to X-ray CT images showing void #'s 4 and 5.

Lastly, there also appears to be a defect along the bottom of the thermal inspection image. This defect is confirmed by X-ray CT to be a near surface crack propagating along the edge as shown in the two bottom images in Fig. 10, which have the same sample orientation as the thermography image. The orientation of the crack is approximately 45 degrees to the edge (shown in the top right X-ray CT image of Fig. 10, which is an image slice showing a different perspective of the sample and crack compared to the other image slices). The crack along the edge is sufficient to block heat flow and appears to be wider in the thermal inspection image compared to the X-ray CT images, which is due to the in-plane heat flow and time window used to process the thermal data.

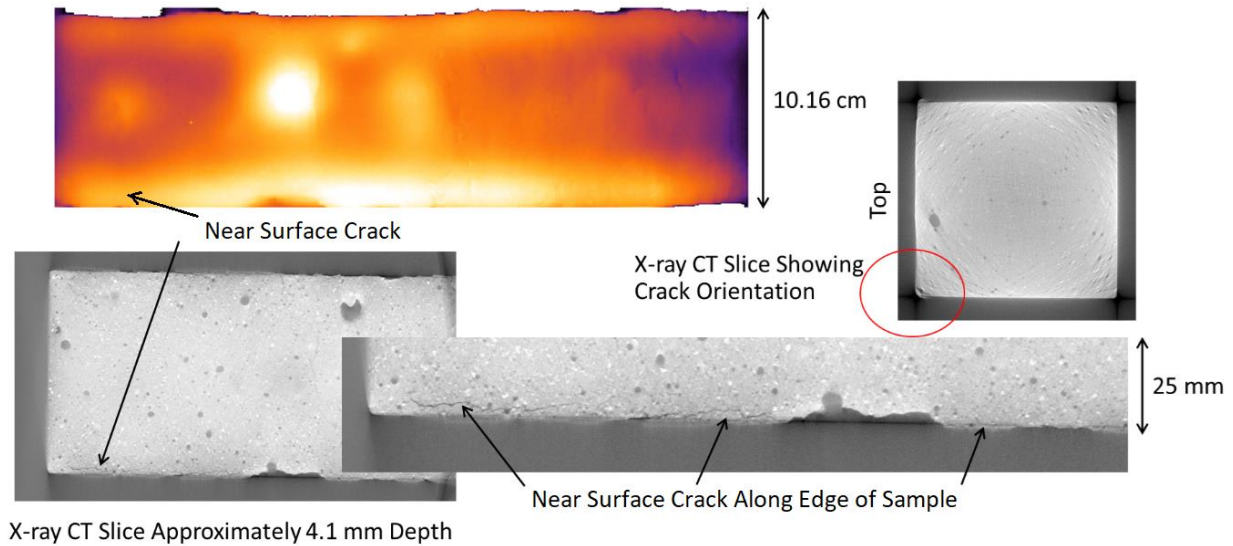


Figure 10. Comparison of thermal inspection to X-ray CT results for cementitious sample A where a near surface crack highlighted. Here, the bottom X-ray CT images are of the sample in the same orientation as how the thermography results were obtained while the right X-ray CT image is with the sample in a different orientation to show the angle of the crack.

The thermography results show that void defects (#1- 5) were detectable as well as a near surface crack. The smallest and deepest void defect detected was void #4, which had a diameter of approximately 11.4-12.7 mm (0.45-0.5 in.) and was located at a depth of approximately 12.5 mm (0.49 in.). As expected, the intensity of the features in the image relate to their depth and size. Therefore, the other numerous smaller voids seen in the X-ray CT images are not visible in the thermography results due to their size and depth. A near surface crack oriented at approximately 45 degrees relative to the input heat flux was detectable using thermography. The results suggests that this method would provide more optimal results for detecting smaller voids in thinner version of this sample or in cases where it was desirable to detect smaller, near-surface voids or cracks. The surface of the cementitious sample appeared to have good emissivity and therefore no emissivity enhancing coating was required. A possible drawback of using thermography as an inspection technique for this application is the long data acquisition time required to detect deeper defects, which is due to the low thermal diffusivity of the regolith. This drawback can potentially be overcome by inspection during the build process as the layers are deposited especially in cases where heat treatments are already being employed. As an in-situ inspection method, during the additive build process, thermography could potentially be an effective technique to detect defects and perform corrective actions during the build process.

3.2 Microwave and Other Electromagnetic-based NDE:

Next, various electromagnetic imaging techniques with frequencies ranging from the THz to microwave were tested to see what frequency imaging methods can penetrate and successfully image defects in this type of construction material. Initial efforts to explore the use of various electromagnetic imaging for measuring cementitious-based samples showed that the previously described THz and microwave imaging systems, the latter operating in the Ka-band (26.5-40

GHz), could not image through these materials (not shown here), which was attributed to absorption of the higher frequency radiation by binder and/or water in the material.

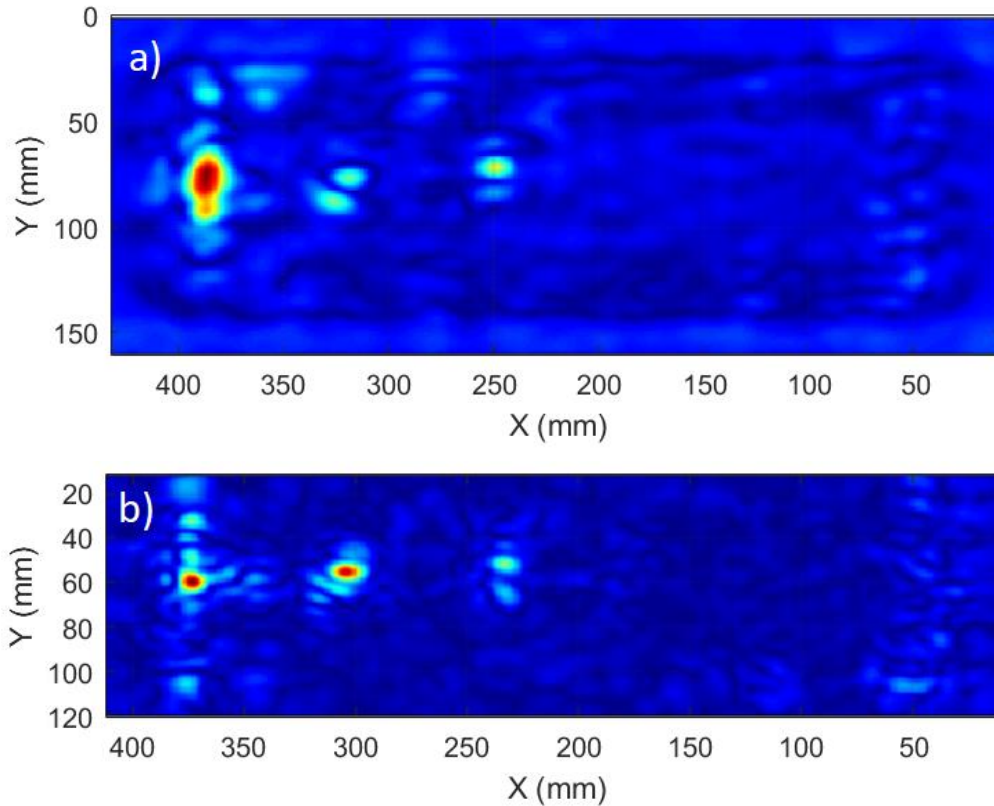


Figure 11. Microwave Inspection images showing representative SAR processed microwave data of cementitious-based sample A captured using a bistatic measurement setup at (a) X-band (8.2-12.4 GHz) frequencies at roughly 42.5 mm (1.67 in.) in depth and (b) Ku-band (12.4-18 GHz) frequencies at roughly 47.5 mm (1.87 in.) in depth. The sample was oriented with the side labeled “top” facing up as in the thermography and bottom x-ray CT image in Fig. 3.

However, similar microwave frequency measurements were performed compared to the microwave imaging system, but at lower frequencies, namely; X-band (8.2-12.4 GHz) and Ku-band (12.4-18 GHz) using a bistatic waveguide setup, which was able to image through the cementitious sample and detect voids. Fig. 11 shows two images of the cementitious sample using the two different bands of lower frequencies where the “top” side of the sample was measured, which is the same orientation as was used for the thermography measurements and consistent with the X-ray CT images in Fig. 3. Here, three voids could be observed, similar to what was seen by single-sided thermography and X-ray CT. Indeed, the distances and location between the voids is consistent with what was obtained by X-ray CT, confirming that the same three largest voids were detected. The depth resolution was not sufficient to determine the different depths of the voids, but these results show that lower microwave frequency-based inspection can image through the material and detect voids. The SNR in the images is stronger than the thermography NDE results. However, the in-plane size of the voids indicated in the image in Fig. 11 is much smaller than the actual size and is the direct result of the bi-static measurement approach. While the images do not directly provide accurate size dimensions, the scanned data may be further processed (if needed) to achieve a closer size indication based on intensity changes due to the presence of the voids. Therefore, this technology is suitable for

applications where void detection is needed and rough size information is adequate. Also, compared to many other methods, microwave imaging methods based on SAR algorithms have a strong potential for lower SWaP. Further, the radiated power is at a safe enough level for operation around humans (this system uses probe with directive pattern and power in the few mW range), which will be more of a concern with the inspection methods utilizing x-ray sources.

3.3 3-D Backscatter X-ray Imaging:

Lastly, 3-D backscatter x-ray imaging was performed on sample A where, as with the other imaging methods, the goal was to attempt to see whether this technology can successfully image voids and other defects in these types of construction materials. Fig. 12 shows a set of 2-D slices from the 3-D backscatter x-ray data of sample A at different depths and scanning positions. In this perspective provided by these 2-D images the source is perpendicular to the image plane. In these images voids matching the sizes and locations of void #1-5 from X-ray CT were detected as indicated, similar to the thermography results. However, many additional, smaller voids were detected with sizes down to roughly 0.15 in. in diameter, which was smaller than what was captured by thermography and microwave imaging. Fig. 13 shows two 2-D slices from the 3-D backscatter x-ray data showing a different orthogonal perspective of the volumetric data sets compared to Fig. 12 and a different perspective of the sample's internal structure compared to the images from the other inspection methods. In this perspective, the source is in the direction towards the top of the image at a 45° angle, which explains the rhomboid shape of the image, and is useful for showing the penetration depth of this method. Here, voids #1-5 were detectable from this perspective as well. For example, in the image in Fig. 13(a) void #1 and #2 are visible while the image in Fig. 13(b) shows a portion of void #3. In addition, as in Fig. 12, smaller voids were detectable, which were also observed by X-ray CT, but not the other techniques. Still, the image resolution and SNR is lower than X-ray CT. Also, the perspective used to generate the images in Fig. 13 clearly show that the SNR decreases with depth of penetration of the x-ray beam from top to bottom in the images. This limitation in terms of penetration depth is in contrast to X-ray CT and shows that backscatter x-ray imaging is more limited in this aspect, but in this case voids as deep as approximately 2 in. are still detectable, beyond that point the SNR is diminished significantly. This limited penetration depth (depth of defect detection) is similar to the thermography results. Smaller voids of approximately 0.15 in. diameter can be observed near the top of Fig. 13(b), but would clearly be more difficult to detect deeper within the sample. Despite some of the more limited SNR, penetration depth, and resolution compared to X-ray CT, the benefit of the system is it has a much smaller SWaP.[17] Further, in contrast to the lower frequency microwave and thermography inspection results, more accurate size dimensions of the voids were obtained due to the better spatial resolution, although the SNR is lower compared to the microwave inspection results.

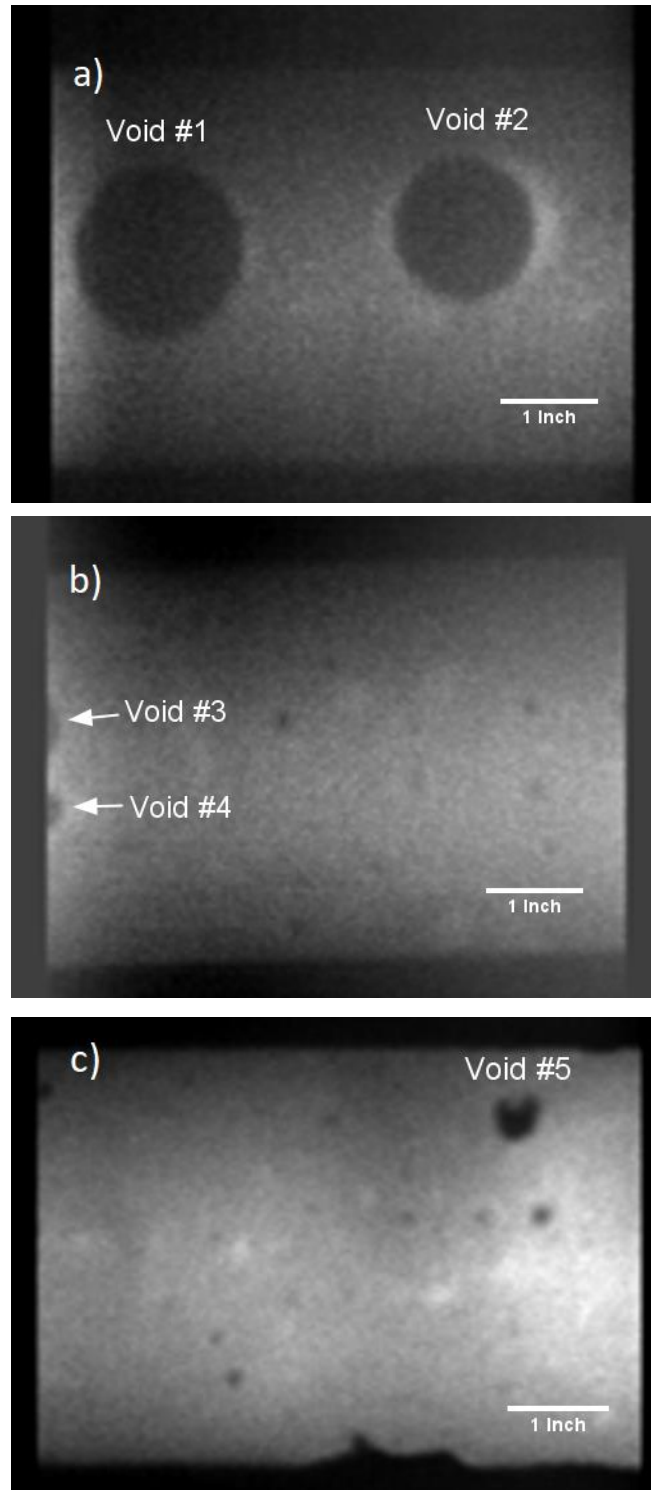


Figure 12. 2-D images from the 3-D backscatter x-ray data of the cementitious-based sample A with the sample oriented with the side labeled “top” facing up as in the thermography and microwave imaging results where (a) shows void #1-2, (b) shows void #3-4, and (c) shows void #5. Additional, smaller voids are visible in the images, which were only captured by the X-ray CT and no other NDE imaging method.

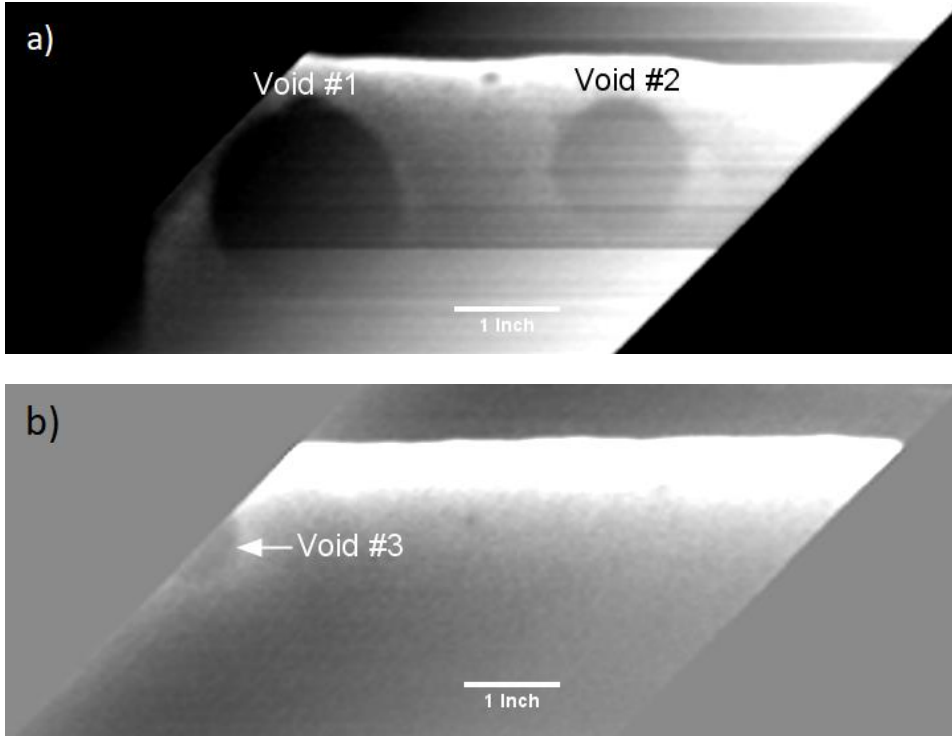


Figure 13. 2-D images from the 3-D backscatter x-ray data of the cementitious-based sample A with the sample oriented with the side labeled “top” facing up as in the thermography and microwave imaging results, but these images show orthogonally oriented slices of the 3-D volumetric data compared to Figure 12. Here, (a) shows void #1-2 while (b) shows void #3. Additional, smaller voids are visible in the images, which were only captured by the X-ray CT and no other NDE imaging method.

3.4 Comparison of detectability, depth of defect detection and accuracy in size indication:

Each method offers unique advantages and limitations in terms of penetration depth, detection limit, accuracy in size indication, and potential for a space-qualified instrument with an optimally low SWaP. Table 2 compares the detection limits for voids in the cementitious-based construction material (sample A) tested in this study, but it’s important to note that these limits are specific to the configurations used and may vary with different instrument setups. With a voxel size of 80 μm and a corresponding expected resolution of around the same magnitude, X-ray CT significantly surpasses these other methods in terms of detection limit.[11] The depth of defect detection for these methods was qualitatively shown to be different between each method, but it is difficult to assign quantitative values to define these differences more exactly with the data collected here. Similarly, it is difficult to quantify the accuracy in size indication

with this data and in some instances, like with the lower frequency-based microwave imaging, calibration can be done to provide for more accuracy than what was shown here.

Table 2. Table of approximate void detection limits from cementitious sample A for the various methods in this report.

NDE Methods	Void Detection Limit (in.)
Single-Sided Thermography	0.45-0.5
Lower Frequency Microwave Imaging	0.8
3-D Backscatter X-ray	0.15

4. CONCLUSION

These results show that a cementitious-based lunar simulant construction material can be inspected by thermography; backscatter x-ray; and X- and Ku-band microwave frequency imaging methods. More specifically, simulant voids down to diameter of roughly 0.8 in. could be detected in this type of construction material by all of these techniques as shown by the capture of the same three largest intentional voids identified by X-ray CT. In contrast, THz and higher frequency microwave inspection were not able to image through the sample to detect any voids. In the case of the single-sided thermography method, other defects and additional smaller voids could be detected. The smallest voids detected by this method were roughly 0.45 in. in diameter. Like the single-sided thermography method, backscatter x-ray imaging was limited in depth of sensitivity, but could image voids on the order of 0.1 in. in diameter near the surface, better in this aspect compared to all the other methods except X-ray CT. In addition, the backscatter x-ray measurements data capture the true size of the defects.

Future work could involve quantitative comparison of the backscatter x-ray images to X-ray CT images using advanced image analysis, such as with a segmentation based algorithm. Further, follow-up lower frequency microwave images will be done with the waveguide probe opening in closer proximity and a more optimized system for inspecting cementitious samples is being developed through a SBIR Phase I. Also, other types of construction materials, which are not cementitious-based, have been tested to a lesser extent with some of these inspection methods, but the inspectability of other varieties of cementitious-based lunar construction materials is of particular interest.

References:

- [1] P. Hintze, Building a vertical take off and landing pad using in situ materials, *Space Manufacturing* 14 (2010) 29–31.
- [2] Y.C. Toklu, P. Akpınar, Lunar soils, simulants and lunar construction materials: An overview, *Advances in Space Research* 70 (2022) 762–779. <https://doi.org/10.1016/j.asr.2022.05.017>.
- [3] S. Lim, V.L. Prabhu, M. Anand, L.A. Taylor, Extra-terrestrial construction processes—Advancements, opportunities and challenges, *Advances in Space Research* 60 (2017) 1413–1429. <https://doi.org/10.1016/j.asr.2017.06.038>.
- [4] M. Isachenkov, S. Chugunov, Z. Landsman, I. Akhatov, A. Metke, A. Tikhonov, I. Shishkovsky, Characterization of novel lunar highland and mare simulants for ISRU research applications, *Icarus* 376 (2022) 114873. <https://doi.org/10.1016/j.icarus.2021.114873>.

- [5] M.M. Battler, J.G. Spray, The Shawmere anorthosite and OB-1 as lunar highland regolith simulants, *Planetary and Space Science* 57 (2009) 2128–2131. <https://doi.org/doi.org/10.1016/j.pss.2009.09.003>.
- [6] L. Song, J. Xu, S. Fan, H. Tang, X. Li, J. Liu, X. Duan, Vacuum sintered lunar regolith simulant: Pore-forming and thermal conductivity, *Ceramics International* 45 (2019) 3627–3633. <https://doi.org/10.1016/j.ceramint.2018.11.023>.
- [7] R.G. Clinton, J.E. Edmunson, M.R. Effinger, C.C. Pickett, M.R. Fiske, J. Ballard, E. Jensen, M. Yashar, M. Morris, C. Ciardullo, NASA's Moon-to-Mars Planetary Autonomous Construction Technology Project: Overview and Status, in: 73rd International Astronautical Congress (IAC 2022), Paris, France, 2022.
- [8] A. Khitab, W. Anwar, I. Mehmood, S.M.S. Kazmi, M.J. Munir, Lunar concrete: Prospects and challenges, *Astronomy Reports* 60 (2016) 306–312. <https://doi.org/doi.org/10.1134/S1063772916020050>.
- [9] Z. Hu, T. Shi, M. Cen, J. Wang, X. Zhao, C. Zeng, Y. Zhou, Y. Fan, Y. Liu, Z. Zhao, Research progress on lunar and Martian concrete, *Construction and Building Materials* 343 (2022) 128117. <https://doi.org/doi.org/10.1016/j.conbuildmat.2022.128117>.
- [10] I. Giwa, M. Dempsey, J. Lamendola, A. Kazemian, M. Fiske, On the Development of Sulfur Concrete as an ISRU-Based Construction Material for Lunar Infrastructure Applications, in: ASCE Earth & Space 2024, Miami, FL, 2024.
- [11] A. du Plessis, W.P. Boshoff, A review of X-ray computed tomography of concrete and asphalt construction materials, *Construction and Building Materials* 199 (2019) 637–651. <https://doi.org/doi.org/10.1016/j.conbuildmat.2018.12.049>.
- [12] N. Rajic, Principal component thermography for flaw contrast enhancement and flaw depth characterisation in composite structures, *Composite Structures* 58 (2002) 521–528. [https://doi.org/doi.org/10.1016/S0263-8223\(02\)00161-7](https://doi.org/doi.org/10.1016/S0263-8223(02)00161-7).
- [13] J.M. Buckley, I. Duling, Practical NDE and QC applications of time domain terahertz technology, *E-Journal of Nondestructive Testing* 28 (2023). <https://doi.org/10.58286/28456>.
- [14] K. Fukunaga, I. Hosako, M. Palazzo, L. Dall'Aglia, F. Aramini, C. Cucci, M. Picollo, T. Ikari, I.N. Duling, Terahertz time-domain imaging of “The Last Supper,” in: 2020 45th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), IEEE, 2020: pp. 1–2. <https://doi.org/10.1109/IRMMW-THz46771.2020.9370630>.
- [15] D. Zimdars, J. Valdmantis, J.S. White, G. Stuk, S. Williamson, W.P. Winfree, E.I. Madaras, Technology and applications of terahertz imaging non-destructive examination: inspection of space shuttle sprayed on foam insulation, in: AIP Conference Proceedings, American Institute of Physics, 2005: pp. 570–577. <https://doi.org/doi.org/10.1063/1.1916726>.
- [16] M. Dvorsky, S.Y. Sim, D. Motes, T. Watt, A. Shah, M.T. Al Qaseer, R. Zoughi, Multi-Static Ka-Band (26.5-40 GHz) Millimeter Wave 3-D Imaging System, *IEEE Transactions on Instrumentation and Measurement* 72 (2023). <https://doi.org/10.1109/TIM.2023.3306535>.
- [17] E.R. Burke, V. Grubsky, V. Romanov, K. Shoemaker, NDE of spacecraft materials using 3D Compton backscatter x-ray imaging, in: 42ND ANNUAL REVIEW OF PROGRESS IN QUANTITATIVE NONDESTRUCTIVE EVALUATION: Incorporating the 6th European-American Workshop on Reliability of NDE, Minneapolis, Minnesota, 2016: p. 110006. <https://doi.org/10.1063/1.4940577>.
- [18] Edward T. Dugan, Alan M. Jacobs, Dan Shedlock, Dan Ekdahl, Detection of defects in foam thermal insulation using lateral migration backscatter x-ray radiography, in: Proc. SPIE 5541, Penetrating Radiation Systems and Applications VI, 2004: pp. 47–57. <https://doi.org/10.1117/12.559719>.
- [19] V. Grubsky, V. Romanov, N. Patton, T. Jansson, Compton imaging tomography technique for NDE of large nonuniform structures, in: Penetrating Radiation Systems and Applications XII, San Diego, California, USA, 2011: pp. 117–127. <https://doi.org/10.1117/12.894059>.