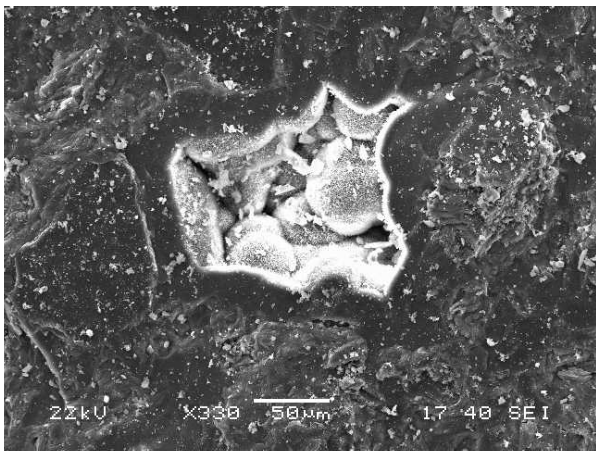
New Mexico Small Business Assistance (NMSBA) Grant 2017: United Materials

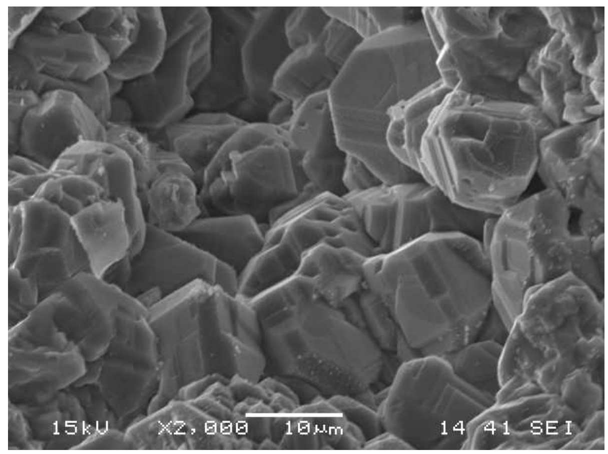
Jandi Knox, Chemistry Analyst; Leslie Kirkes, Geoscience Engineer; Dale Bowman, Hydrogeologist

Sandia National Laboratories (SNL), Carlsbad Programs Group, 4100 National Parks Highway, Carlsbad, NM 88220, USA. *Funded by New Mexico Small Business Assistance Grant.*

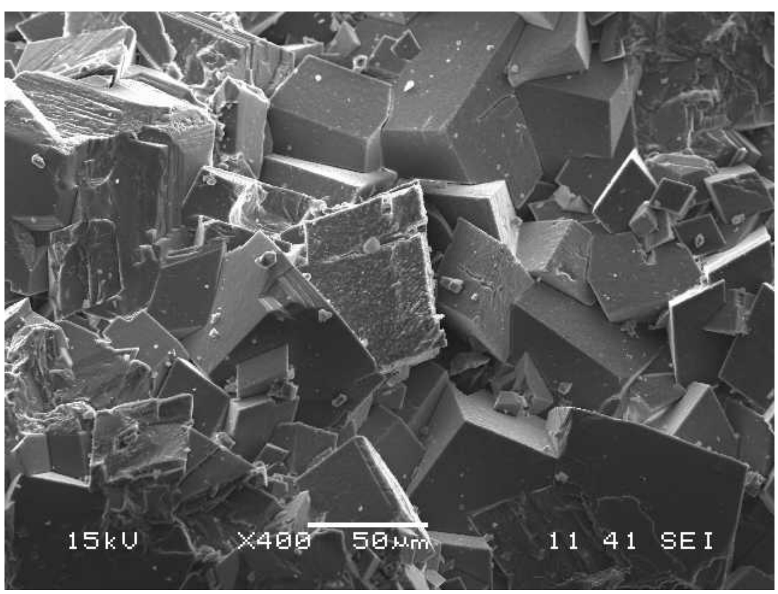
email: lkirkes@sandia.gov



Opal crystals (Jal)



Calcite Crystals (Travelstead)



Dolomite Crystals (Boyd)

ABSTRACT

Sandia National Laboratories (SNL) was awarded an NMSBA grant in August of 2017 to assist in the characterization of aggregate from United Materials, LLC. The aggregates produced in the various locations were characterized for: mineral composition, trace element inclusion, mineral surface topography, surface area, and porosity. The pit locations analyzed in this study were: Travelstead, Jal, Railroad Mountain, Boyd, and Rio Felix. At each location, various aggregate sizes were collected including: 1" or equivalent rock, 3/8" rock, and Crusher Fines (CF). Visual inspection of the 1" aggregate showed differences in appearance between the rocks making up the whole. In each of these locations the 1" rock was separated by visual appearance and then each visual type was characterized individually. While numerous aggregate characteristics can affect the quality of the final product, perhaps the most important characteristic is mineral composition. In summary, mineral compositions for the following sites were determined as follows:

Travelstead: Primarily Dolomite ($CaMg(CO_3)_2$) and Calcite/Limestone ($CaCO_3$)

Jal: Primarily Calcite/Limestone ($CaCO_3$) and Quartz (SiO_2) Note: In some of the 1" samples Anorthite ($CaAl_2Si_2O_8$) was identified.

Railroad Mountain: Primarily Basalt: Plagioclase Feldspar (likely Anorthite ($CaAl_2Si_2O_8$) or Labradorite $(Ca,Na)Al_{1-2}Si_{3-2}O_8$) with trace Silica, Iron and Titanium.

Boyd: Primarily Dolomite ($CaMg(CO_3)_2$), Calcite/Limestone ($CaCO_3$) and Quartz (SiO_2)

Rio Felix: Approximately equal Dolomite ($CaMg(CO_3)_2$) and Calcite/Limestone ($CaCO_3$) with trace Quartz (SiO_2)

The evaluated aggregate characteristics at these locations are explored in depth below.

INTRODUCTION

Numerous physical and chemical properties can determine the quality of aggregates. Physical properties that were explored in this study are: absorption, porosity, surface texture, and hardness of the minerals. The chemical property that was explored was: mineral composition. Understanding the physical and chemical properties that make up an aggregate can be crucial in determining the usefulness of the aggregate for a specific project.

Absorption is the ability of a rock or material to absorb a liquid (e.g. water, oil). Liquid absorption can greatly affect the ability of the rock to bind to oil or water. Absorption is highly controlled by the hydrophobicity of the rock. Hydrophilic (water loving) materials will absorb water more readily while hydrophobic (water hating) materials will repel water. Ideally, hydrophobic rocks are preferred for paving type operations (Roberts et al., 1996). Hydrophilic rocks tend to be more acidic (AI Spring Meeting 2002). Acidic rocks tend to suffer from stripping more readily than alkaline rocks due to their propensity to bind to water and repel or separate from the oil. The hydrophobicity of the rock is highly dependent upon the mineral composition of the rock. Certain minerals are hydrophobic (more alkaline) in nature and will therefore more readily bind to oil. Porosity of a material can also affect the absorption or trapping of water to a material. Highly porous materials will trap water and make binding of oil more difficult.

Surface texture can affect the quality of an aggregate. Surface texture is the physical roughness or smoothness of the aggregate. A rough surface texture is likely to produce a stronger bond between the aggregate and the cementing material whether the product be hot mix asphalt or portland cement concrete.

Hardness of the mineral making up the aggregate is also crucial to quality. Initially, some aggregates may perform well, however over time, softer aggregates are subject to smoothing, limiting the surface texture. This is often the case with Calcite ($CaCO_3$) minerals such as Limestone. The presence of magnesium in the $CaCO_3$ structure, which is the mineral known as Dolomite ($CaMg(CO_3)_2$), changes the mineral structure to allow the aggregate to hold up better under repeated friction and stress.

Mineral Composition is perhaps the most important component in determining the usability of an aggregate for a project. The minerals making up a rock affect almost all of the physical aspects previously discussed. The composition of the minerals making up an aggregate can affect:

absorption, hydrophobicity, surface texture, and hardness. Knowing the mineral composition of an aggregate could determine the success or failure of a project.

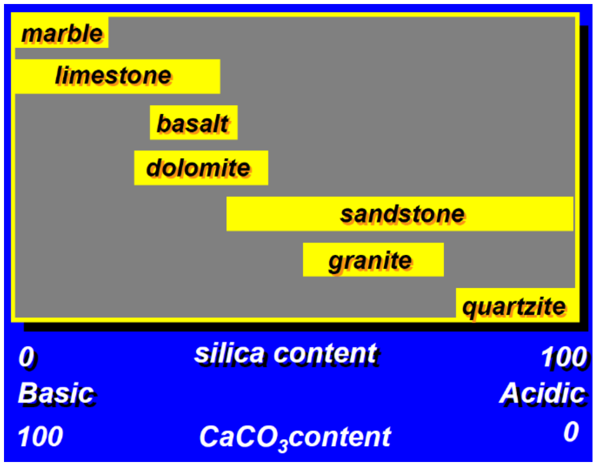
MATERIALS AND METHODS

Mineral Composition

Bulk mineral composition was determined using a Bruker powder XRD. Each of the samples was prepared by hand grinding to a fine powder, using a mortar and pestle. The powder sample was then analyzed on the XRD and matched using the PDF4+ software and the International Centre for Diffraction Database (ICDD). The relative concentration of a mineral presence can be visualized by the XRD peak heights or the peak intensity generated by the mineral. Mineral composition of the aggregate is perhaps the single most important characteristic of aggregates, as it determines many of the other properties already discussed. For Example, calcite ($CaCO_3$) is the primary mineral that makes up Limestone. While limestone initially performs well as an aggregate, it has been shown to be subject to wear over-time. Dolomite ($CaMg(CO_3)_2$) is a mineral that is similar to Calcite, however it contains magnesium in the structure. The presence of magnesium in the mineral structure greatly increases the ability of the aggregate to withstand wear over-time. XRD can easily differentiate between Calcite and Dolomite and provide increased confidence in aggregate use on critical projects. The mineral composition can greatly affect the adhesion between the binder and the aggregate.

The absorption of a liquid and the adhesion of the aggregate and the binder are highly dependent upon the hydrophobicity of the rock mineral composition. Hydrophobic minerals tend to be more alkaline in nature, while hydrophilic minerals tend to be more acidic. For example, $CaCO_3$ is a hydrophobic mineral and aggregates containing high concentrations of $CaCO_3$ tend to be more resistant to stripping due to their ability to repel water and sorb to the oil binder. Silica containing minerals tend to be more acidic (hydrophilic) in nature and have issues with stripping. The diagram below demonstrates the hydrophobic nature of minerals/aggregates based on the mineral composition. Ultimately, aggregates listed on the left side of the diagram will be more resistant to stripping, because they will bind to the oil more readily. Aggregates that contain a high concentration of silica are more acidic and will be more susceptible to stripping when exposed to water.

Chemical Nature of Road Aggregates by Mineral Percentage



AI Spring Meeting 2002. http://www.asphaltinstitute.org/wp-content/uploads/public/engineering/pdfs/materials/Chemistry_AA.pdf

Hardness

After each of the samples in this study were subjected to XRD, the minerals were classified using the Mohs hardness scale. The hardness of the minerals in aggregates can play a huge role in determining the quality of the final product. Once the mineral composition is known of the aggregate, the mineral can be classified for hardness using the Mohs Hardness Scale. The hardness of the minerals in the aggregate, will control its ability to resist abrasion and degradation over-time. Figure 1 shows the relative hardness according to the Mohs Hardness Scale for some common minerals. Mineral harness increases with increasing number on the scale such that Diamond (10) is harder than Talc (1). The hardness of the minerals making up the aggregate of interest, can drastically alter the utility of a specific aggregate for a specific job. While increased mineral hardness can be beneficial to aggregate resistance to abrasion, it can also be a detriment to crushing equipment, increasing wear and tear on equipment.

Figure 1 Mohs Hardness Scale

Indiana Geological Survey. 2011. http://www.geologypage.com/wp-content/uploads/2016/04/Mohs-scale-of-mineral-hardness-GeologyPage.jpg

Surface Texture and Trace Element Analysis

Surface texture and trace element analysis was performed using a JEOL Scanning Electron Microscope (SEM) with Electron Dispersion Spectroscopy (EDS). The SEM/EDS technique will provide microscopic inspection of the surface of the aggregate to determine roughness or smoothness. In addition, the EDS will provide elemental analysis to confirm XRD analysis and determine trace elemental presence. XRD cannot identify minerals in the lower percent by weight range (trace concentrations). SEM/EDS can be used to evaluate crystal morphology of trace minerals in the aggregate for shape and elemental composition. Trace elemental analysis using the SEM/EDS can help to identify trace clay ribbons such as Kaolinite and other trace elements of interest such as Iron and Titanium. All locations and sizes were analyzed for surface texture and trace elemental analysis.

The SEM/EDS will also provide visible evidence of porosity and pore quantity. Ideally, an aggregate with low porosity and high surface area is desired (rough surface texture increases surface area). A particle having lots of pores can potentially trap water inside or on the surface of the mineral causing problems with aggregate/oil adhesion. A higher surface area will provide more area for the oil to coat and bind, while a low porosity will keep water from penetrating the surface.

RESULTS

TRAVELSTEAD

Three sizes of aggregate were obtained from the Travelstead location including: 1” rock, 3/8” rock and Crusher Fines. The 1” rock was separated visually into 4 different types as seen in the figure below. XRD was performed on a mix of the separated 1” rocks because they did not show great diversity in visual appearance. SEM/EDS analysis was used to explore the trace elements in the 4 different types of 1”.

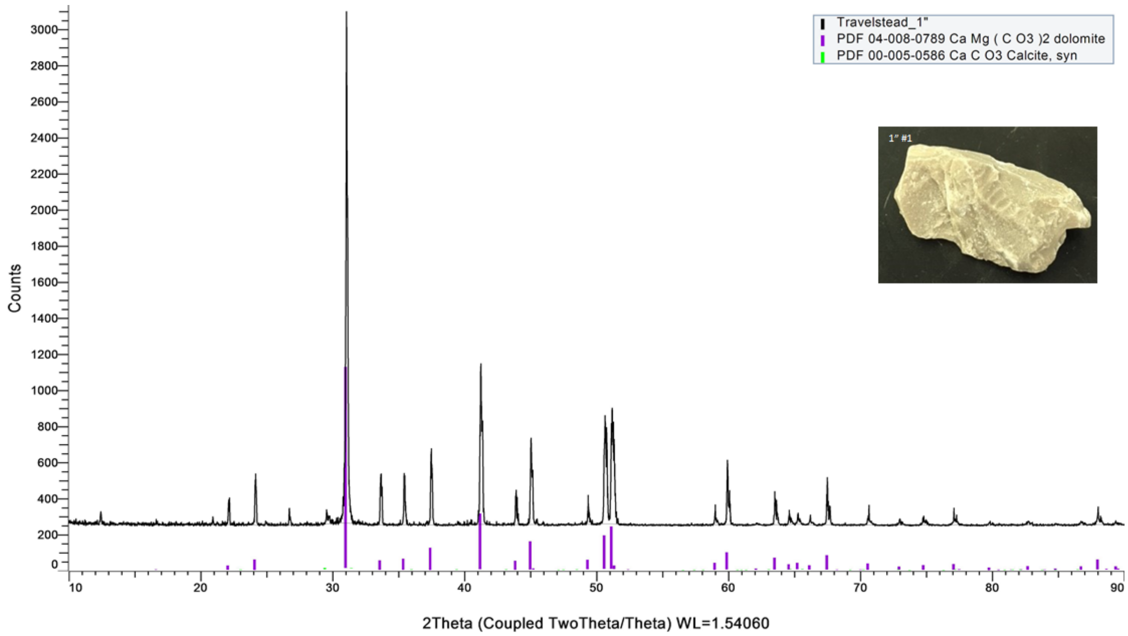
Travelstead Quarry	
1" Rock Type	Percentage of collected sample by weight
#1	67.06%
#2	8.60%
#3	11.60%
#4	12.74%

Mineral Composition and Mohs Hardness

Mineral composition data was collected using an XRD. XRD analysis gave information on the bulk minerals present within the sample. Trace elemental analysis was conducted using the

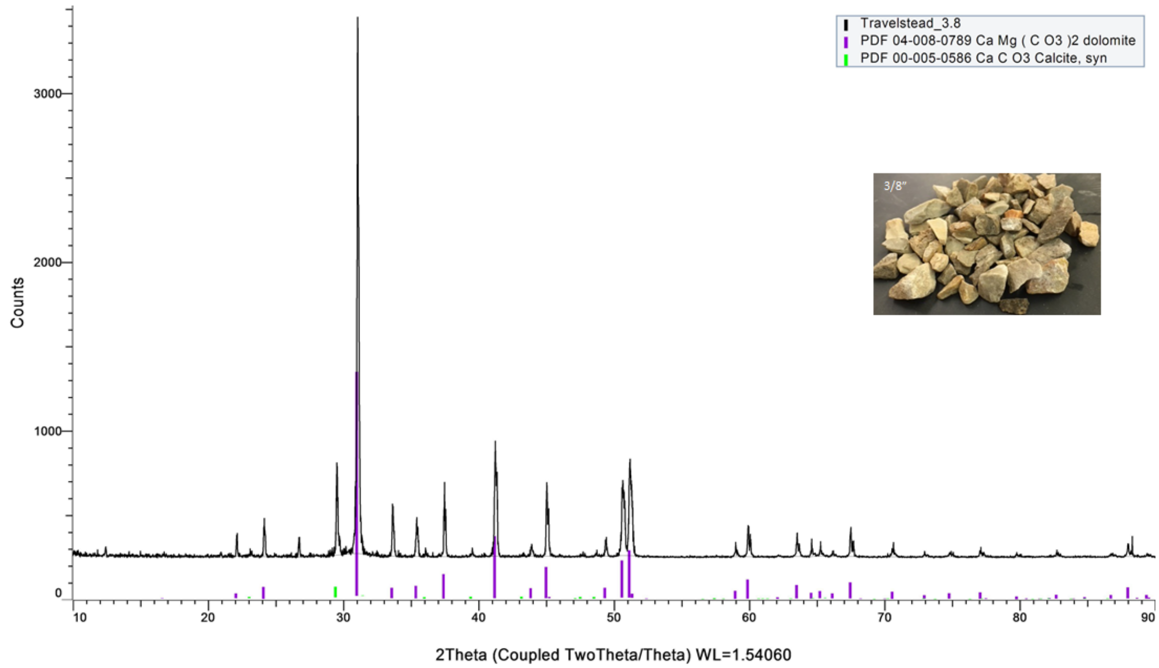
SEM/EDS. Based on the XRD analysis performed, it is evident that the Travelstead sample is comprised primarily of Dolomite ($CaMg(CO_3)_2$) with low concentrations of Calcite ($CaCO_3$). The heights of each of the peaks represent the relative concentration of each of the minerals identified, based on intensity generated by the crystalline structure of the mineral being measured. Dolomite has a Mohs hardness of 3.5-4 while Calcite has a Mohs hardness of 3. The hardness of dolomite, along with its alkaline nature (hydrophobic) makes it a better candidate for various paving projects due to its ability to resist wear and stripping. Calcite is a slightly softer mineral however, its alkaline nature makes it a good candidate to prevent stripping, although in time it may be subject to smoothing under heavy traffic or heavy abrasion.

Travelstead 1" rock XRD



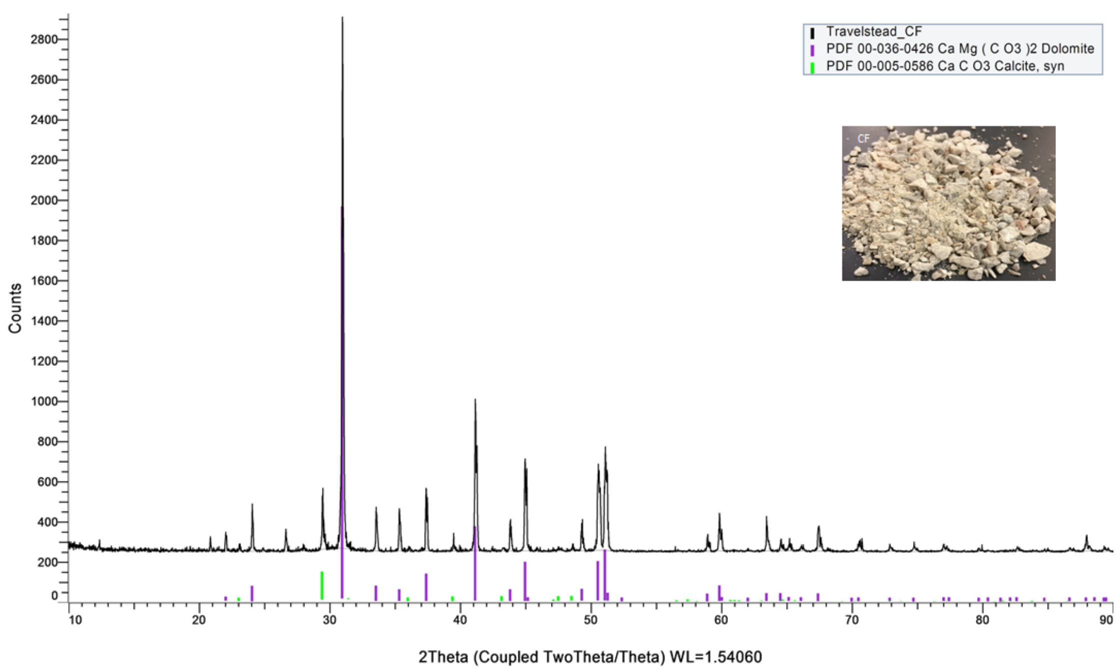
The Travelstead 1" sample showed an almost pure specimen of Dolomite ($CaMg(CO_3)_2$). In the image, the black line represents the peaks that were generated on the XRD by the sample. The purple lines on the figure represent where peaks should appear on a Dolomite sample according to the ICDD (International Centre for Diffraction Database).

Travelstead 3/8" rock XRD



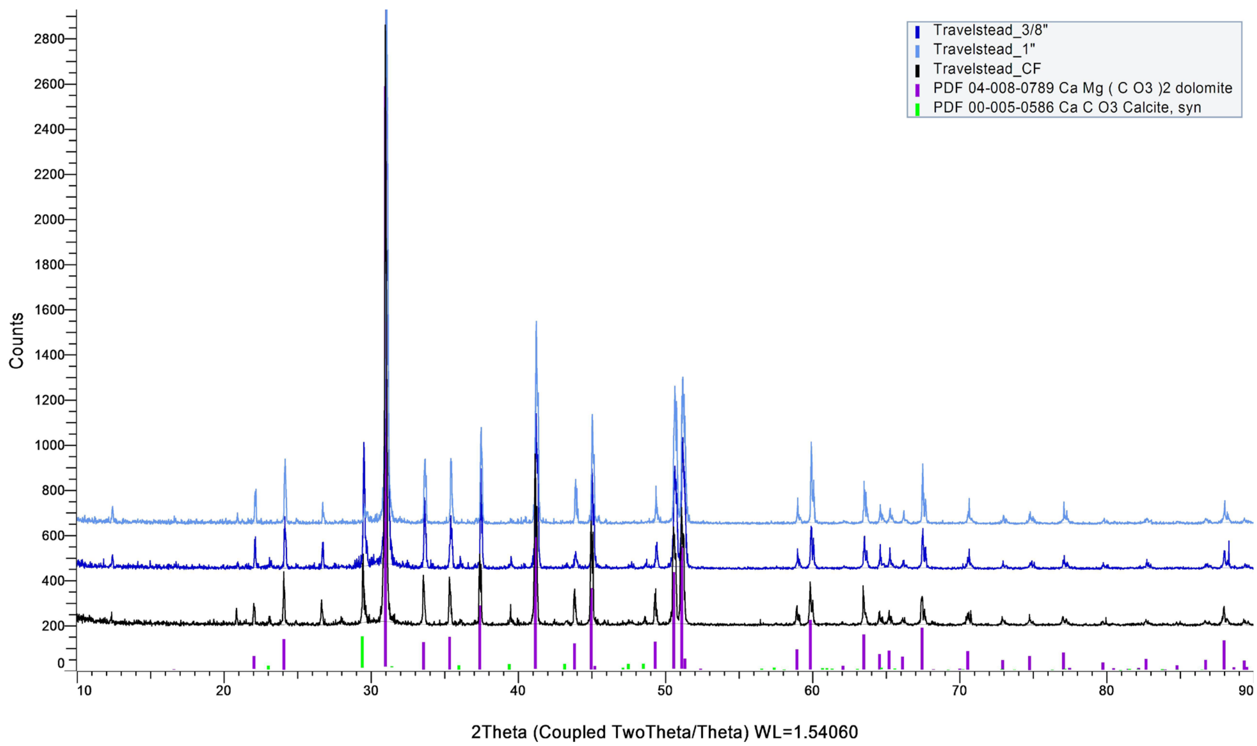
The Travelstead 3/8" rock sample is represented by the black line in the image above. The purple lines indicate where peaks should appear for a Dolomite ($CaMg(CO_3)_2$) sample and the green lines represent where peaks of Calcite ($CaCO_3$) should appear according to the ICDD. This sample has a slightly higher presence of Calcite than the 1" sample.

Travelstead Crusher Fines



The Travelstead crusher fines rock sample is represented by the black line in the image above. The purple lines indicate where peaks should appear for a Dolomite ($CaMg(CO_3)_2$) sample and the green lines represent where peaks of Calcite ($CaCO_3$) should appear according to the ICDD. This sample has a slightly higher presence of Calcite than the 1" sample. The figure below represents all of the rock sizes on one figure for easier comparison.

Travelstead All



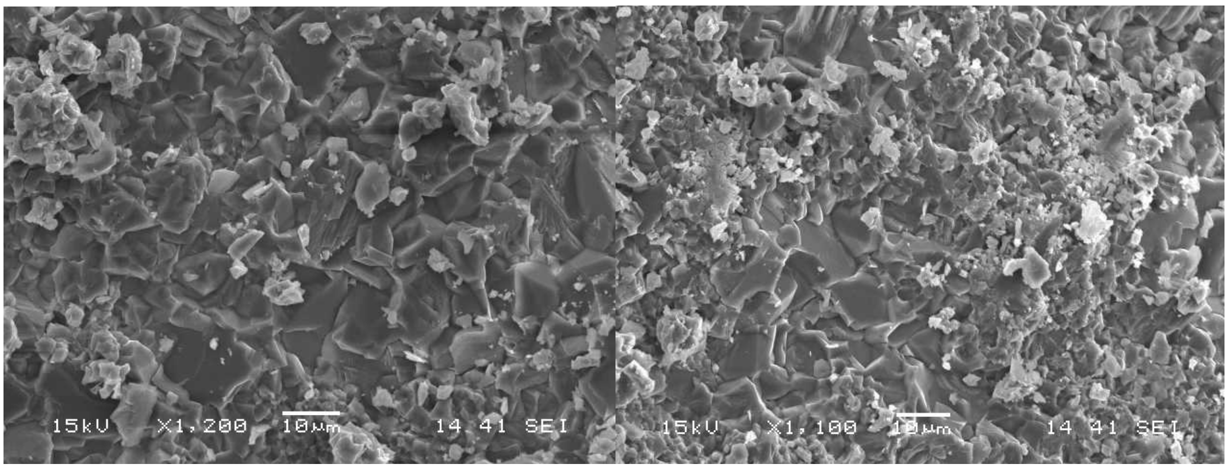
Surface Texture and Trace Elemental Analysis

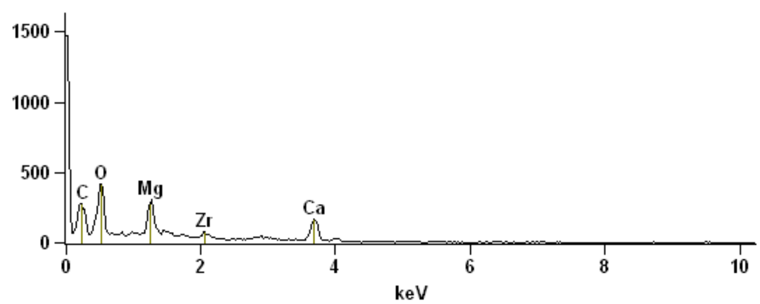
Surface texture measurement and trace elemental analysis was performed on all sizes of the Travelstead rock. Each of the 1" rock types were analyzed individually for better trace element characterization.

Travelstead 1" Sample #1

Under microscopic inspection, the Travelstead 1" #1 sample shows a sealed surface topography with few pores. This should lead to a low porosity. The surface texture is visibly rough which should allow good adhesion between the aggregate and the binder material. The EDS/elemental analyses of the various phases of the sample show consistency with the XRD in being a very pure Dolomite, presenting the elements Calcium, Magnesium, Carbon and Oxygen.

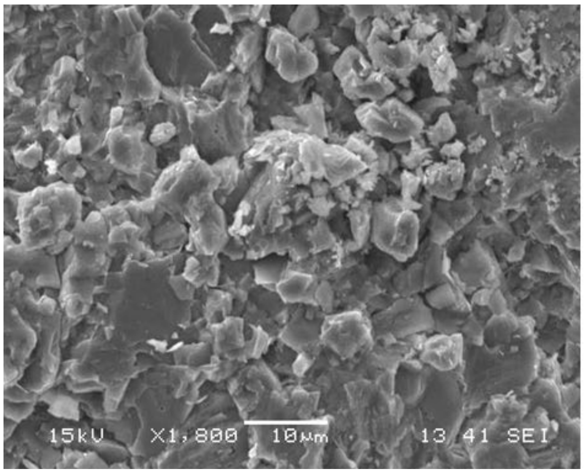
Interestingly a very small elemental presence of Zirconium was found, although the concentration is so low that it will not likely add or detract from the over-all quality of the product.

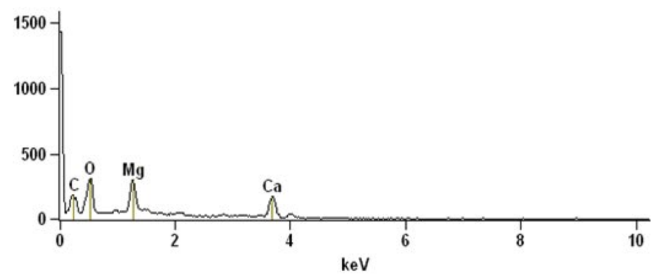




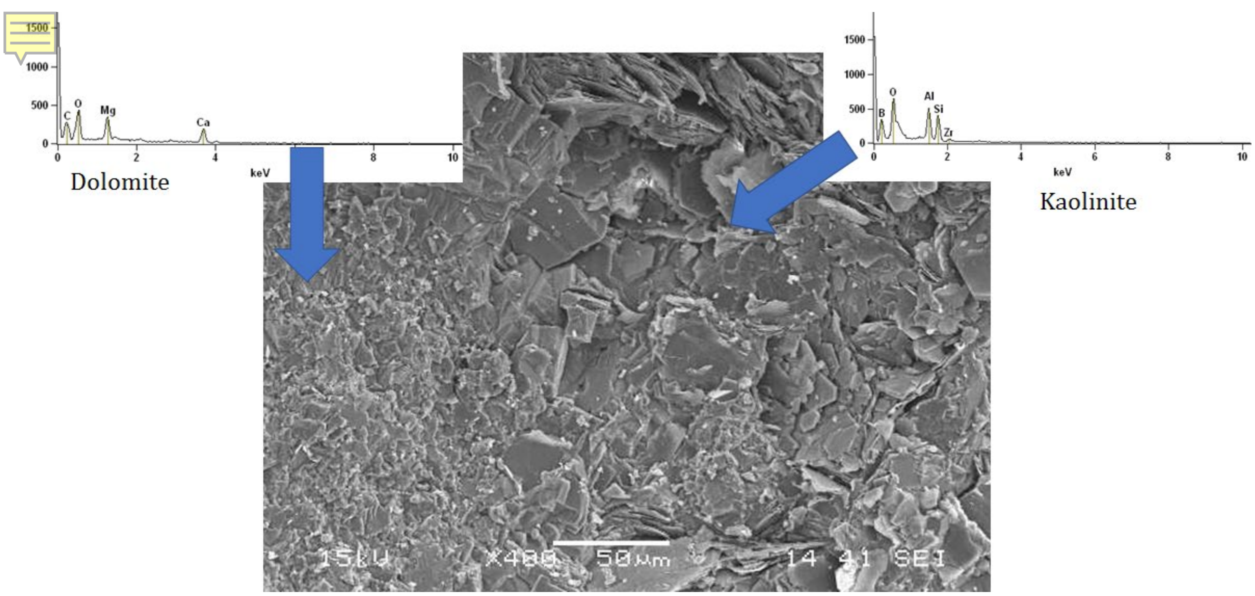
Travelstead 1” Sample #2

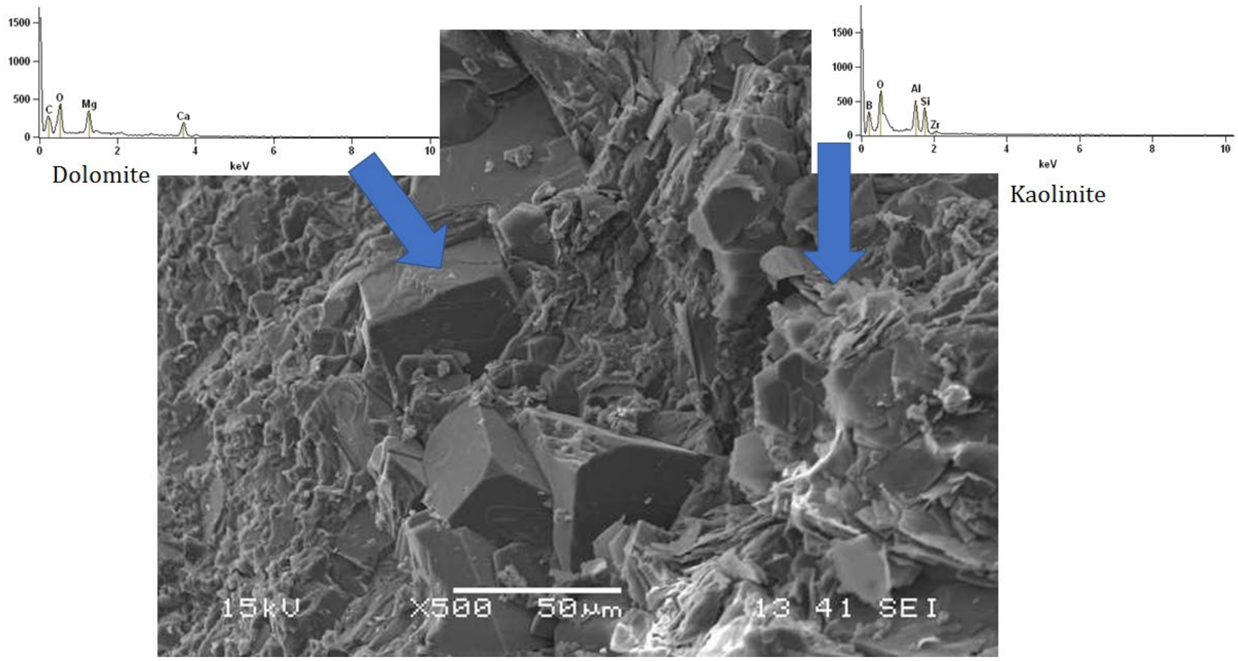
The Travelstead 1” #2 sample is visibly more brown in color than the #1 sample. The majority of the sample presented a sealed surface and a pure elemental composition of Dolomite. Very few pores were visibly present in the sample, indicating a low porosity but high surface area. The elemental composition was very similar to the #1 sample as seen in the figure below.





The sample also presented with a trace concentration of embedded Kaolinite ($Al_2Si_2O_5(OH)_4$) (Likely less than 5%). Kaolinite is a layered clay mineral commonly found in conjunction with other minerals. The images below show the structure of the Kaolinite mineral (flaky sheets) embedded in the Dolomite rock.





The typical Kaolinite structure is flat sheets of soft mineral, and it is can be found embedded within Dolomite. The majority of the Travelstead 1” #2 sample was composed of Dolomite and very trace amounts of the Kaolinite were found. The Kaolinite presence is not likely to adversely affect the quality of the over-all product, especially considering that the 1” #2 type only makes up 8.6% of the total 1” rock sample. Kaolinite was not detected in the XRD analysis that was completed for the 1” Travelstead sample, indicating that it is less than 1-2% by weight of the total 1” specimen.

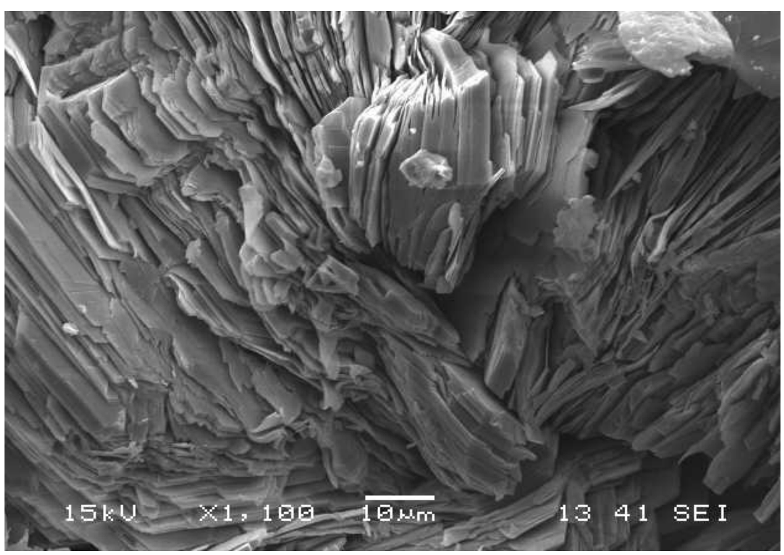
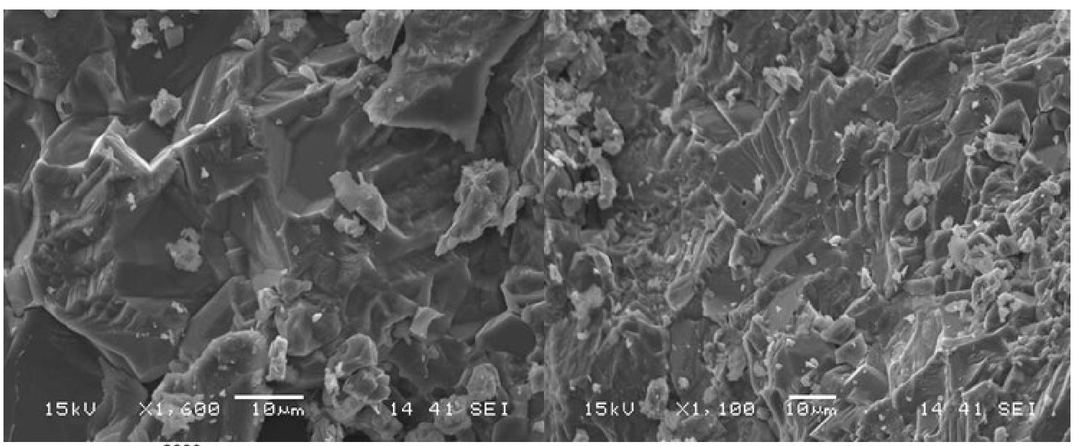
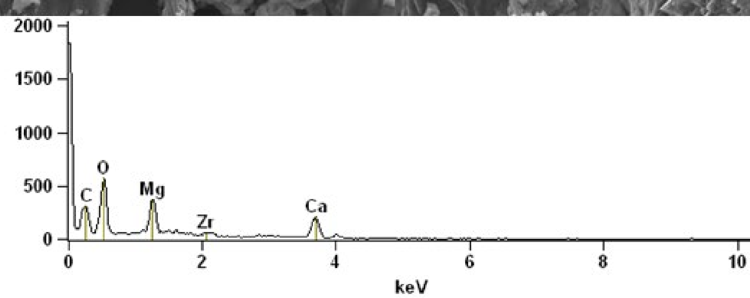


Image of Kaolinite sheets in the Travelstead sample.

Travelstead 1” Sample #3

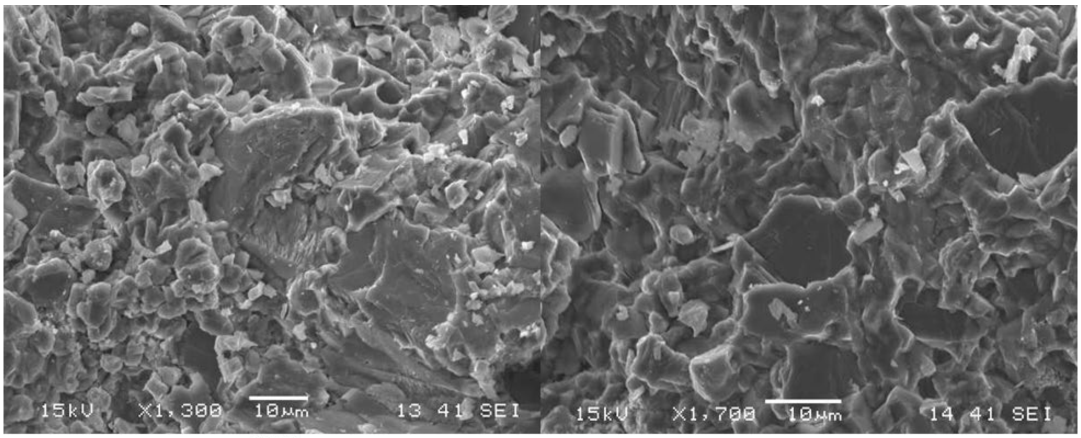
The Travelstead 1" #3 sample shows a sealed surface topography with few pores, representative of low porosity. The surface texture is visibly rough which should allow good adhesion between the aggregate and the binder material. The EDS/elemental analysis of the various phases of the sample shows consistency with the XRD in being a very pure Dolomite, presenting the elements Calcium, Magnesium, Carbon, and Oxygen. Interestingly a very small elemental presence of Zirconium was found, although the concentration is so low that it will not likely add or detract from the over-all quality of the product. The flat sheet-like structures found in the first SEM image for this sample are not Kaolinite. These were analyzed and the elemental analysis was indicative of Calcite ($CaCO_3$).

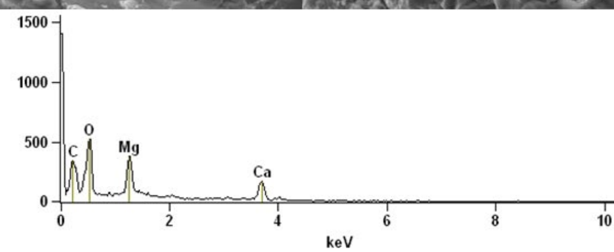


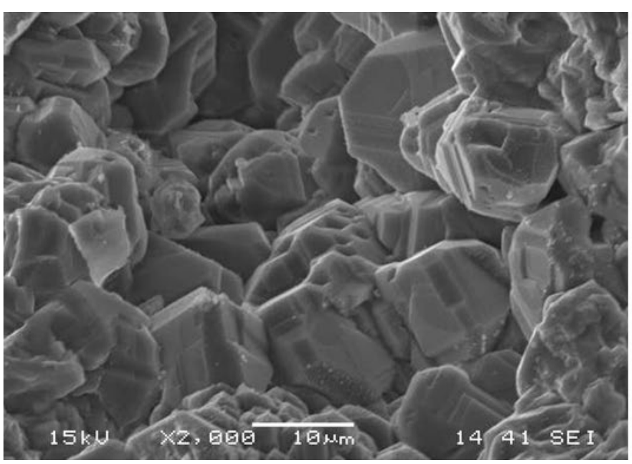


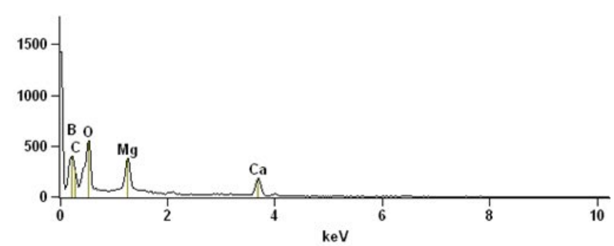
Travelstead 1" Sample #4

The Travelstead 1" #4 sample shows an almost identical surface and elemental profile as the previous 1" samples, presenting a sealed surface topography with few pores. Interestingly, a new shape of Dolomite crystal was found as shown in the last image of this section. It is difficult to determine whether this structure is magnesium rich Calcite or pure Dolomite crystals. This blocky dolomite or calcite structure will allow an increase in surface area while still providing the hardness and structure needed for aggregate resilience.







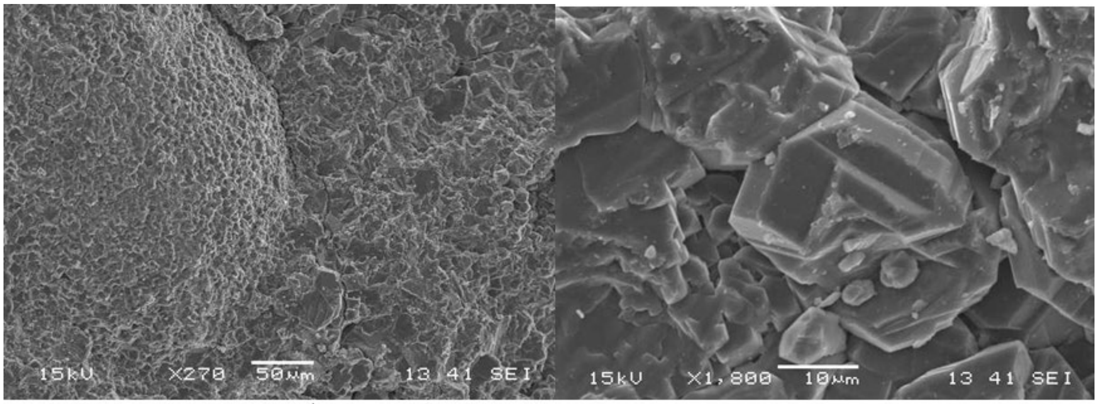


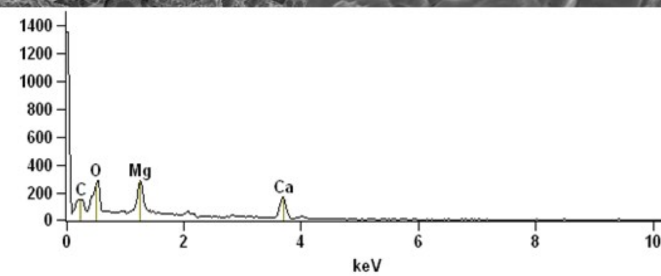
Dolomite or Magnesium rich Calcite crystals

Travelstead 3/8" and Crusher Fines

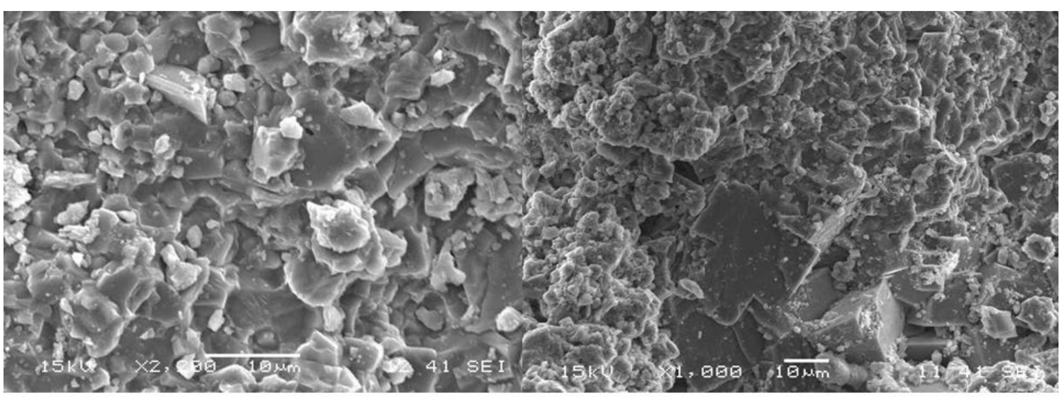
The Travelstead 3/8" and Crusher Fines were similar to the 1" samples, showing a dolomitic nature with sealed surface, high surface texture.

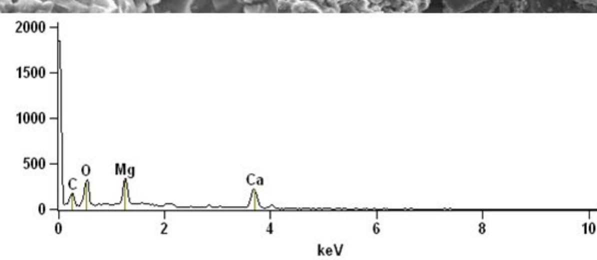
3/8" sample





Crusher Fines





JAL Quarry

Two sizes of aggregate were obtained from the Jal location including: 1” rock, and Crusher Fines. Once at SNL, the 1” rock was separated visually into 5 different types as seen in the figure below. XRD was performed on each of the 1” rock types because they showed diversity in visual appearance. SEM/EDS analysis was performed on each of the sizes and types.

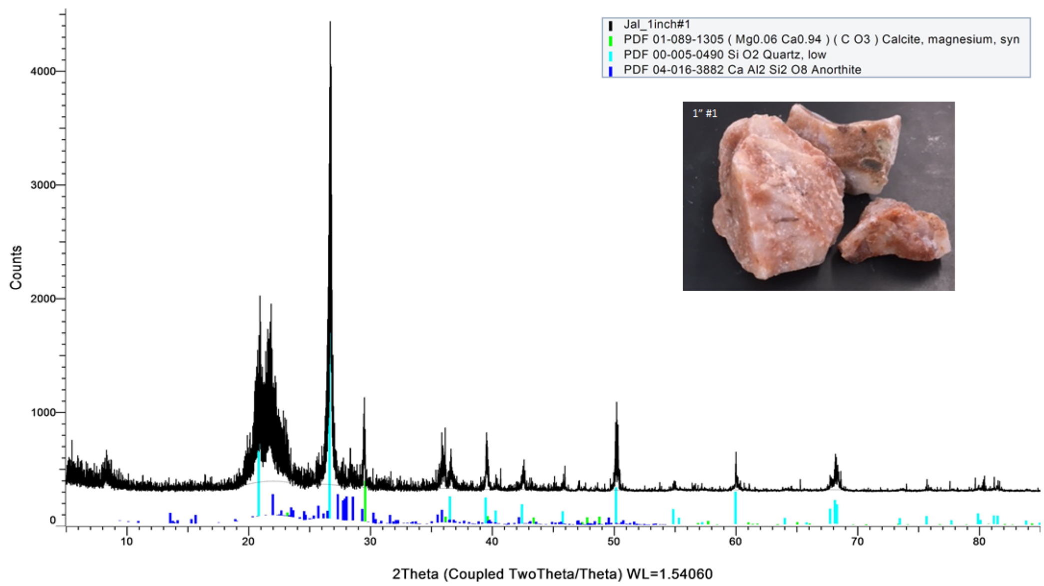
Jal Quarry	
1" Rock Type	Percentage of collected sample by weight
#1	7.90%
#2	4.73%
#3	0.73%
#4	13.30%
#5	73.35%

Mineral Composition and Mohs Hardness

Based on the XRD analysis performed, it is evident that the Jal 1” samples are comprised primarily of Quartz (SiO_2), Calcite ($CaCO_3$) and Plagioclase Feldspar likely, Anorthite ($CaAl_2Si_2O_8$). The heights of each of the peaks represent the relative concentration of each of the minerals identified, based on intensity generated by the crystalline structure of the mineral being measured.

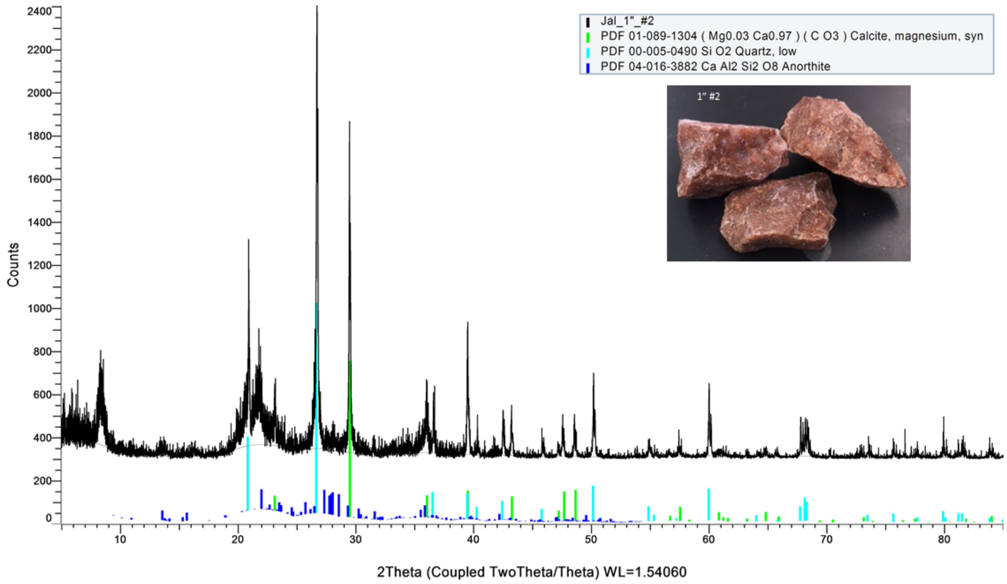
Quartz has a hardness of 7, Calcite has a Mohs hardness of 3 and Plagioclase Feldspars have a Mohs hardness of approximately 6-6.5. The hardness of the Quartz and Plagioclase Feldspar minerals make them highly resistant to abrasion and wear, although the higher silica (more hydrophilic) content of them may make them more susceptible to stripping. In addition, the hardness of these minerals may cause more damage to crushing equipment when the rock is being processed. The Jal crusher fines are comprised almost entirely of Calcite and Quartz. The form of calcite identified in these samples is a form that contains magnesium in its structure, however it is not a high enough concentration of magnesium to be considered dolomite.

Jal 1" Sample #1



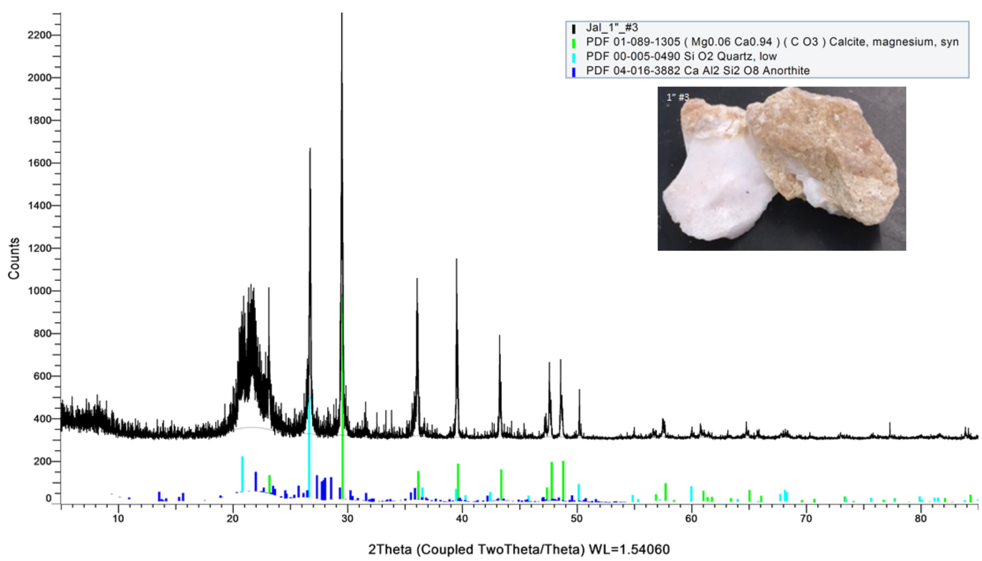
The black line above shows the peaks generated on the XRD by the Jal 1" #1 sample. The Green lines represent where Calcite peaks should appear, the Cyan lines represent there the Quartz peaks should appear and the dark blue lines represent where the Plagioclase Feldspar or Anorthite peaks should appear according to the ICDD. Based on the intensities of these mineral peaks, this sample contains a majority of quartz and plagioclase feldspar with some calcite.

Jal 1" Sample #2



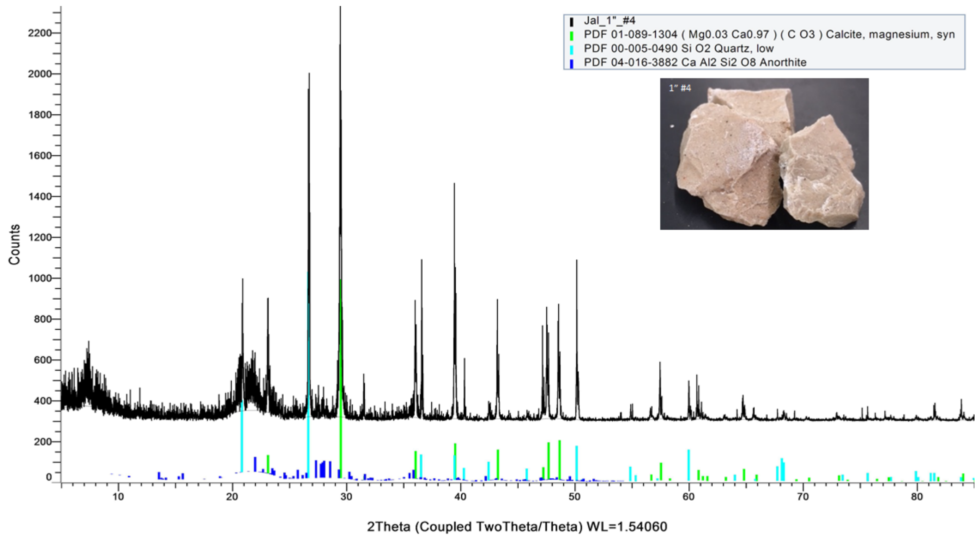
The black line above shows the peaks generated on the XRD by the Jal 1” #2 sample. The Green lines represent where Calcite peaks should appear, the Cyan lines represent where Quartz peaks should appear and the dark blue lines represent where the Plagioclase Feldspar or Anorthite peaks should appear according to the ICDD. This sample has a higher relative concentration of calcite than the #1 sample and a lower concentration of plagioclase feldspar.

Jal 1” Sample #3



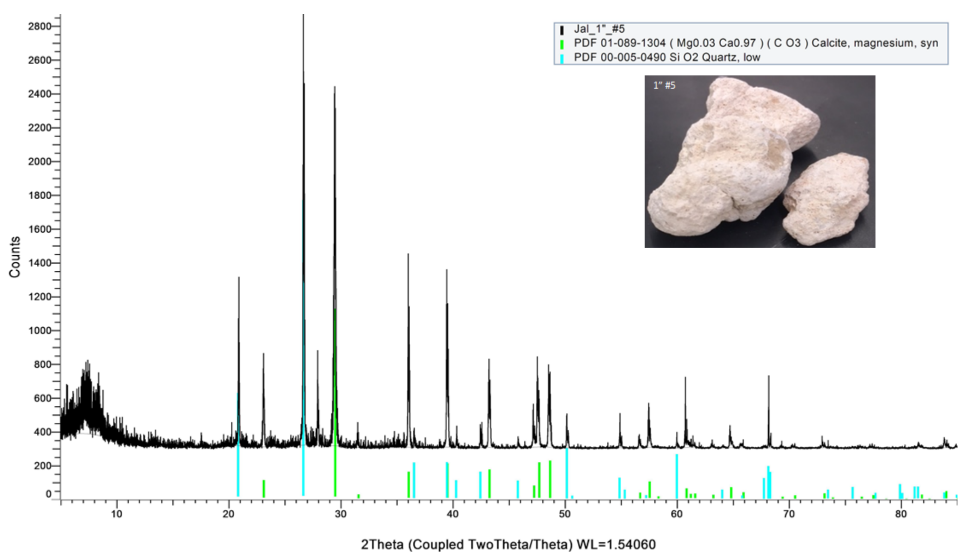
The black line above shows the peaks generated on the XRD by the Jal 1” #3 sample. The green lines represent where Calcite peaks should appear, the cyan lines represent where Quartz peaks should appear and the dark blue lines represent where the Plagioclase Feldspar or Anorthite peaks should appear according to the ICDD. This sample has a higher relative concentration of calcite than quartz or plagioclase feldspar.

Jal 1" Sample #4



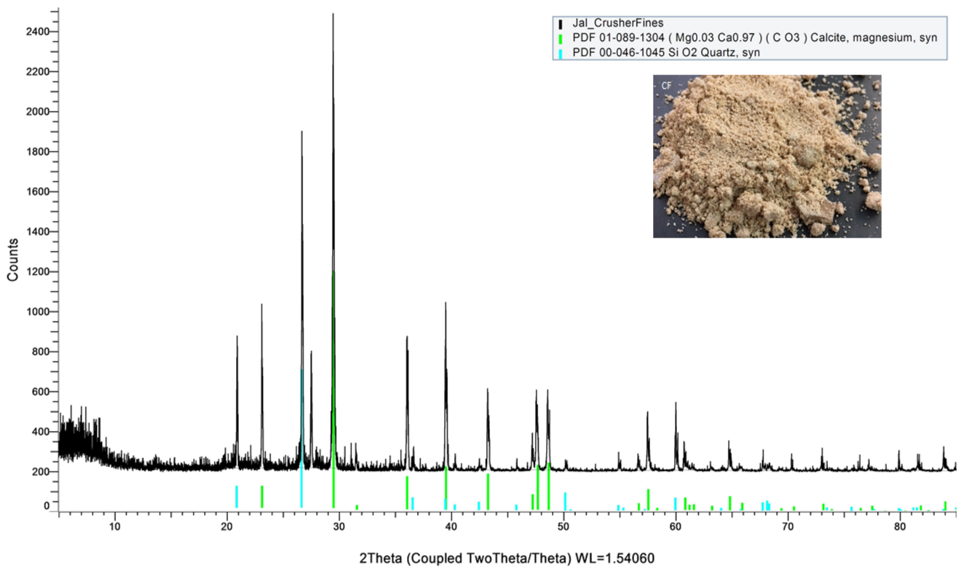
The black line above shows the peaks generated on the XRD by the Jal 1" #4 sample. The green lines represent where Calcite peaks should appear, the cyan lines represent where Quartz peaks should appear and the dark blue lines represent where the Plagioclase Feldspar or Anorthite peaks should appear according to the ICDD. The relative concentration of calcite and quartz are almost equal for this sample with the plagioclase feldspar being the lowest concentration.

Jal 1" Sample #5



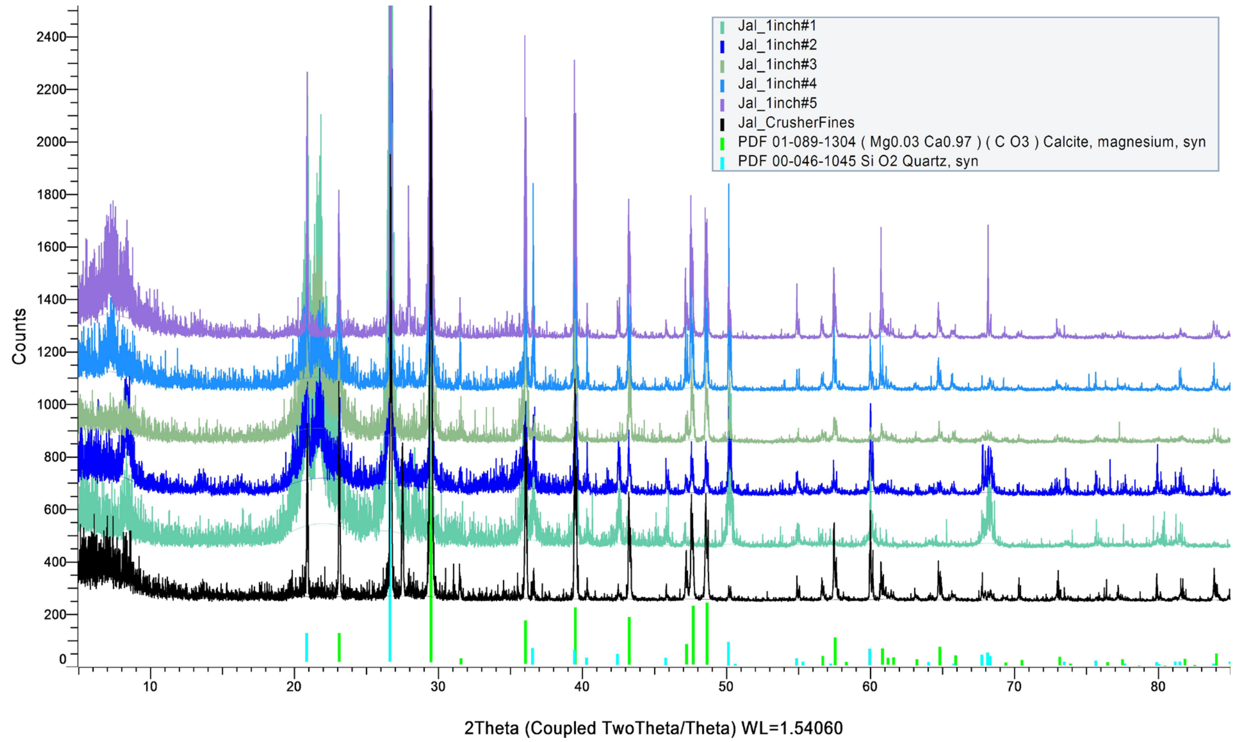
The black line above shows the peaks generated on the XRD by the Jal 1" #5 sample. The green lines represent where Calcite peaks should appear, the cyan lines represent where Quartz peaks should appear and the dark blue lines represent where the Plagioclase Feldspar or Anorthite peaks should appear according to the ICDD. The Quartz and Calcite relative concentrations are almost equal in this sample however there is no presence of plagioclase feldspar.

Jal Crusher Fines



The black line above shows the peaks generated on the XRD by the Jal crusher fines sample. The green lines represent where Calcite peaks should appear, the cyan lines represent where Quartz peaks should appear and the dark blue lines represent where the Plagioclase Feldspar or Anorthite peaks should appear according to the ICDD. The Quartz and Calcite relative concentrations are almost equal in this sample however there is no presence of plagioclase feldspar. The XRD below shows all the analyzed samples together on one image for easier comparison.

Jal All XRDs

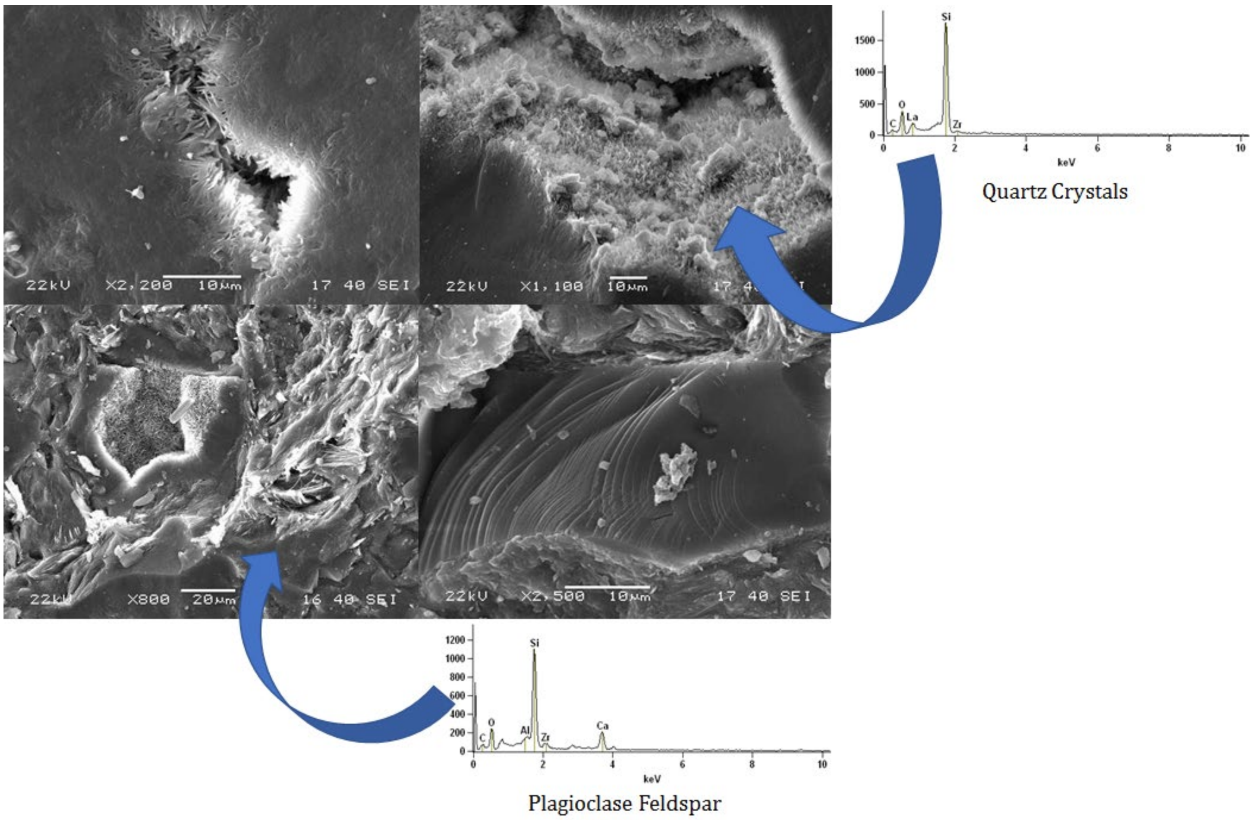


Surface Texture and Trace Elemental Analysis

Surface texture and trace elemental analysis using the SEM/EDS was performed on all types of the 1" rock as well as the crusher fines. Each of the 1" rock types were analyzed individually for better trace element characterization.

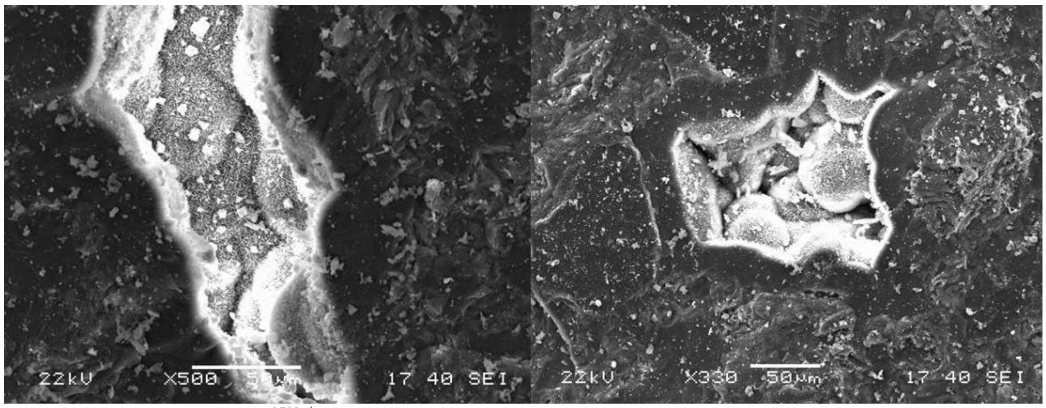
Jal 1" #1 Sample

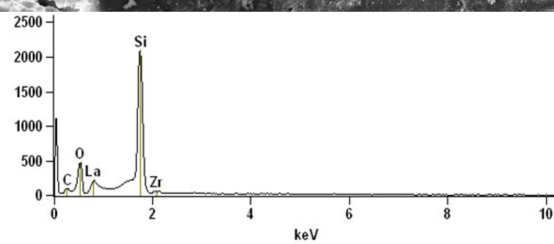
Under microscopic inspection, the Jal 1" #1 sample shows a sealed surface topography with a fair number of pores filled with quartz crystals. The quartz crystals, based on morphology, are likely a form of hydrated SiO_2 (such as Opal). The areas that do not contain pores, have a solid sealed composition with a visibly low surface texture. The EDS/elemental analysis of the various phases of the sample shows consistency with the XRD in being highly composed of Quartz with lower concentrations of plagioclase feldspar.



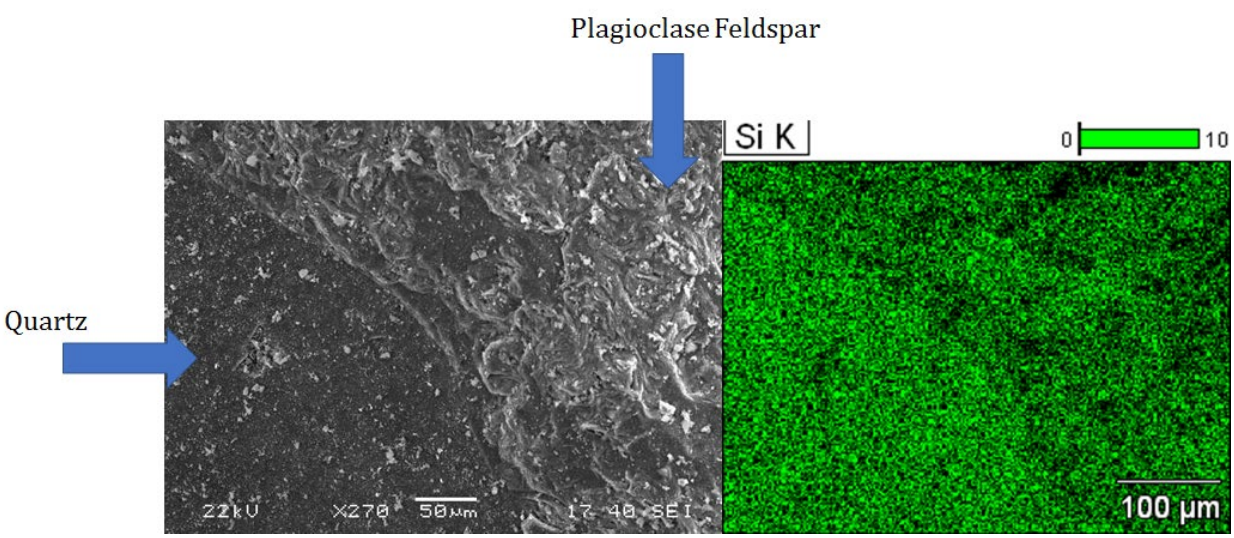
Jal 1” Sample #2

The Jal 1” #2 sample was visibly more red in color than the #1 sample. While the majority of the surface was sealed and smooth, there were many pores that contained hydrated quartz crystals (likely Opal). The dark smooth surface is indicative of quartz while the rougher surface is plagioclase feldspar or calcite (as shown in the last figure in this section). The elemental analysis provided by the EDS for this sample confirms the findings of the XRD.





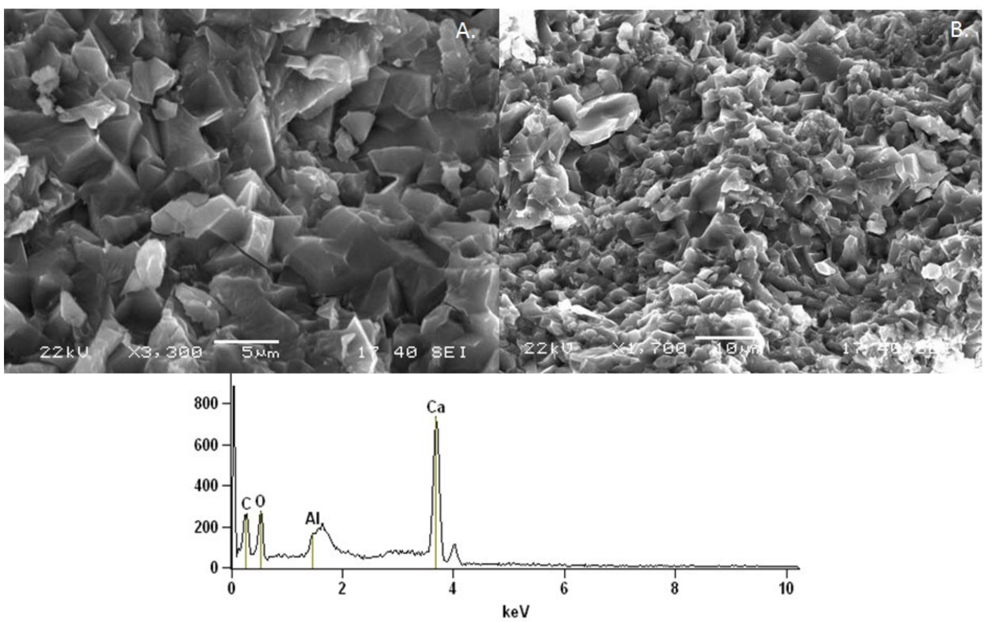
Analysis showing Quartz with pores filled with hydrated Quartz crystals (Opal)



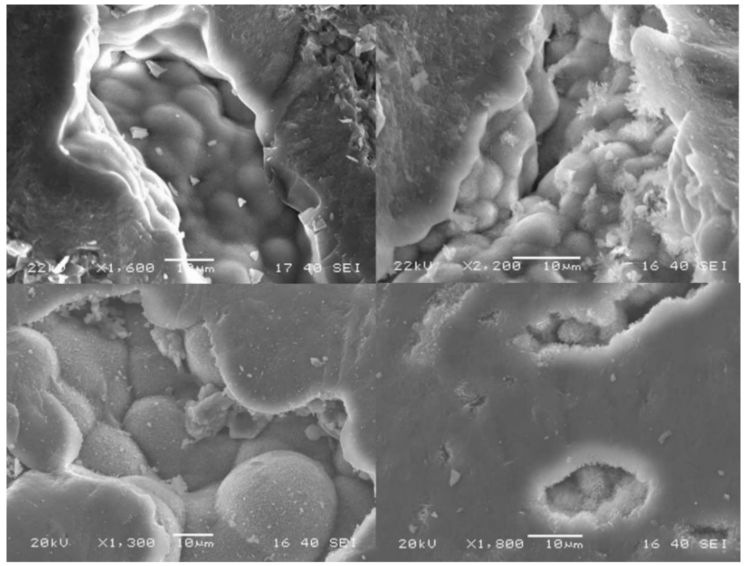
High silica concentrations showing Quartz on the left side of the image and Plagioclase Feldspar on the right.

Jal 1” Sample #3

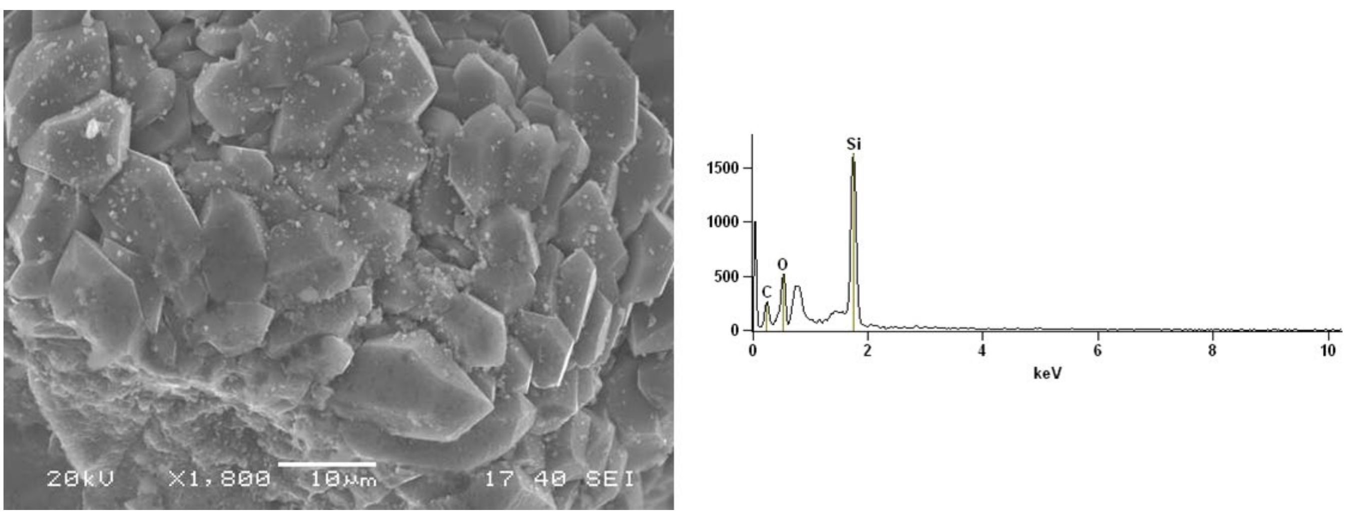
Jal 1” #3 had a high presence of Calcite and Quartz with a smaller concentration of Plagioclase Feldspar. The figures below, show the SEM images and EDS analysis of Calcite and various quartz phases present in the sample. EDS point analysis (spectra with peaks) and EDS phase analysis (colorful dot maps) were both used to better characterize this sample.



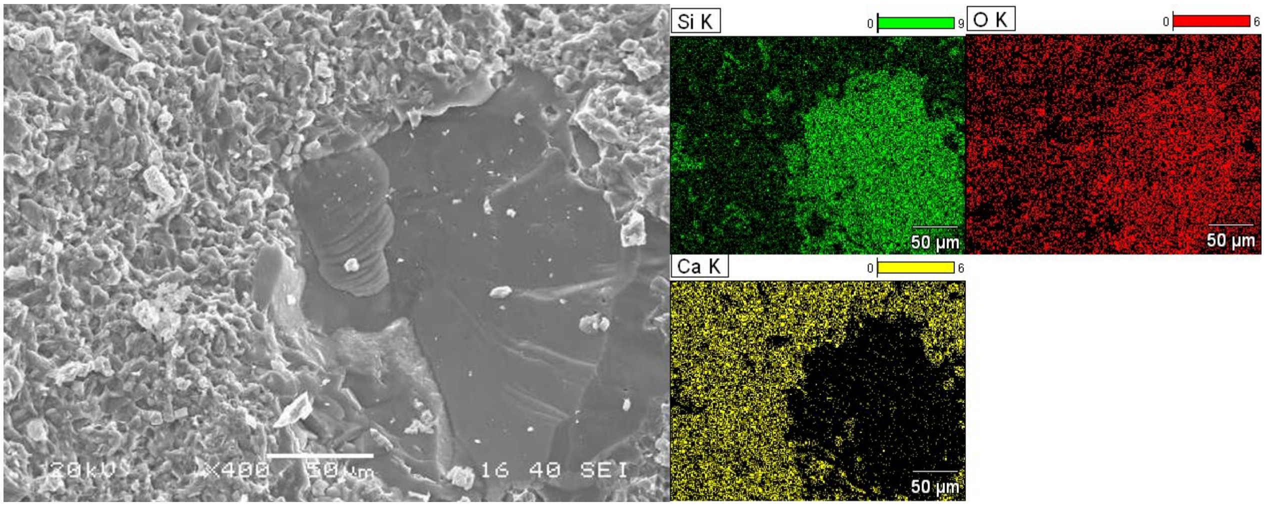
SEM/EDS analysis showing calcite crystals with a trace concentration of Aluminum.



SEM images showing hydrated Quartz crystals (Opal) filling pores.



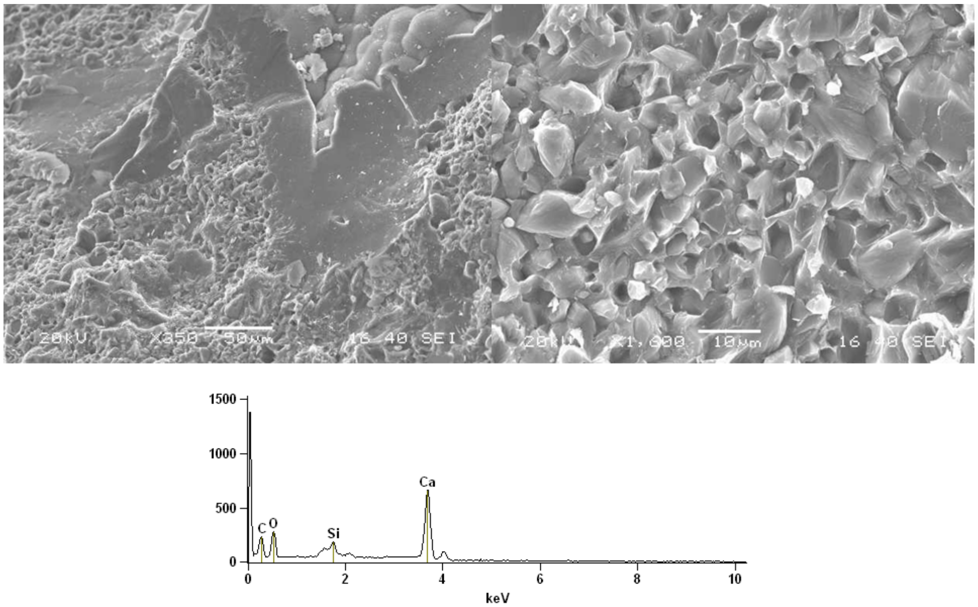
SEM/EDS analysis showing Quartz crystals.



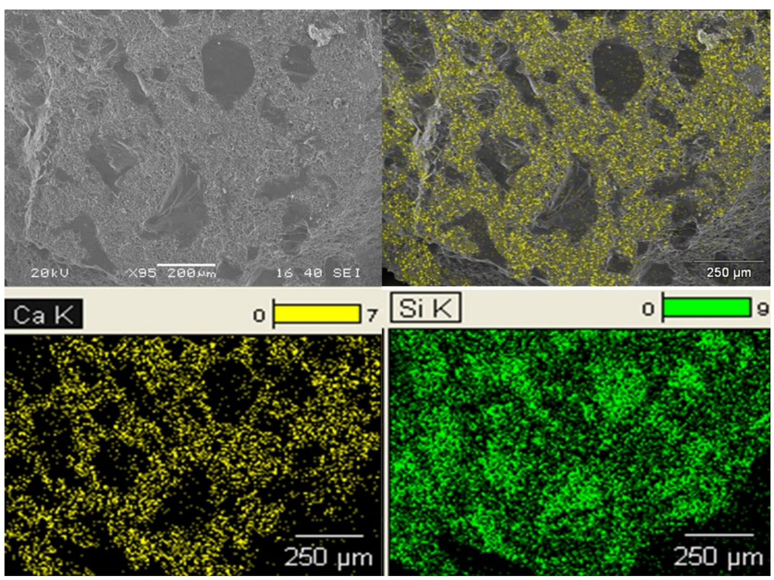
SEM image and EDS phase analysis showing Calcite and Quartz (Calcite is where Calcium is present in yellow, Quartz is Red and Green).

Jal 1” Sample #4

The Jal 1” #4 sample had a high concentration of both Calcite and Quartz, with a lesser concentration of Plagioclase Feldspar. The first SEM image below shows the rough highly sealed surface of the aggregate in a Calcite rich area. The Calcite presents as blocky small crystals, while the Quartz presents as darker, smooth areas. The hydrated Quartz crystal morphology looks like rounded, spiky spheres.



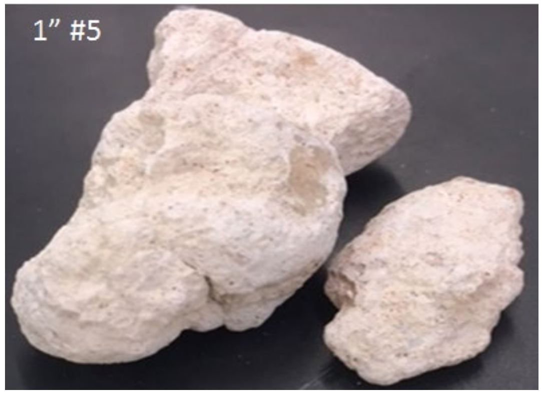
SEM/EDS analysis showing a high Calcite concentration with some Quartz (smooth, darker areas and hydrated Quartz in pore)

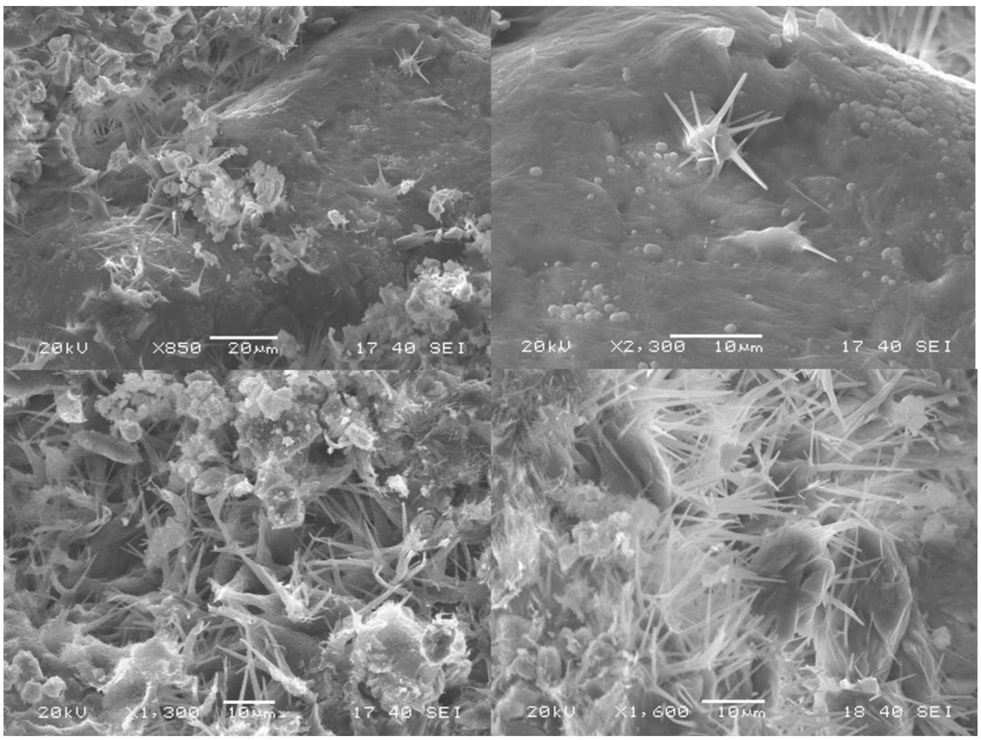


SEM/EDS phase analysis showing Calcite with Quartz grains interspersed. The yellow and green images show the EDS analysis, with the green representing the Quartz and the Yellow representing the Calcite.

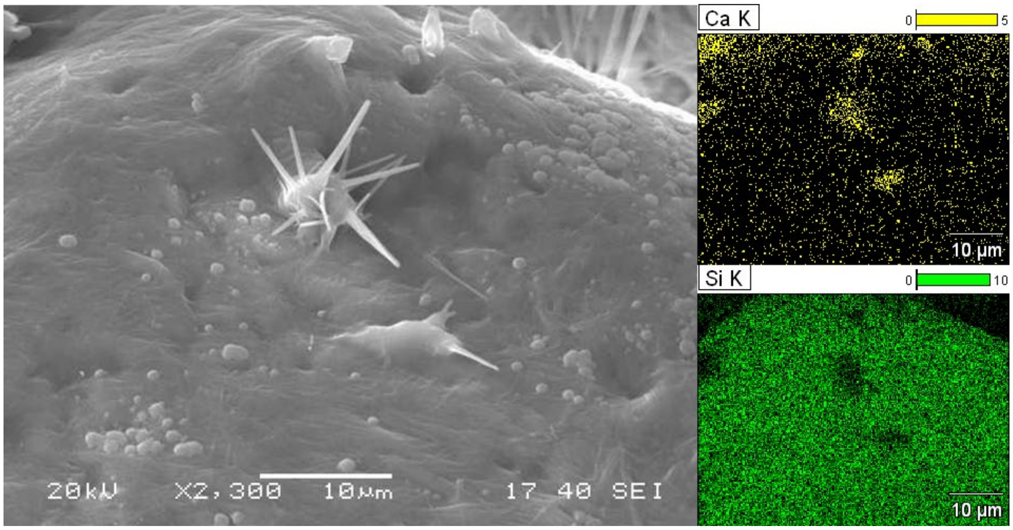
Jal 1" Sample #5

Jal 1" #5 sample was highly composed of Calcite crystals and Quartz.





SEM/EDS analysis showing a new morphology of Calcite crystals (spiky crystals) on Quartz.



SEM/EDS phase analysis showing a Calcite crystal (spiky-yellow represented by Calcium) on a Quartz grain (green represented by Silica).

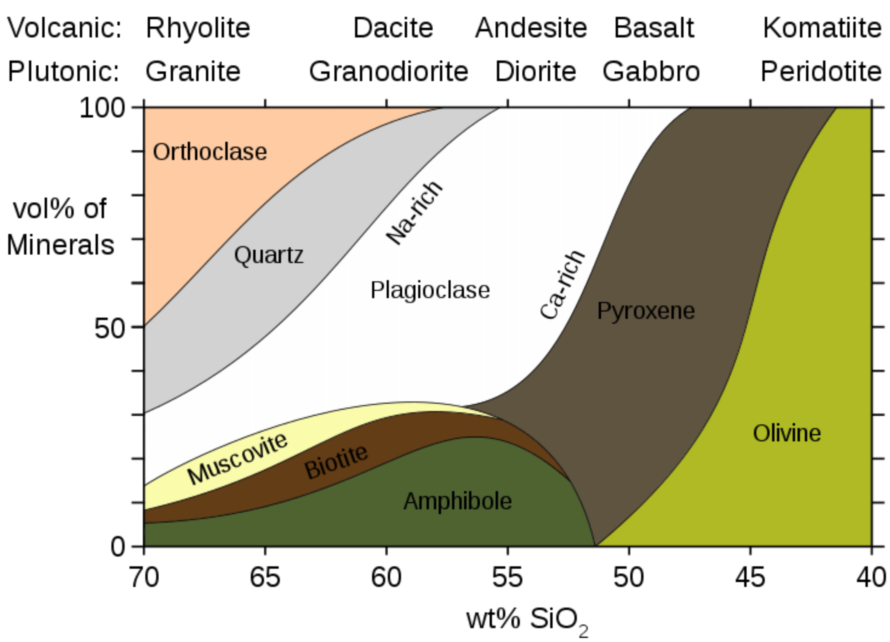
RAILROAD MOUNTAIN QUARRY

Two sizes of aggregate were obtained from the Railroad Mountain location including: a large size ~1" rock (these will be referred to as 1"), and a small size ~3/8"-Crusher Fines (this sample will be referred to as CF or crusher fines). Once at SNL, the 1" rock was separated visually into 3 different types as seen in the figure below. XRD was performed on each of the ~1" rocks and the Crusher Fines. SEM/EDS was performed on all of the size fractions as well.

Railroad Mountain Quarry	
1" Rock Type	Percentage of collected 1" sample by weight
#1	53.67%
#2	45.29%
#3	1.04%

Mineral Composition and Mohs Hardness

Based on the XRD analysis performed, it is evident that the Railroad Mountain sample is composed primarily of basalt. Basalt is an igneous rock composed of plagioclase and pyroxene minerals (King, H. 2005-2017). The chart below shows the generalized compositions of common igneous rocks.



https://en.wikipedia.org/wiki/Igneous_rock

Pyroxene was not detected in the Railroad mountain sample, indicating that the sample is composed primarily of plagioclase feldspar (likely Labradorite or Andesine). Plagioclase Feldspars are made up of 6 different minerals containing various combinations of the same elements. The table below shows the 6 plagioclase feldspar minerals.

	Amount of sodium and calcium	*Percentage of Albite (**Ab**)and Anorthite (**An**)*
Albite	$(Na_{100\%}, Ca_{0\%})\ Al\ Si_3O_8$	90-100% **Ab** ; 0-10% **An**
Oligoclase	$(Na_{90\%}, Ca_{10\%})\ Al_{1-2}Si_{3-2}O_8$	70-90% **Ab** ; 10-30% **An**
Andesine	$(Na_{70\%}, Ca_{30\%})\ Al_{1-2}Si_{3-2}O_8$	50-70% **Ab** ; 30-50% **An**
Labradorite	$(Ca_{70\%}, Na_{30\%})\ Al_{1-2}Si_{3-2}O_8$	30-50% **Ab** ; 70-50% **An**
Bytownite	$(Ca_{90\%}, Na_{10\%})\ Al_{1-2}Si_{3-2}O_8$	10-30% **Ab** ; 70-90% **An**
Anorthite	$(Ca_{100\%}, Na_{0\%})\ Al_2Si_2O_8$	0-10% **Ab** ; 90-100% **An**

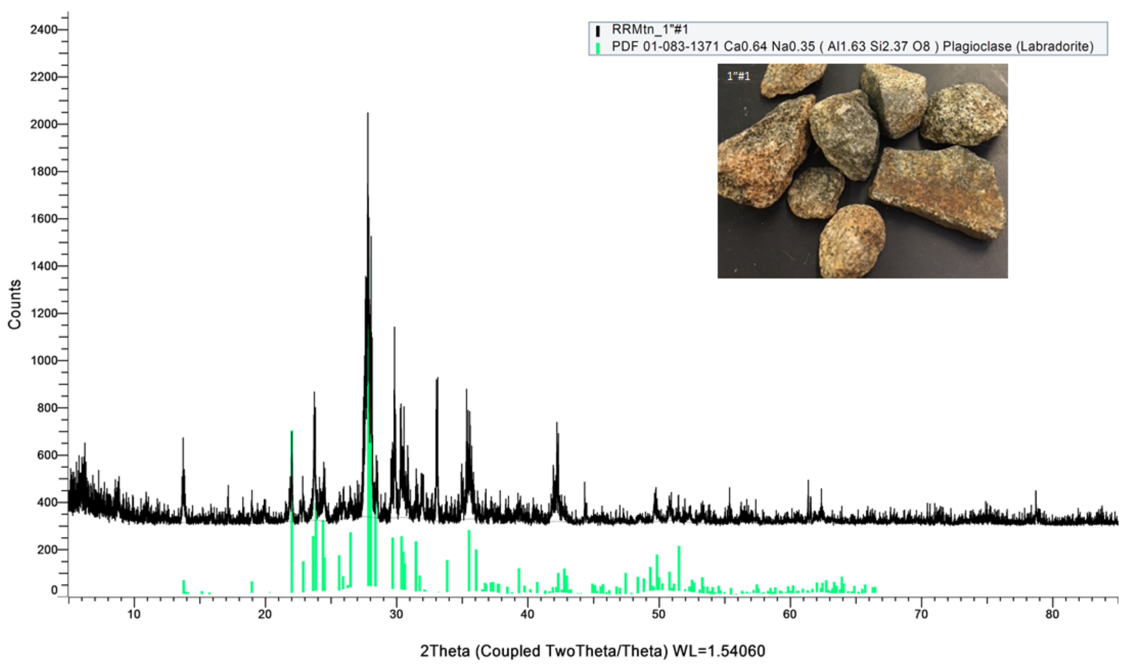
Actual formula of end members are:

Albite	$Na\ Al\ Si_3\ O_8$
Anorthite	$Ca\ Al_2\ Si_2\ O_8$

Minerals.net: http://www.minerals.net/mineral/plagioclase.aspx

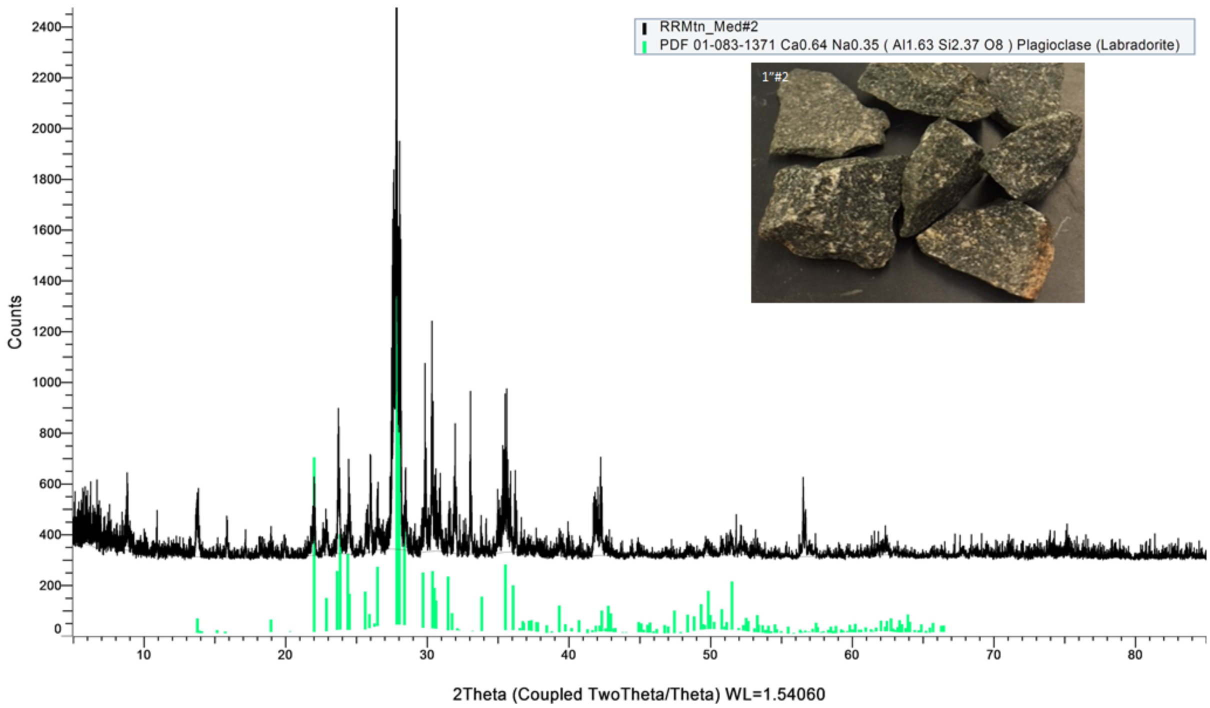
These 6 minerals are very difficult to distinguish using XRD, as the XRD patterns are very similar. Calcium and Sodium were detected in the SEM/EDS analysis in approximately equal abundance. Basalt has a Mohs hardness 6-6.5. The hardness of this mineral makes it highly resistant wear and abrasion. In addition, the higher silica content of this mineral may cause issues with stripping once emplaced in a project.

Railroad Mountain 1" Sample #1

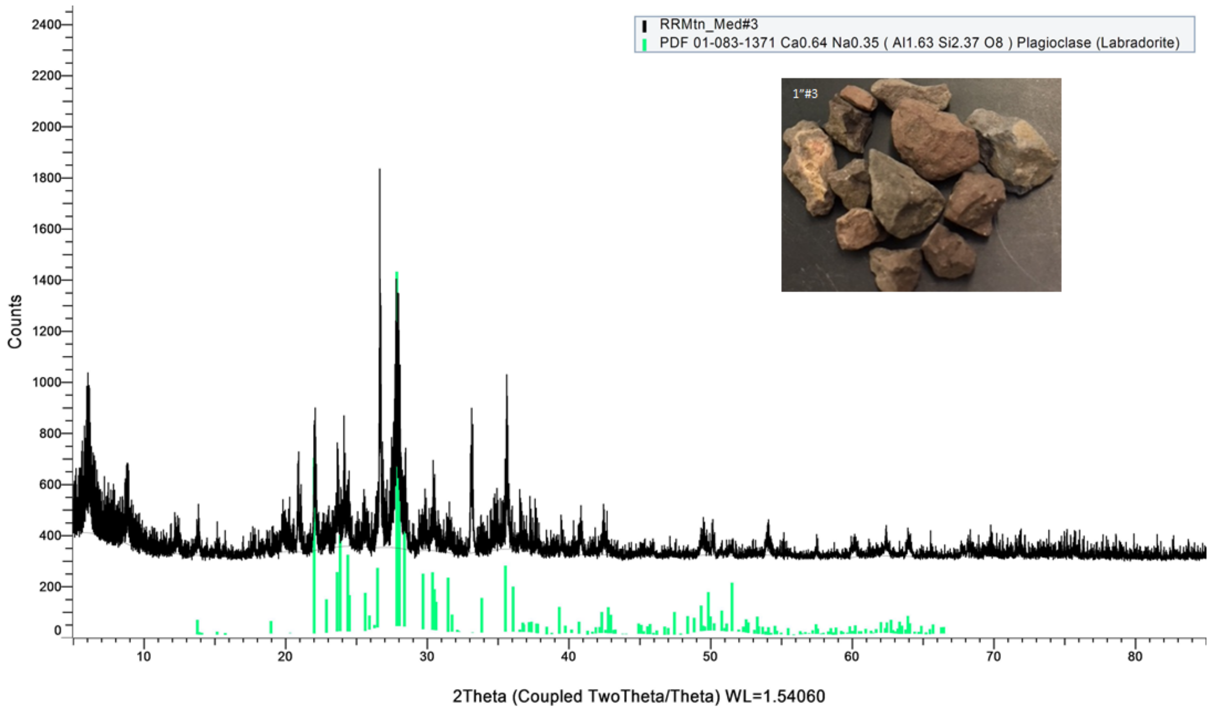


The black line above shows the peaks generated on the XRD by the Railroad Mountain 1” #1 sample. The green lines represent where Plagioclase Feldspar peaks should appear according to the ICDD. There are very few other peaks in the sample that are not identified, indicating an almost pure plagioclase feldspar sample. All of the other samples from Railroad Mountain were very similar to the 1” #1 sample. The XRD patterns for the other samples can be seen below.

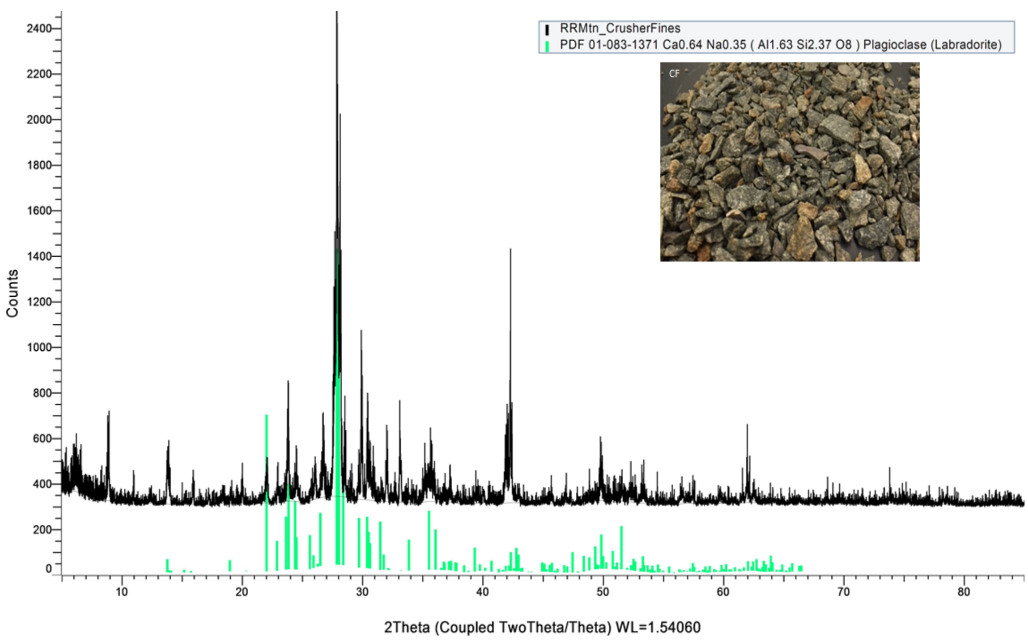
Railroad Mountain 1” Sample #2



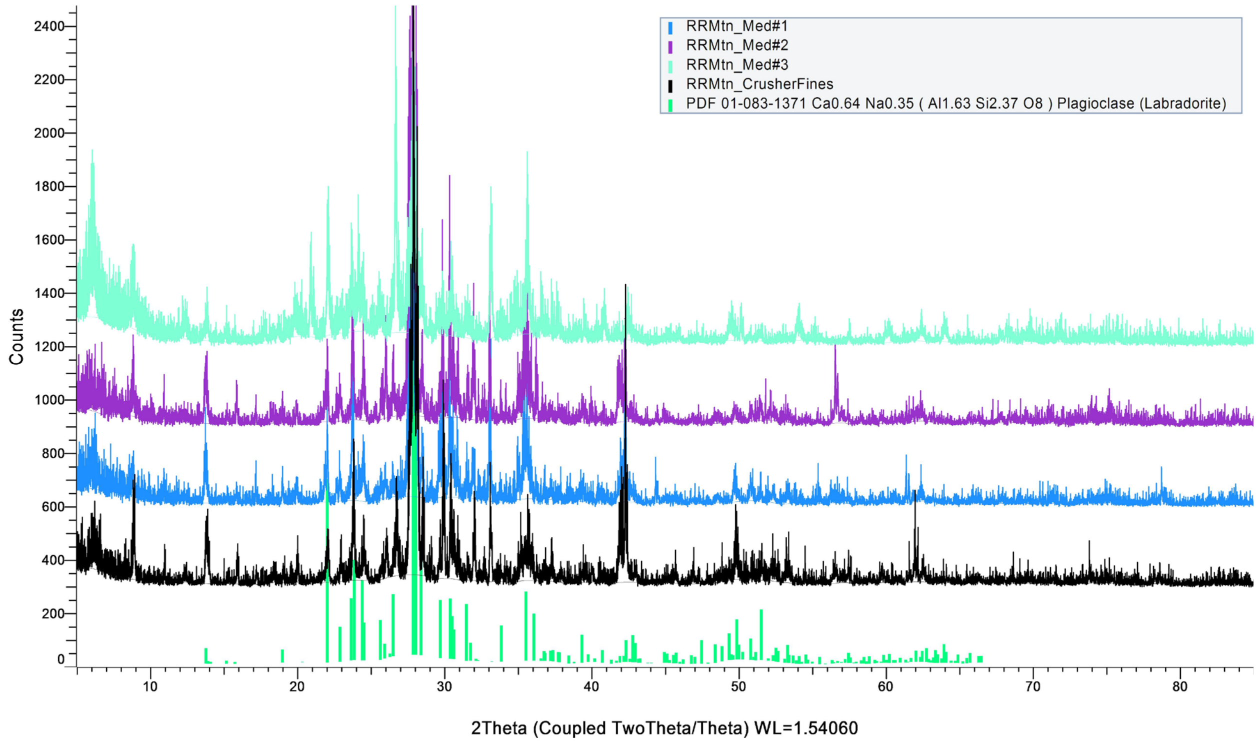
Railroad Mountain 1” Sample #3



Railroad Mountain Crusher Fines



Railroad Mountain ALL

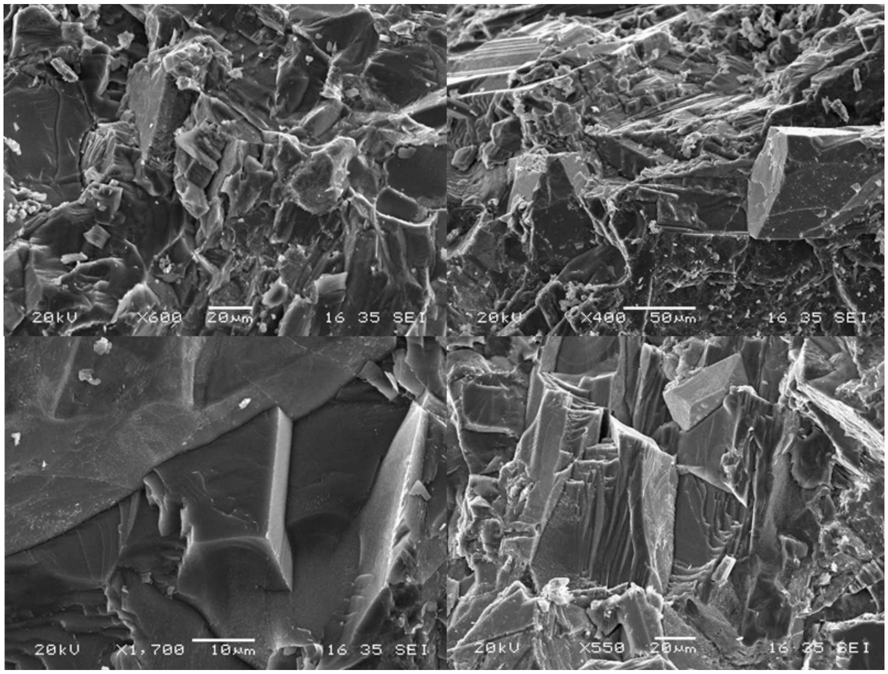


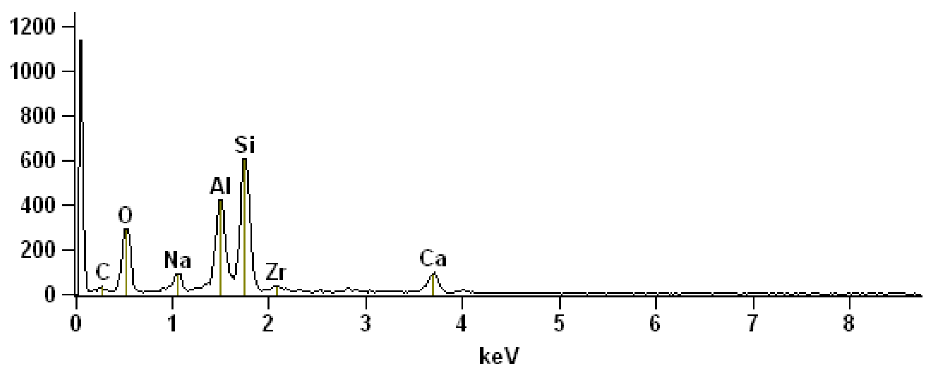
Surface Texture and Trace Elemental Analysis

Surface texture and trace elemental analysis was performed on all types of the 1” rock as well as the crusher fines. Each of the 1” rock types were analyzed individually for better trace element characterization.

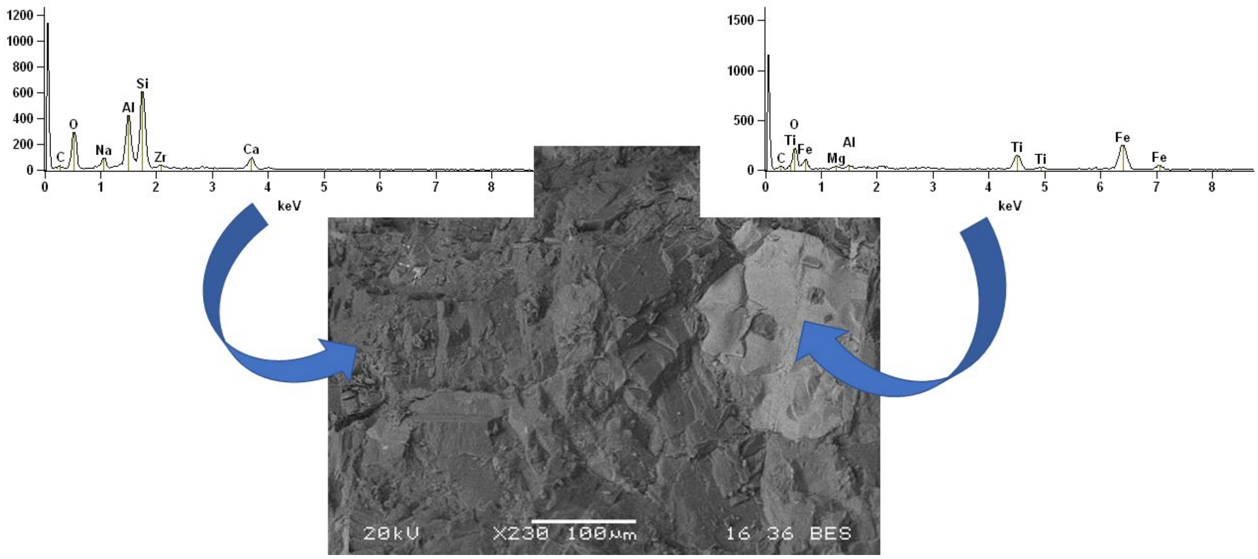
Railroad Mountain 1” #1 Sample

The Railroad Mountain 1” #1 sample shows a sealed surface topography, with very few pores, indicating a low porosity. The elemental analysis from the EDS shows a profile consistent with plagioclase feldspar. Interestingly, when using Back Scatter Electron analysis (SEM technique where heavier elements will show up lighter in color), areas of Iron and Titanium became evident. The final image in this section shows one of the Fe/Ti rich areas.





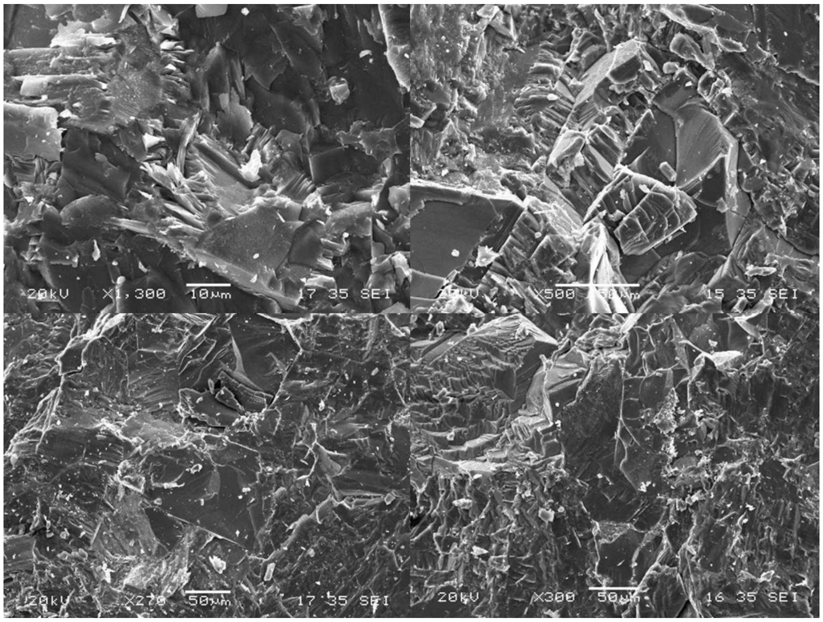
SEM/EDS analysis showing a rough surface topography with few pores. The EDS analysis is consistent with the Plagioclase Feldspar profile ((Na_x, Ca_x) $Al_{1-2}Si_{3-2}O_8$).

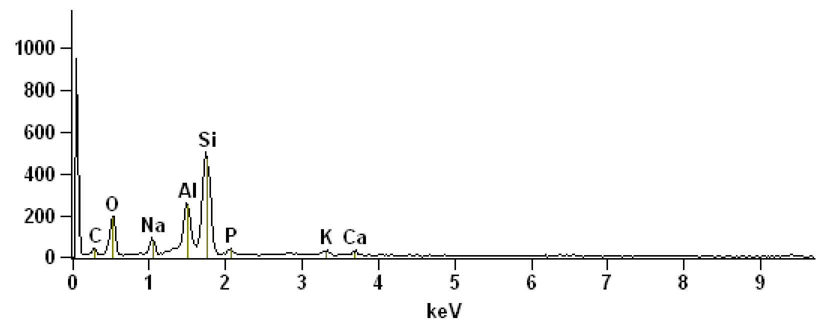


EDS Back Scatter Electron analysis showing lighter colored areas with higher iron and titanium and darker areas with the Plagioclase Feldspar elemental profile.

Railroad Mountain 1” #2

The Railroad Mountain 1” #2 sample showed a very similar surface topography as the #1 sample, with high surface texture and a plagioclase feldspar elemental profile. This sample also presented with areas rich in Iron and Titanium.

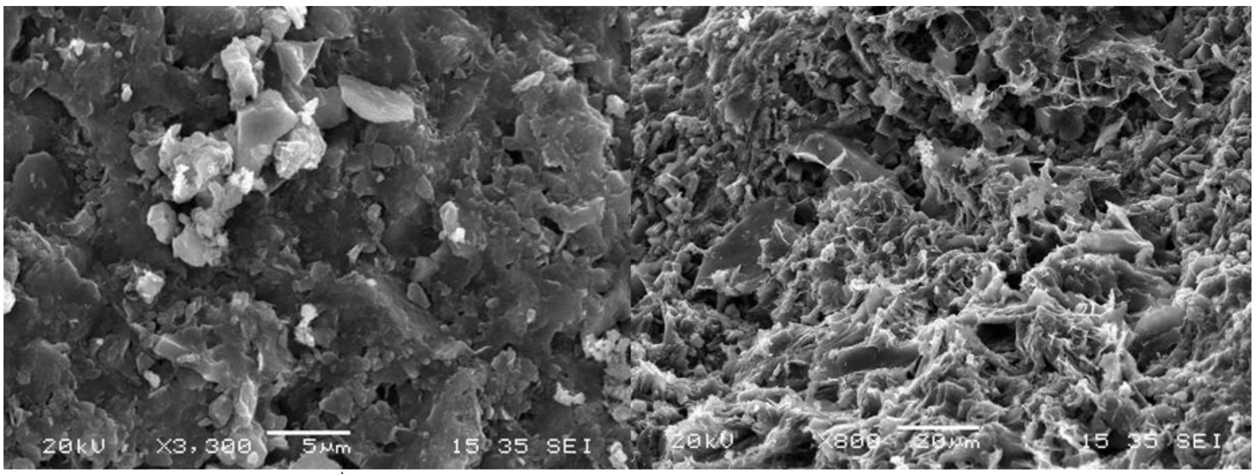


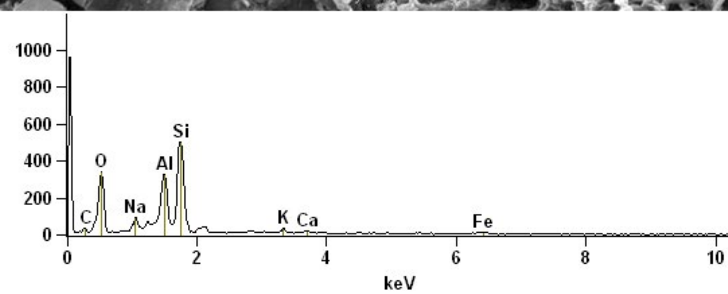


SEM/EDS analysis showing a rough surface topography with few pores. This surface profile should lead to a low porosity and high surface area, creating good adhesion between the binder and aggregate. The elemental profile from this sample is presenting with slightly more sodium than calcium (based on peak heights), however is still consistent with Plagioclase Feldspar.

Railroad Mountain 1” #3

The Railroad Mountain 1” #3 sample was visibly more red in color than the #1 and #2 samples. This rock was the lowest percentage in prevalence at only 1% of the total 1” sample obtained. This sample shows a very similar elemental profile as the #1 and #2 1” samples, however the surface topography is more smooth. In addition, a trace amount of iron was detected which is likely the cause of the reddish color of the rock.

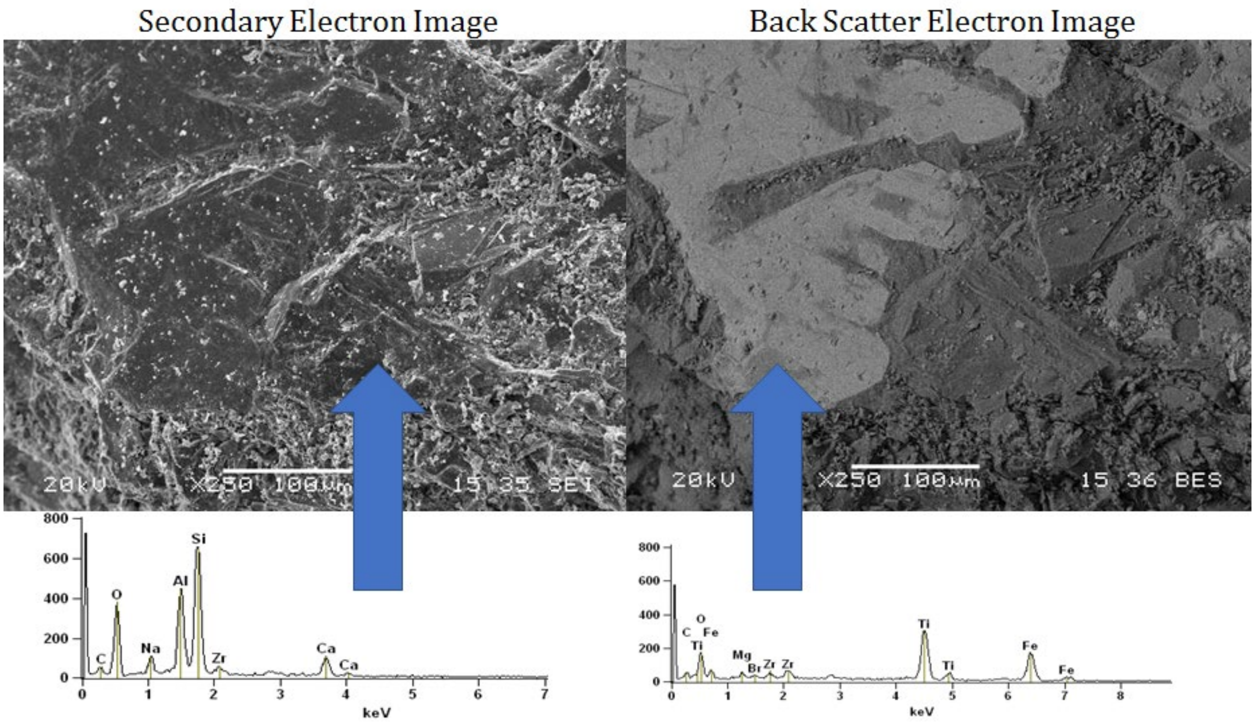




SEM/EDS analysis showing an elemental profile consistent with Plagioclase Feldspar with trace iron. The iron is likely giving the rock its' red color. The surface of this sample is smoother than seen in the #1 and #2 samples.

Railroad Mountain Crusher Fines

The Railroad Mountain crusher fines sample shows a rough surface topography and an elemental profile consistent with Plagioclase Feldspar. Inclusions of iron and titanium rich areas were seen with EDS Back Scatter Electron analysis.



SEM/EDS analysis showing the exact same image with comparison of the two SEM/EDS techniques. The image on the left shows the sample using Secondary Electron EDS analysis. In this image, the Fe/Ti rich areas are not visible and the majority of the sample appears to be a consistent sample of Plagioclase Feldspar. The image on the right shows the same image using Back Scatter Electron analysis, where the Fe/Ti rich areas become highly visible. The lighter colored areas are the Fe/Ti rich areas, while the darker areas are Plagioclase Feldspar.

BOYD QUARRY

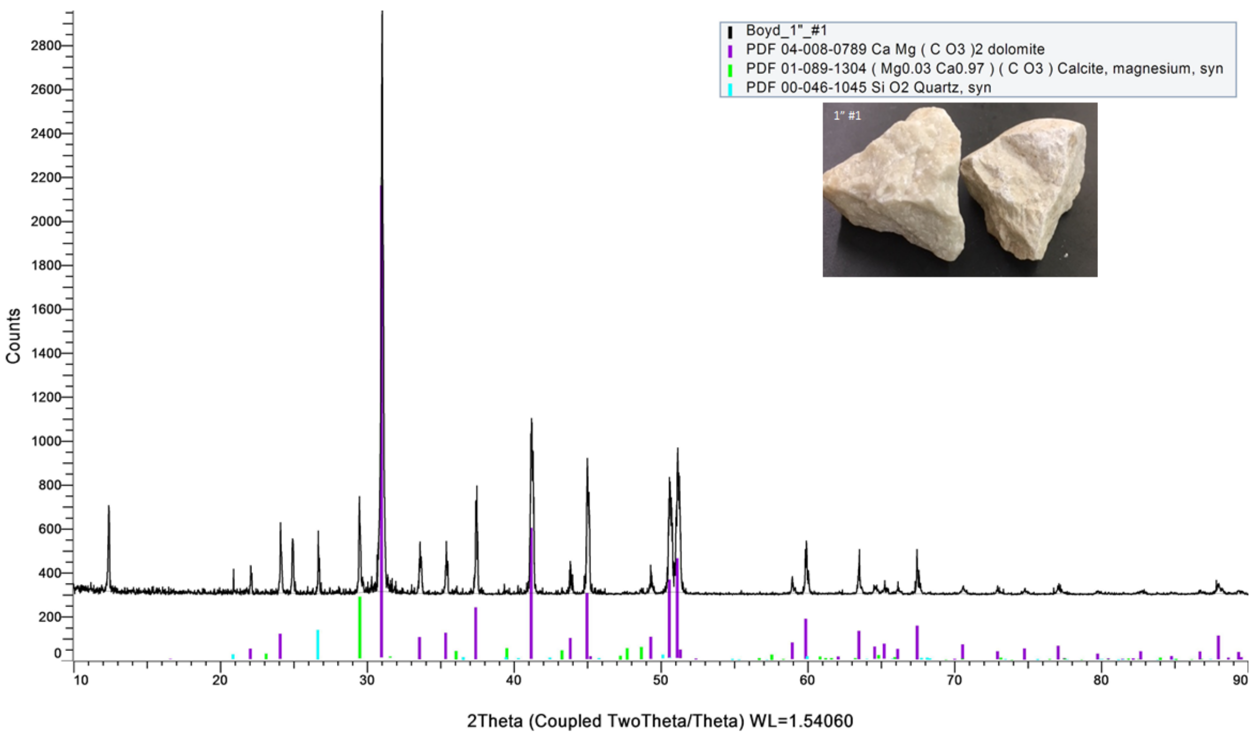
Three sizes of aggregate were obtained from the Boyd location including: 1” rock, 3/8” rock and Crusher Fines. Once at SNL, the 1” rock was separated visually into 5 different types as seen in the figure below. XRD was performed on each of the 1” types, 3/8” and CF.

Boyd Quarry	
1" Rock Type	Percentage of whole sample by weight
#1	16.33%
#2	40.66%
#3	26.75%
#4	14.40%
#5	1.87%

Mineral Composition and Mohs Hardness

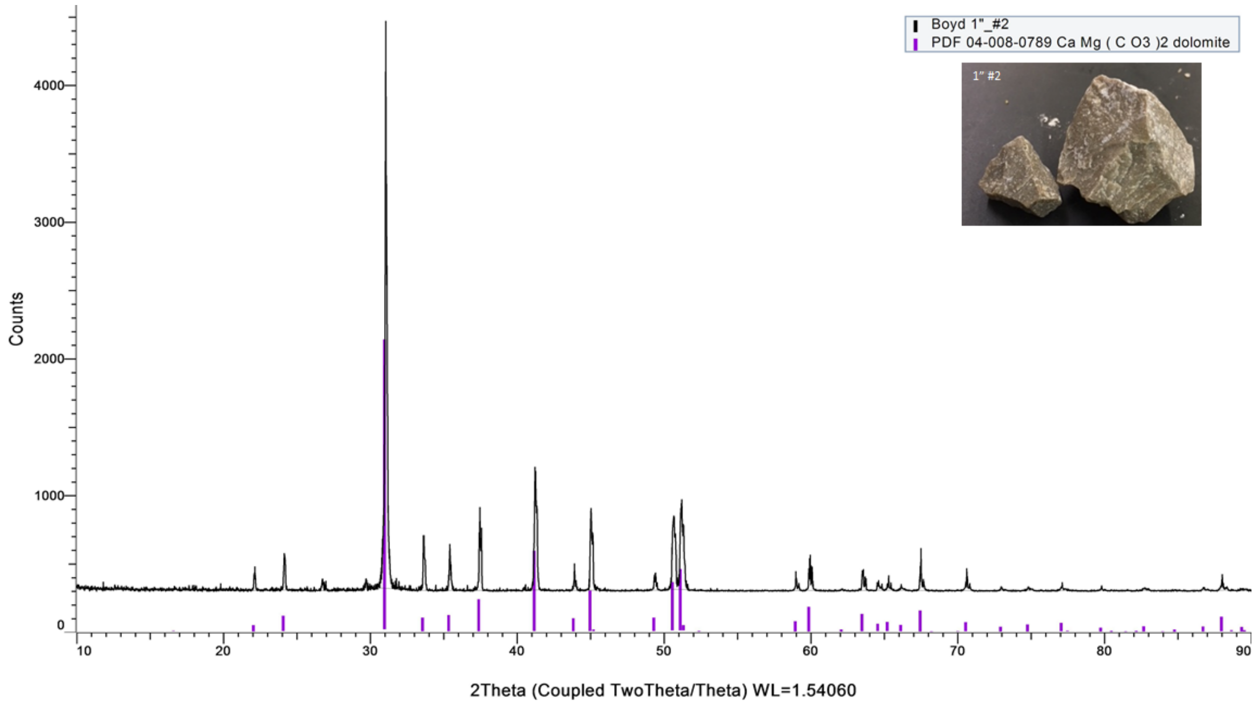
Based on the XRD analysis performed, it is evident that the Boyd aggregate is composed primarily of Dolomite ($CaMg(CO_3)_2$) with smaller percentages of calcite($CaCO_3$) and quartz (SiO_2). The 1” #2 and 1” #3 type rocks make up ~67% of the total 1” rock and they are both pure Dolomite, according to XRD. The heights of each of the XRD peaks represent the relative concentration of each of the minerals identified, based on intensity generated by the crystalline structure of the mineral being measured. Dolomite has a Mohs hardness of 3.5-4, Calcite has a Mohs hardness of 3 and Quartz has a Mohs hardness of 7. The hardness of Dolomite, along with its alkaline nature (hydrophobic) makes it a superior candidate for various paving projects due to its ability to resist wear and stripping. Calcite is a slightly softer mineral however, its alkaline nature makes it a good candidate to prevent stripping, although in time it may be subject to smoothing under heavy traffic or heavy abrasion. The addition of small concentrations of quartz could increase the aggregates resistance to heavy abrasion. The acidic nature of quartz can cause issues with stripping at high concentrations. At the quartz concentrations seen in these samples, it isn't likely to adversely affect aggregate/oil adhesion.

Boyd 1" #1



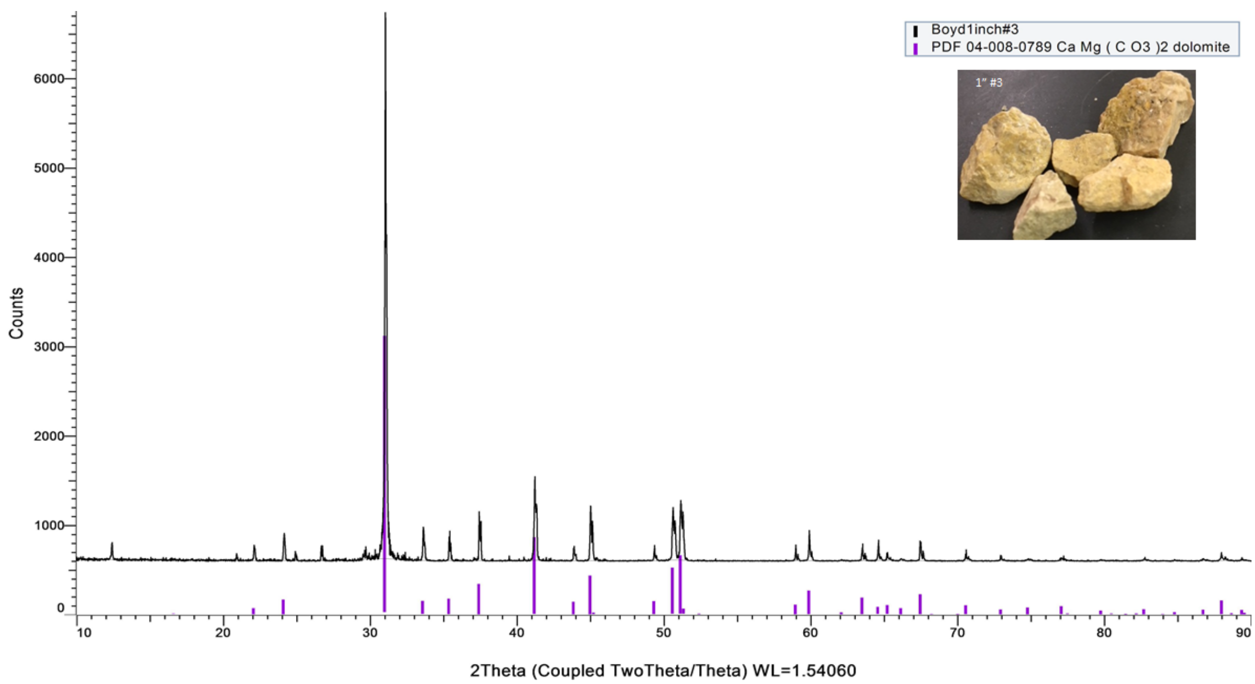
The black line in the image above represents the peaks that were generated on the XRD by the sample. The purple lines represent where peaks of Dolomite should appear according to the ICDD. The green lines represent where peaks of Calcite should appear and the Cyan lines represent where peaks of Quartz should appear in accordance with the ICDD. This XRD pattern shows that the sample is composed primarily of Dolomite with much lower concentrations of Calcite and Quartz.

Boyd 1" #2



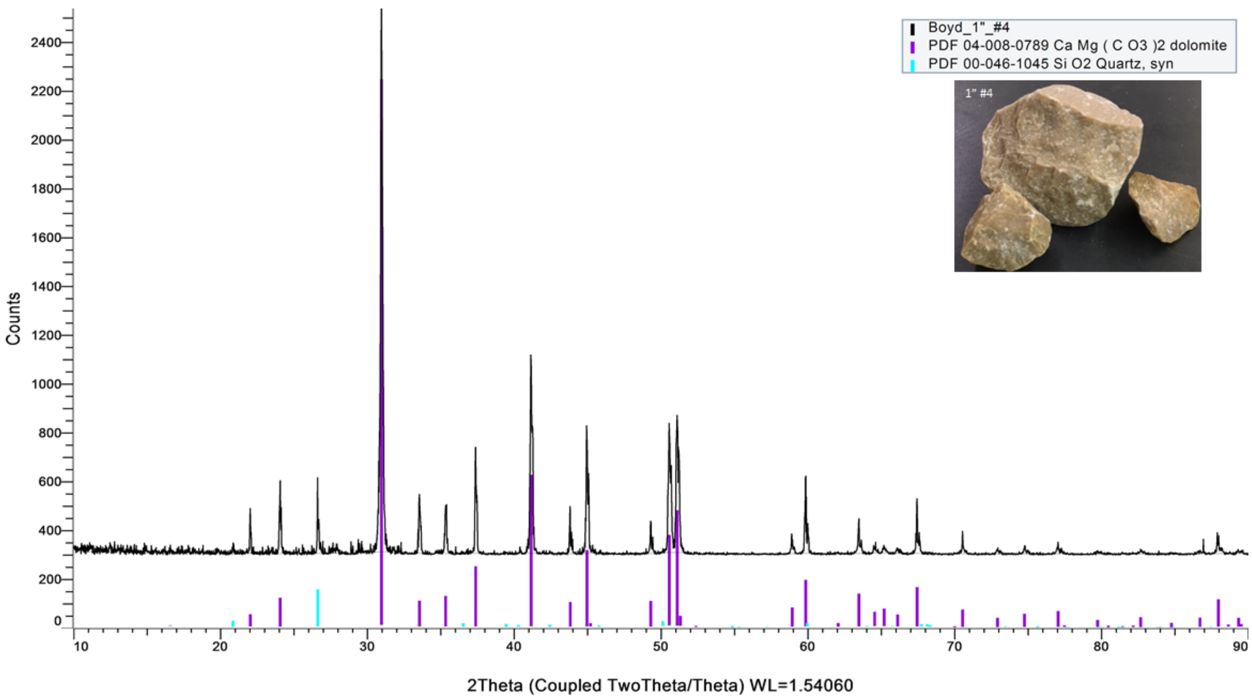
The black line in the image above represents the peaks that were generated on the XRD by the sample. The purple lines represent where peaks of Dolomite should appear according to the ICDD. Boyd 1” #2 sample has a pure dolomite XRD profile, meaning it is 100% dolomite, based on XRD.

Boyd 1” #3



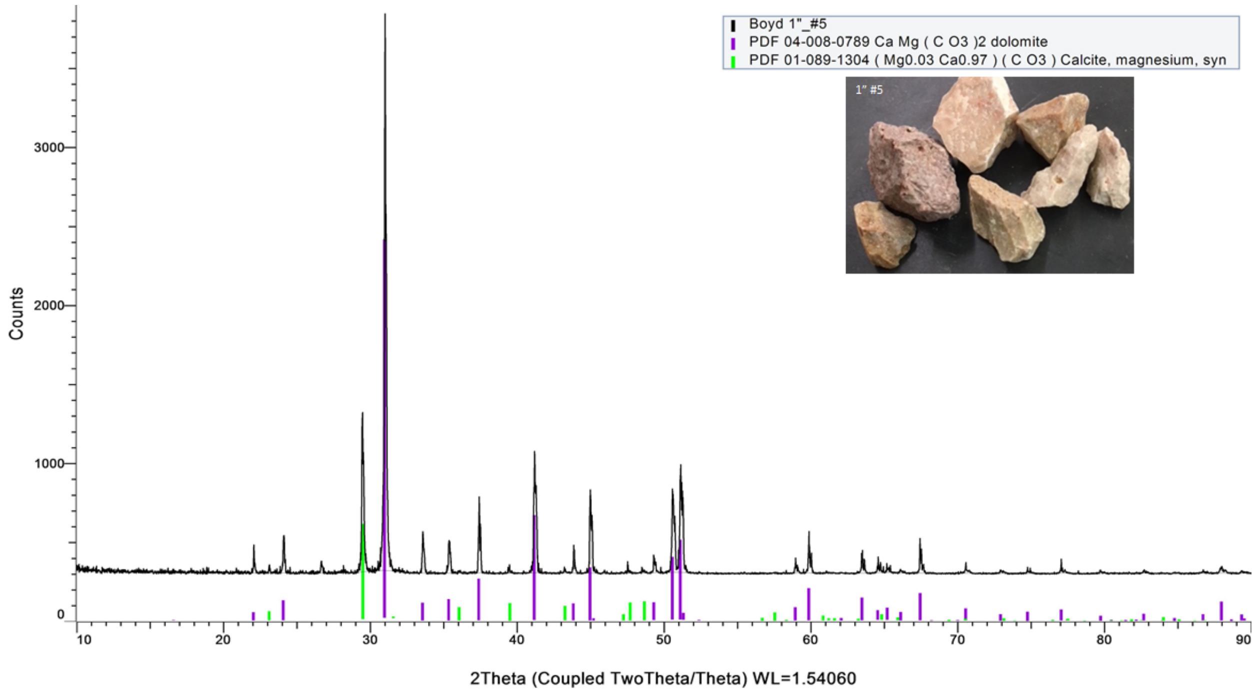
The black line in the image above represents the peaks that were generated on the XRD by the sample. The purple lines represent where peaks of Dolomite should appear according to the ICDD. Boyd 1" #3 sample has a pure dolomite XRD profile, meaning it is 100% dolomite, based on XRD analysis.

Boyd 1" #4



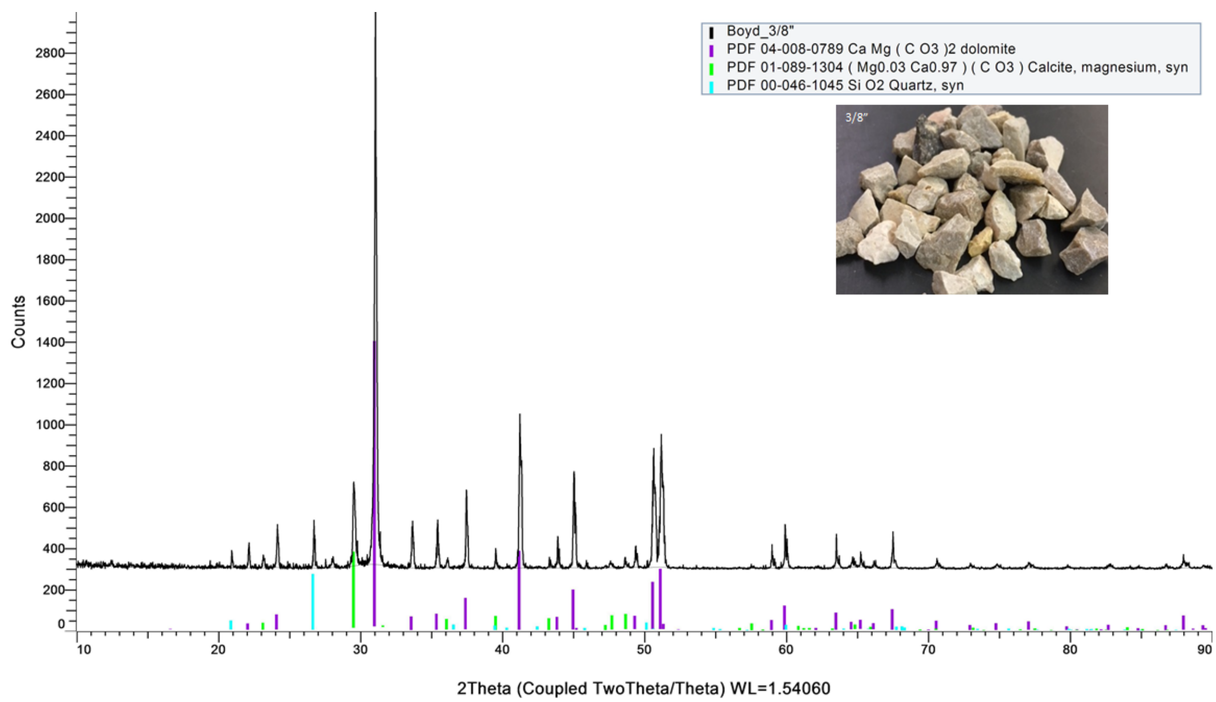
The black line in the image above represents the peaks that were generated on the XRD by the sample. The purple lines represent where peaks of Dolomite should appear and the Cyan lines represent where Quartz peaks should appear according to the ICDD. Boyd 1" #4 sample has a dominant concentration of Dolomite with a small concentration of Quartz.

Boyd 1" #5

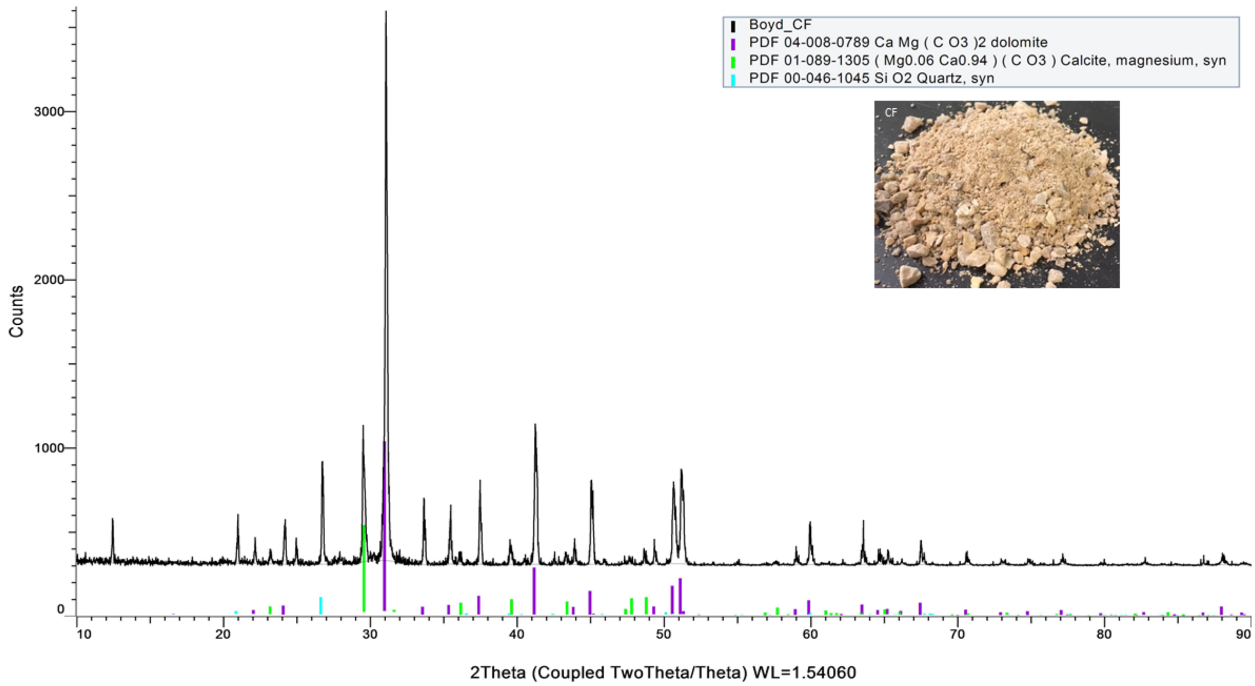


The black line in the image above represents the peaks that were generated on the XRD by the sample. The purple lines represent where peaks of Dolomite should appear and the green lines represent where Calcite peaks should appear according to the ICDD. Boyd 1" #5 sample is composed primarily of Dolomite with a small concentration of Calcite.

Boyd 3/8"

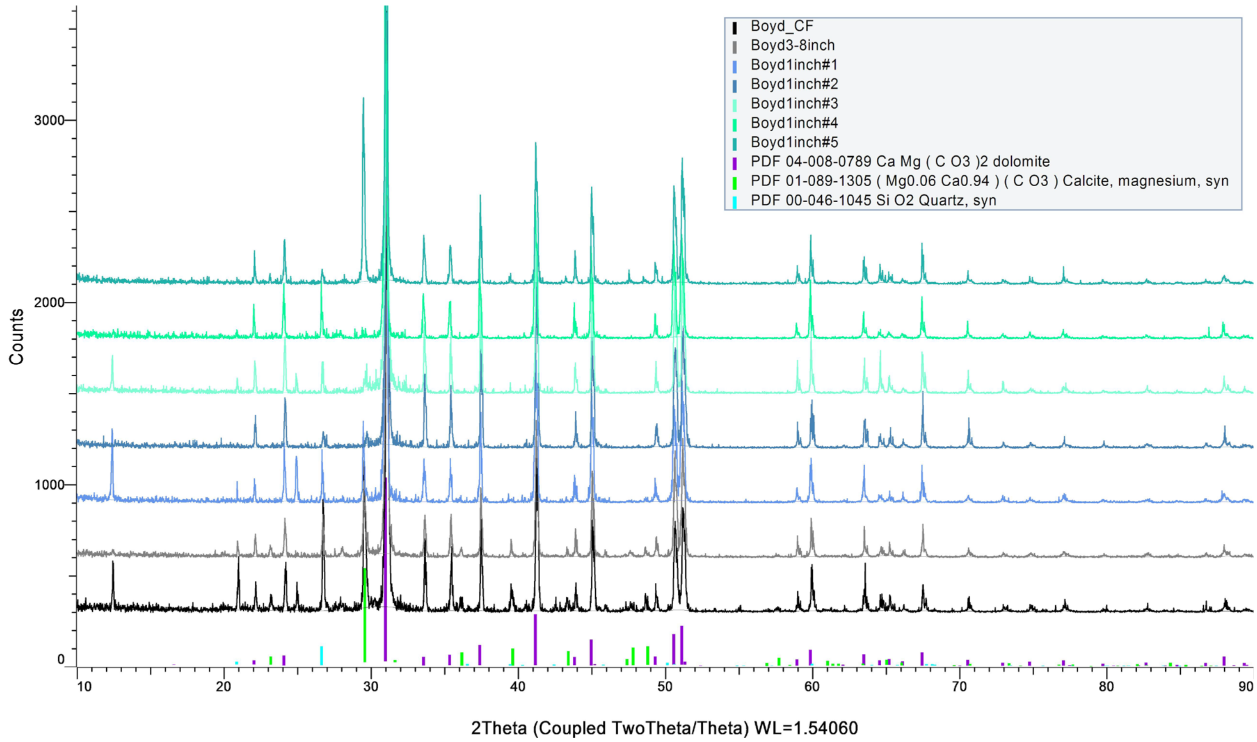


Boyd Crusher Fines



The black lines in the 3/8" and Crusher Fines images above represents the peaks that were generated on the XRD by the sample. The purple lines represent where peaks of Dolomite should appear according to the ICDD. The green lines represent where peaks of Calcite should appear and the Cyan lines represent where peaks of Quartz should appear in accordance with the ICDD. These XRD patterns shows that the sample is composed primarily of Dolomite with much lower concentrations of Calcite and Quartz. All of the XRD patterns are displayed on one image below to make comparison easier.

Boyd ALL

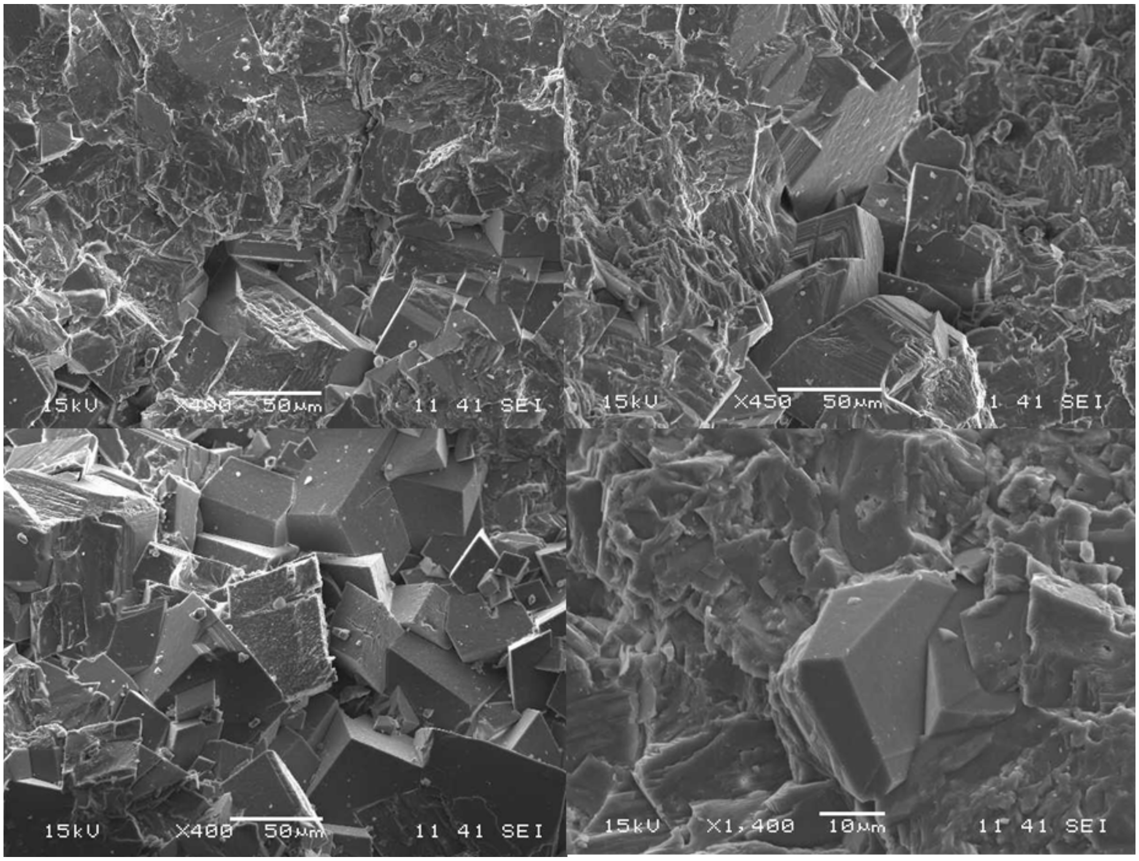


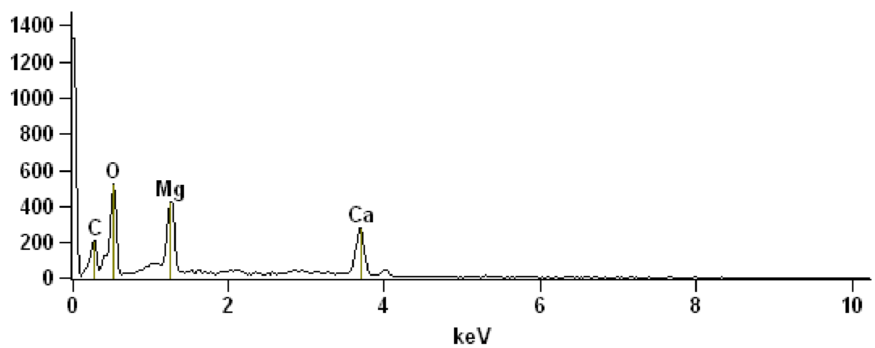
Surface Texture and Trace Elemental Analysis

Surface texture and trace elemental analysis was performed on all sizes of the Boyd rock. Each of the 1" rock types were analyzed individually for better trace element characterization.

Boyd 1" Sample #1

The Boyd 1" #1 sample shows a sealed surface topography with few pores Indicating low porosity. The surface texture is visibly rough, with blocky dolomite crystals very prevalent. This surface profile should allow good adhesion between the aggregate and the binder material. The EDS elemental analysis of the various phases of the sample shows consistency with the XRD in being a very pure Dolomite, presenting the elements Calcium, Magnesium, Carbon and Oxygen.

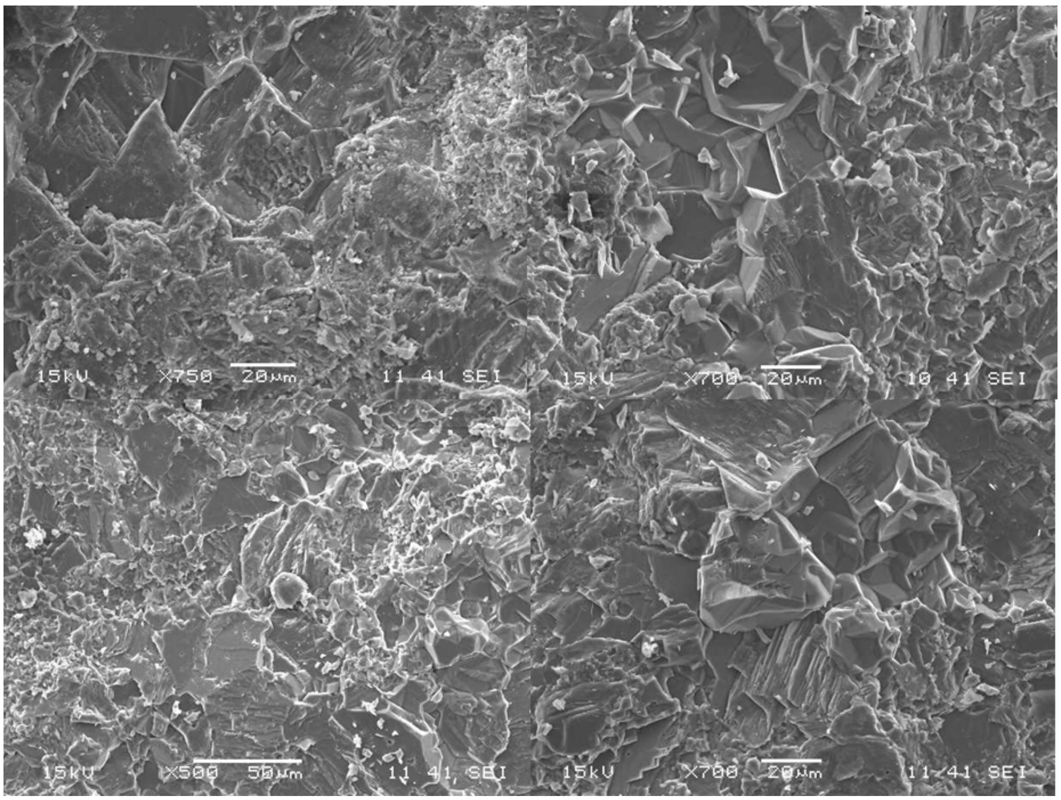


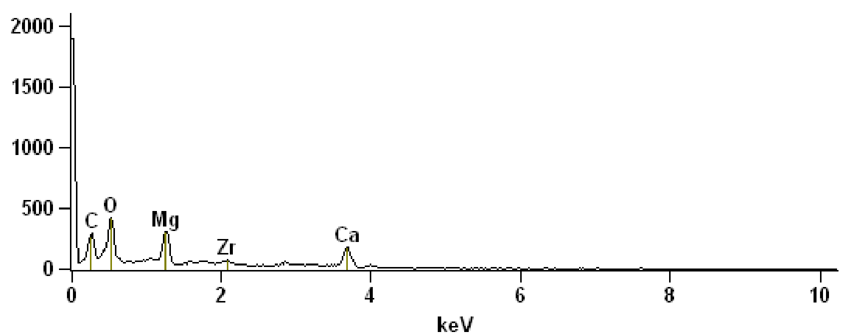


SEM/EDS analysis showing blocky Dolomite crystals and an elemental profile consistent with Dolomite ($CaMg(CO_3)_2$). The surface is visibly sealed with few pores.

Boyd 1" Sample #2

The 1" #2 sample showed a sealed surface topography that was also very rough. Very few pores were seen, indicating a low porosity. Fewer of the blocky Dolomite crystals were visible, however all phases analyzed with the EDS showed a pure elemental profile consistent with Dolomite.

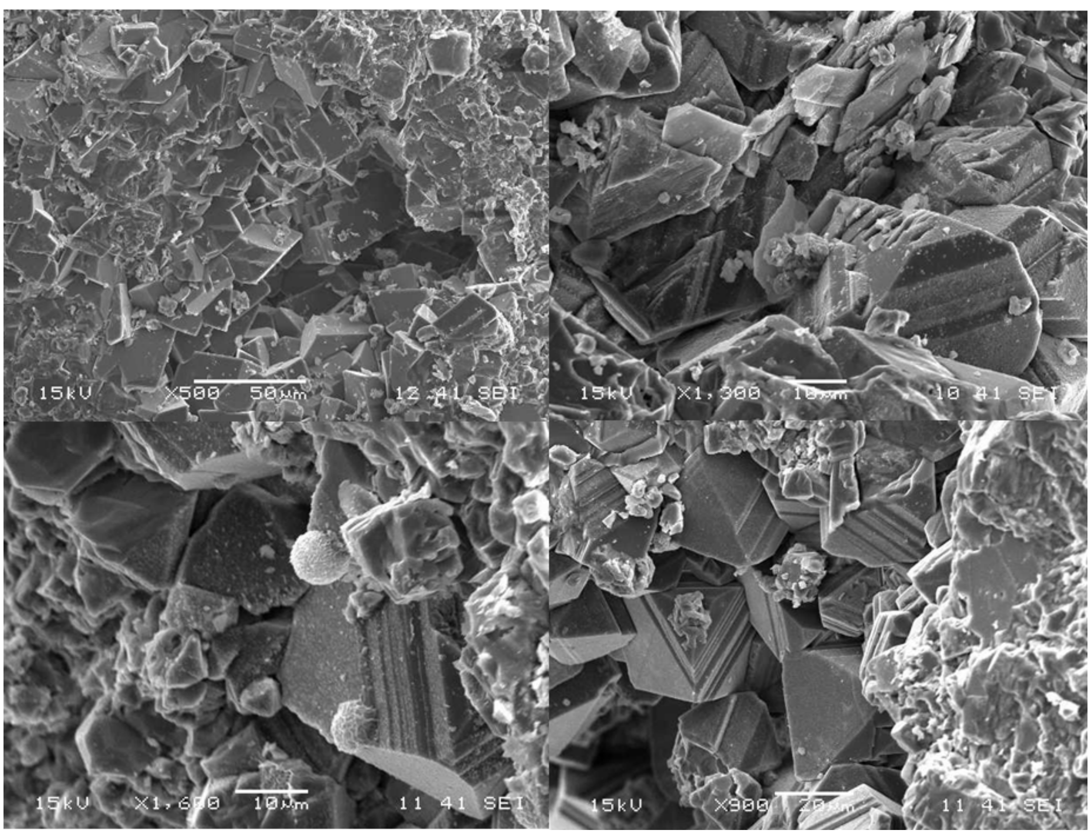


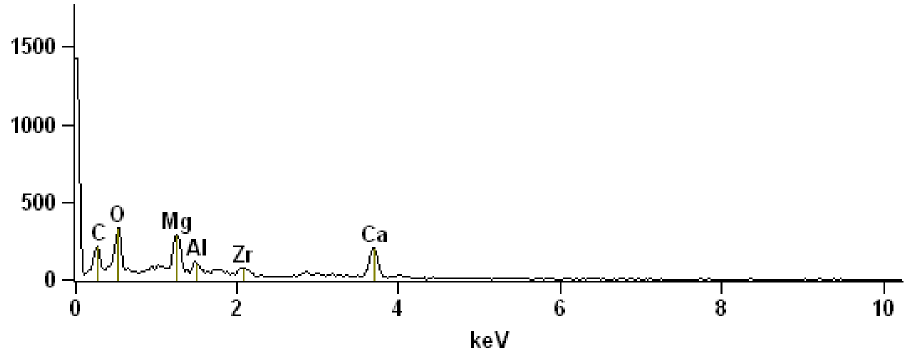


SEM/EDS analysis showing rough surface topography, low pore volume and an EDS elemental profile consistent with Dolomite.

Boyd 1” Sample #3

The Boyd 1” #3 sample was visibly yellow in color. The SEM/EDS analysis confirmed the XRD analysis and showed an elemental profile consistent with Dolomite. More pores were seen in this sample however the other areas of the aggregate presented a sealed, rough surface topography. This sample had numerous blocky Dolomite crystals. Interestingly, these crystals are not the same shape as the crystals seen in the 1” #1 sample. It is possible that the trace elements in this sample (Al, and Zr) are contributing to the altered (more triangular) shape of these Dolomite crystals.

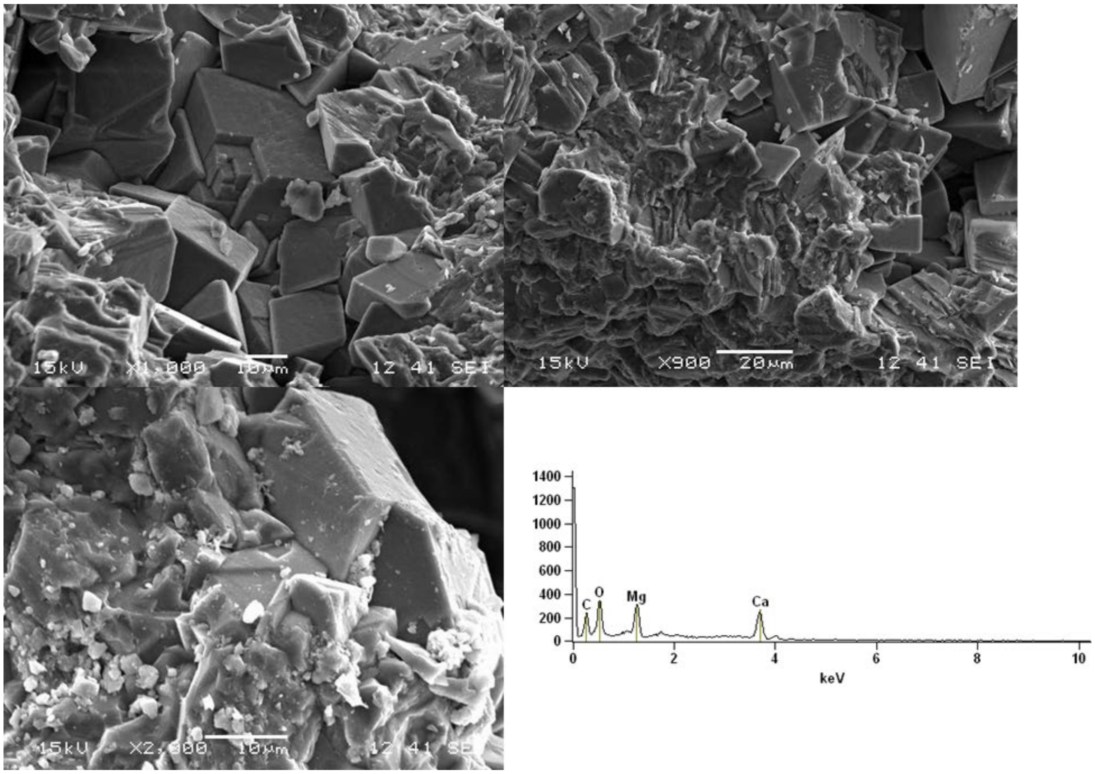




SEM/EDS analysis showing blocky (triangular) Dolomite crystals with trace Aluminum and Zirconium. Rough surface topography is prevalent, however more pores are also present than seen in previous samples.

Boyd 1" Sample #4

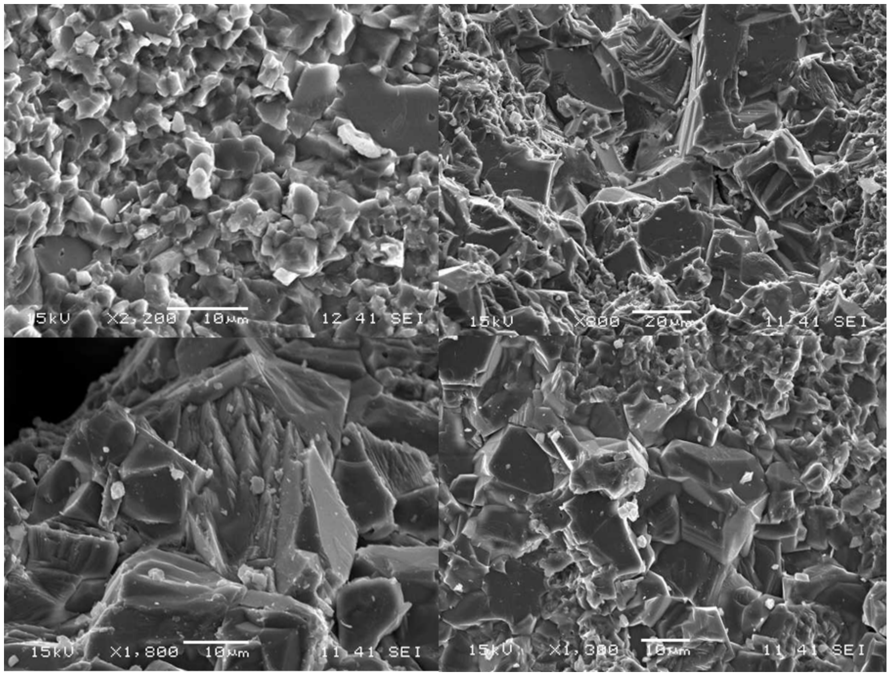
Boyd 1" Sample #4 shows a sealed surface topography with Dolomite crystals highly prevalent through-out. Very few pores were seen in this sample, indicating a low porosity. The elemental profile generated by the EDS was consistent with Dolomite and confirmed the XRD analysis.

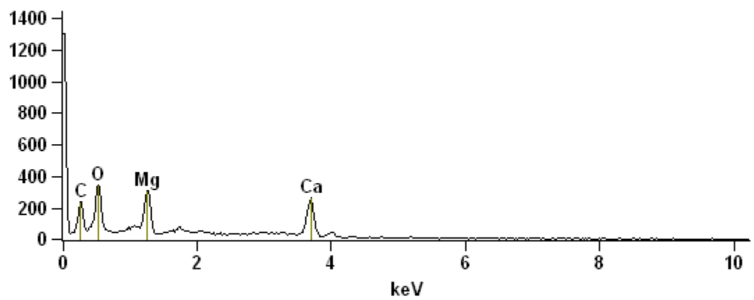


SEM/EDS analysis showing a sealed surface topography with blocky Dolomite crystals prevalent. EDS elemental analysis shows a profile consistent with Dolomite.

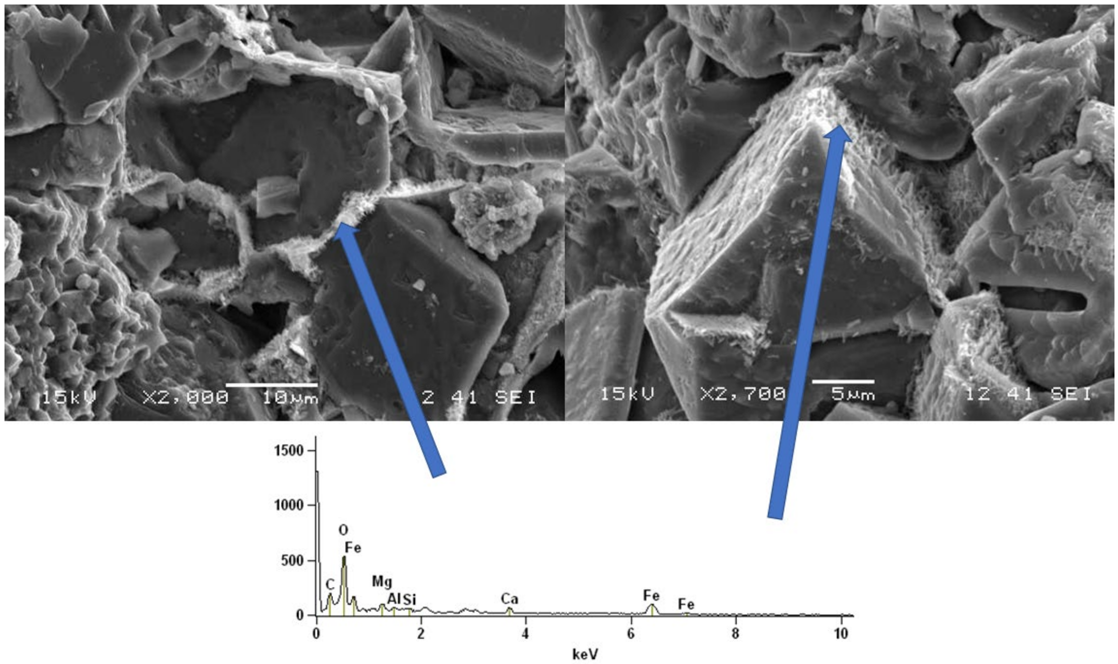
Boyd 1” Sample #5

Boyd 1” sample #5 was visibly red in color. This sample has a visibly rough surface with some pores being visible through-out. The elemental profile of this sample is consistent with Dolomite. Some of the Dolomite crystals had phases of hair-like crust on the surface. This crust was analyzed and iron was found to be present. The high iron presence in this crust, is likely what is causing the aggregate to appear red in color.





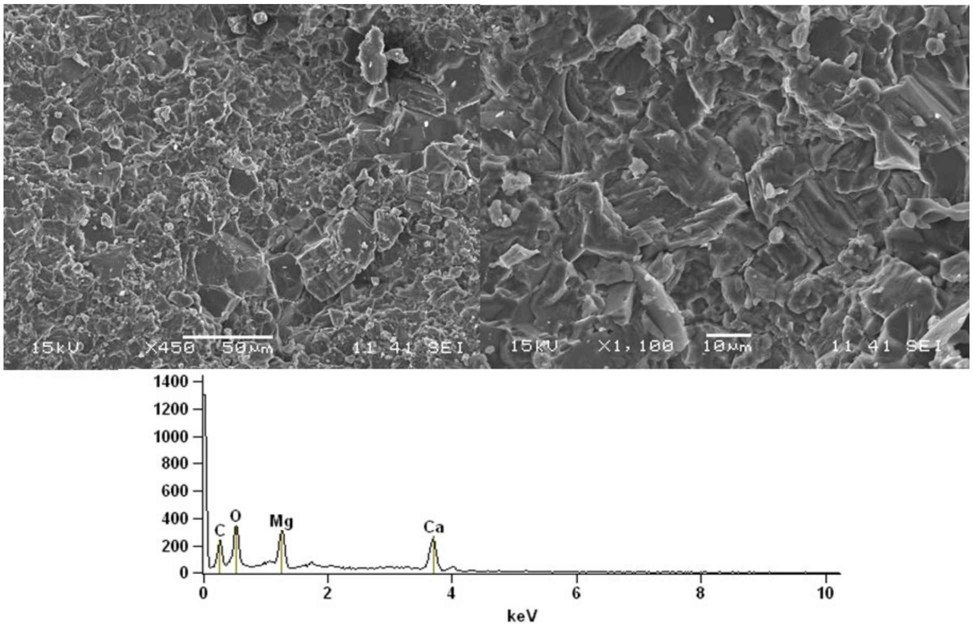
SEM/EDS analysis showing a sealed, rough surface topography with numerous Dolomite crystals present. Elemental profile is consistent with Dolomite.



SEM/EDS analysis showing the hair-like crust present on numerous Dolomite crystals. The crust was found to have a high concentration of iron, which is likely causing the visibly red color of the aggregate.

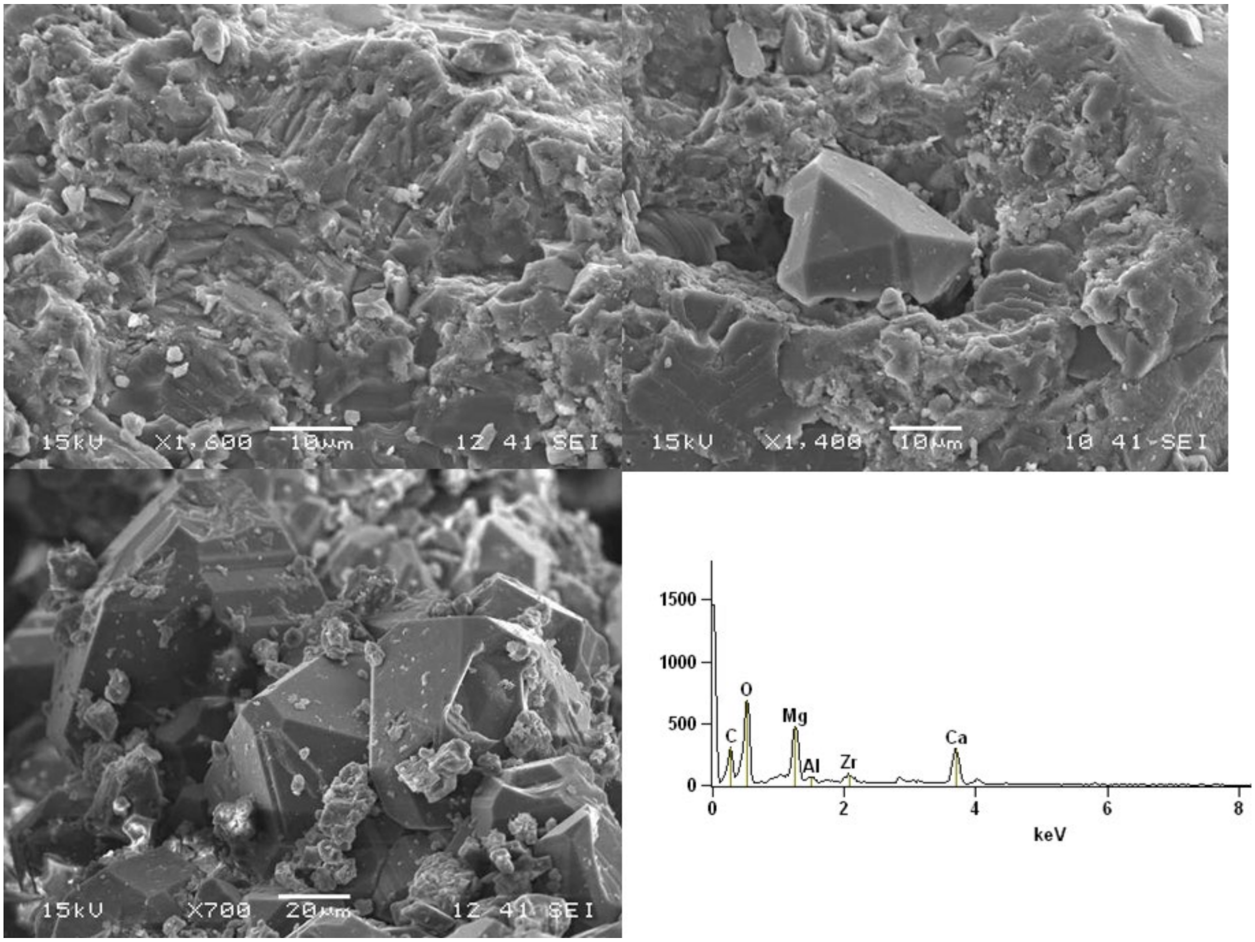
Boyd 3/8”

The Boyd 3/8” sample showed a surface and elemental profile consistent with the 1” samples. The elemental profile was consistent with Dolomite.



Boyd 1” Crusher Fines

The Boyd Crusher Fines sample showed a surface and elemental profile consistent with the 1” samples. The elemental profile was consistent with Dolomite.



SEM/EDS analysis showing a sealed surface topography with Dolomite crystals strewn through-out. Interestingly these crystals have a triangular type shape as seen in the 1" #3 sample. The elemental profile for these crystals contains Aluminum and Zirconium as seen in the 1"#3 sample. This indicates that the triangular Dolomite morphology may be linked to the trace elements, Al and Zr.

RIO FELIX QUARRY

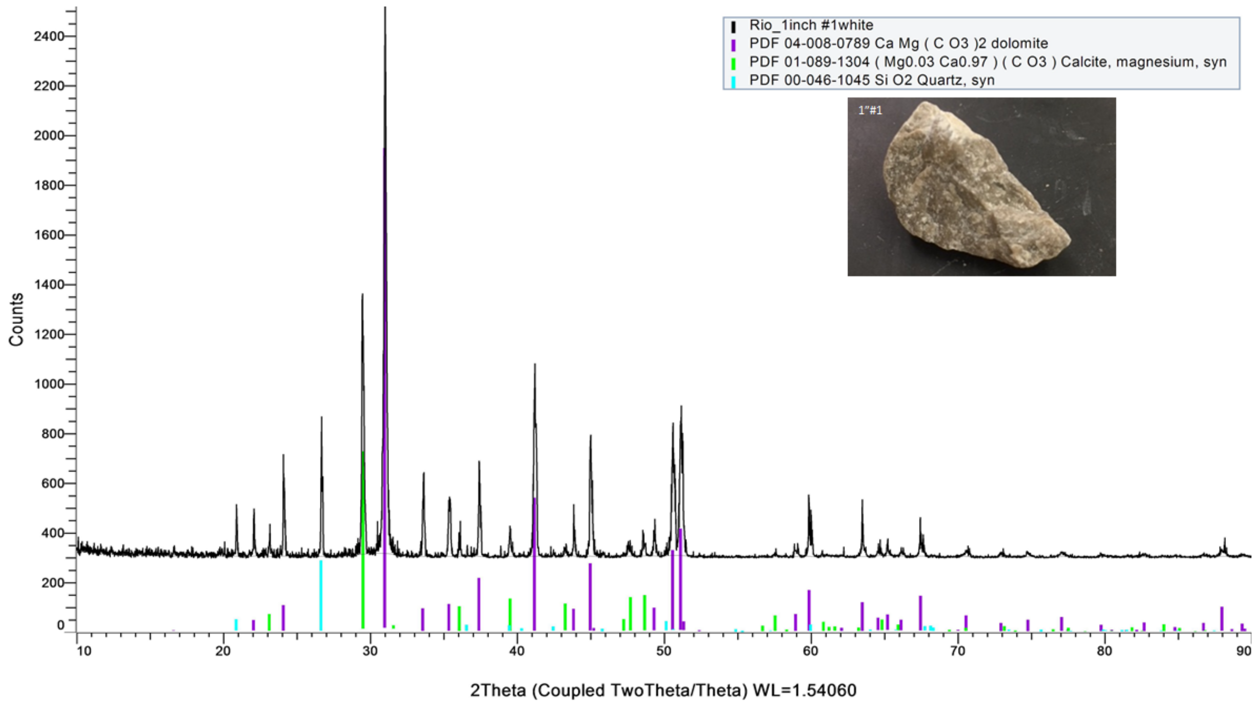
Three sizes of aggregate were obtained from the Rio Felix location including: 1" rock, 3/8" rock and Crusher Fines. Once at SNL, the 1" rock was separated visually into 2 different types as seen in the figure below. XRD was performed on each of the 1" types, 3/8" and Crusher Fines.

Rio Felix	
1" Rock Type	Percentage of whole sample by weight
#1	53.67%
#2	45.29%

Mineral Composition and Mohs Hardness

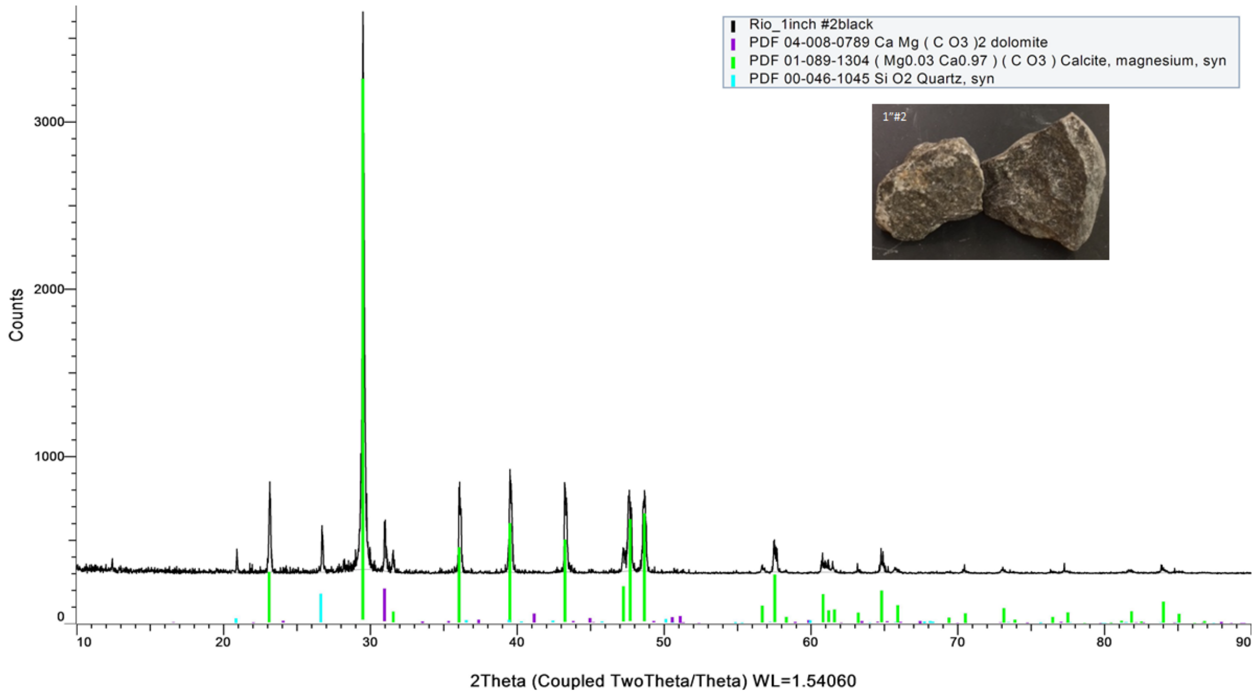
Based on the XRD analysis performed, it is evident that the sample is composed of almost an almost equal percentage of Dolomite ($CaMg(CO_3)_2$) and calcite($CaCO_3$) (Calcite possibly higher) with smaller percentages of quartz (SiO_2). The heights of each of the XRD peaks represent the relative concentration of each of the minerals identified, based on intensity generated by the crystalline structure of the mineral being measured. Dolomite has a Mohs hardness of 3.5-4, Calcite has a Mohs hardness of 3 and Quartz has a Mohs hardness of 7. The hardness of dolomite, along with its alkaline nature (hydrophobic) makes it a superior candidate for various paving projects due to its ability to resist wear and stripping. Calcite is a slightly softer mineral however, its alkaline nature makes it a good candidate to prevent stripping, although in time, it may be subject to smoothing under heavy traffic or heavy abrasion. The addition of small concentrations of quartz could increase the aggregates resistance to heavy abrasion. The acidic nature of quartz can cause issues with stripping at high concentrations. At the quartz concentrations seen in these samples, it isn't likely to adversely affect aggregate/oil adhesion.

Rio Felix Quarry 1" Sample #1



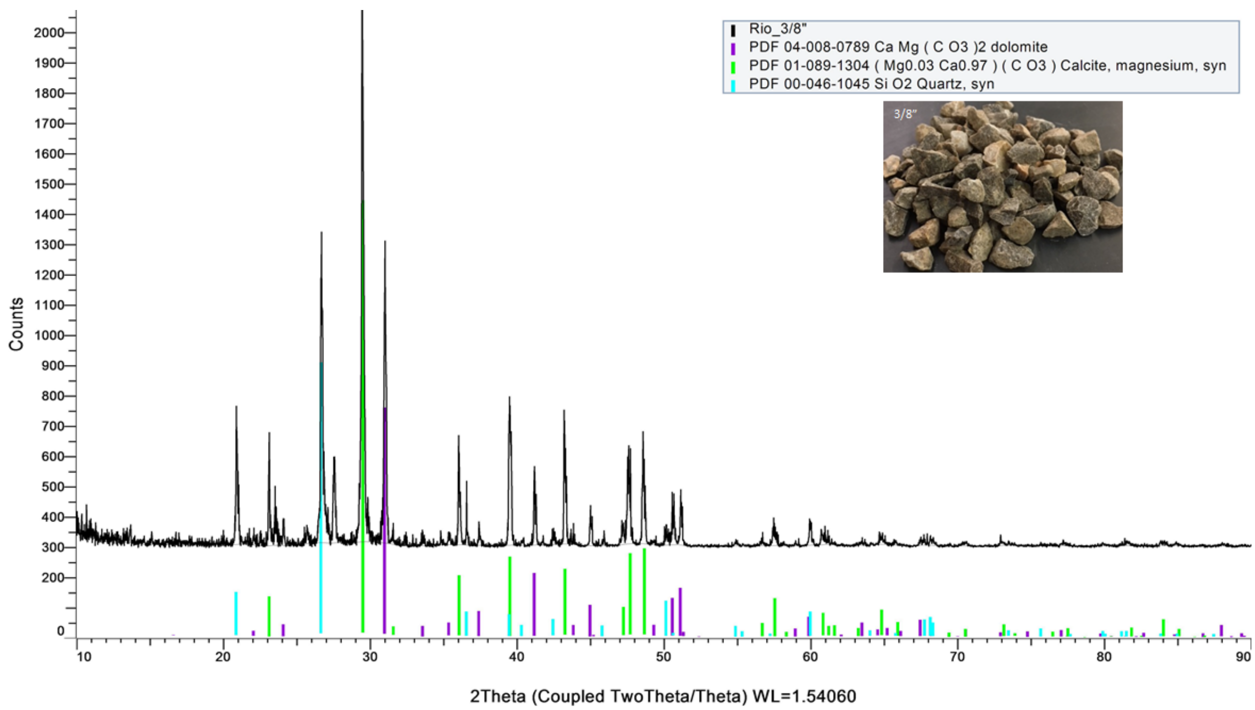
The black line in the image above represents the peaks that were generated on the XRD by the sample. The purple lines represent where peaks of Dolomite should appear according to the ICDD. The green lines represent where peaks of Calcite should appear and the Cyan lines represent where peaks of Quartz should appear in accordance with the ICDD. This XRD pattern shows that the sample is composed primarily of Dolomite with lower concentrations of Calcite and Quartz.

Rio Felix Quarry 1" Sample #2

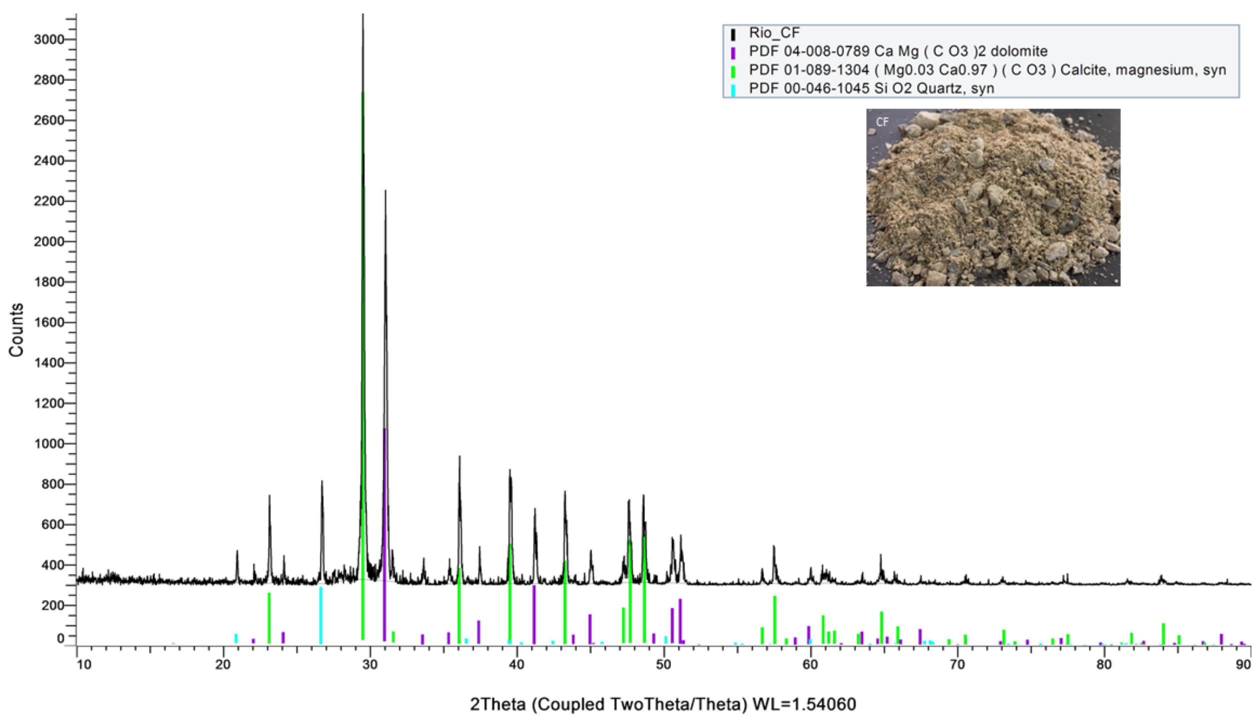


The black line in the image above represents the peaks that were generated on the XRD by the sample. The purple lines represent where peaks of Dolomite should appear according to the ICDD. The green lines represent where peaks of Calcite should appear and the Cyan lines represent where peaks of Quartz should appear in accordance with the ICDD. This XRD pattern shows that the sample is composed primarily of Calcite with lower concentrations of Dolomite and Quartz.

Rio Felix Quarry 3/8”

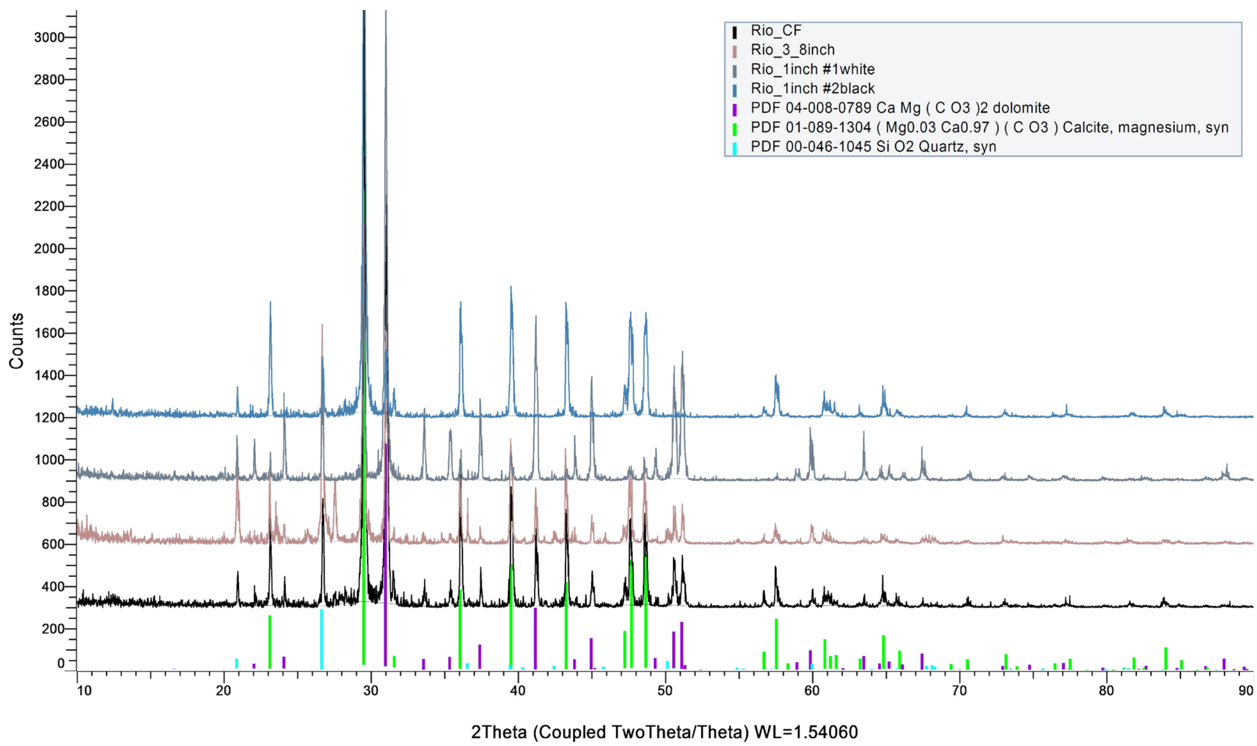


Rio Felix Crusher Fines



The black lines in the 3/8" and Crusher Fines images above represents the peaks that were generated on the XRD by the sample. The purple lines represent where peaks of Dolomite should appear according to the ICDD. The green lines represent where peaks of Calcite should appear and the Cyan lines represent where peaks of Quartz should appear in accordance with the ICDD. This XRD pattern shows that the samples are composed primarily of Calcite and Dolomite (with possibly higher Calcite) and lower concentrations Quartz.

Rio Felix ALL

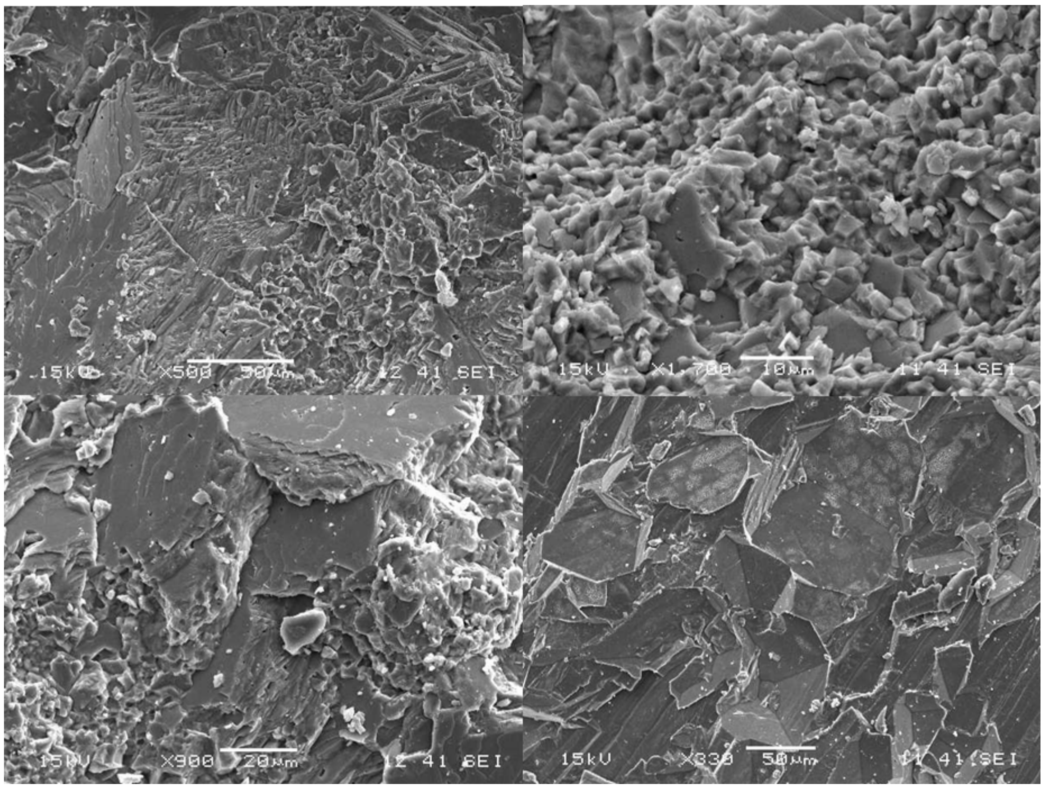


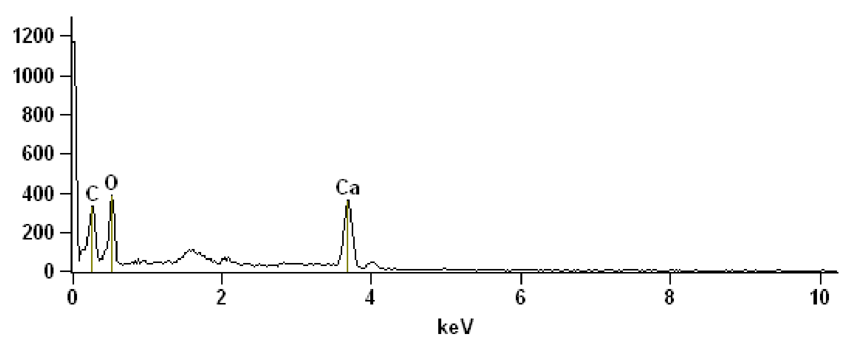
Surface Texture and Trace Elemental Analysis

Surface texture and trace elemental analysis was performed on all sizes of the Rio rock. Each of the 1" rock types were analyzed individually for better trace element characterization.

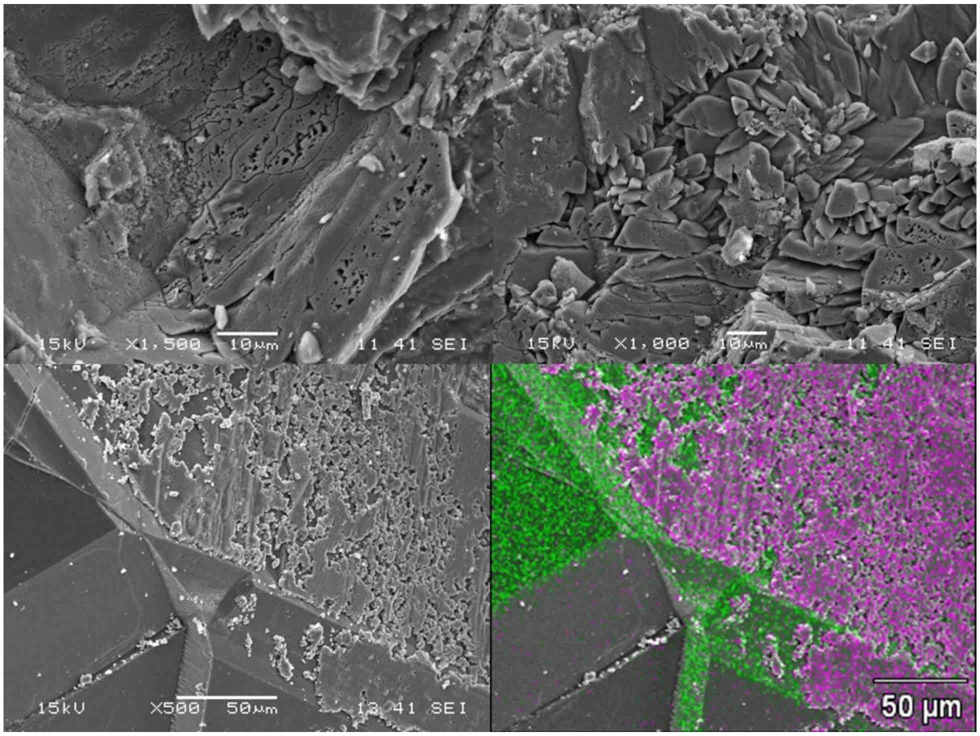
Rio Felix 1" Sample #1

The majority of the Rio Felix 1" #1 sample shows a sealed surface topography with few pores. This represents a profile of a low porosity. The surface texture is visibly rough, with numerous Calcite crystals prevalent. This surface profile should allow good adhesion between the aggregate and the binder material. Some of the Calcite crystals showed lots of pores.





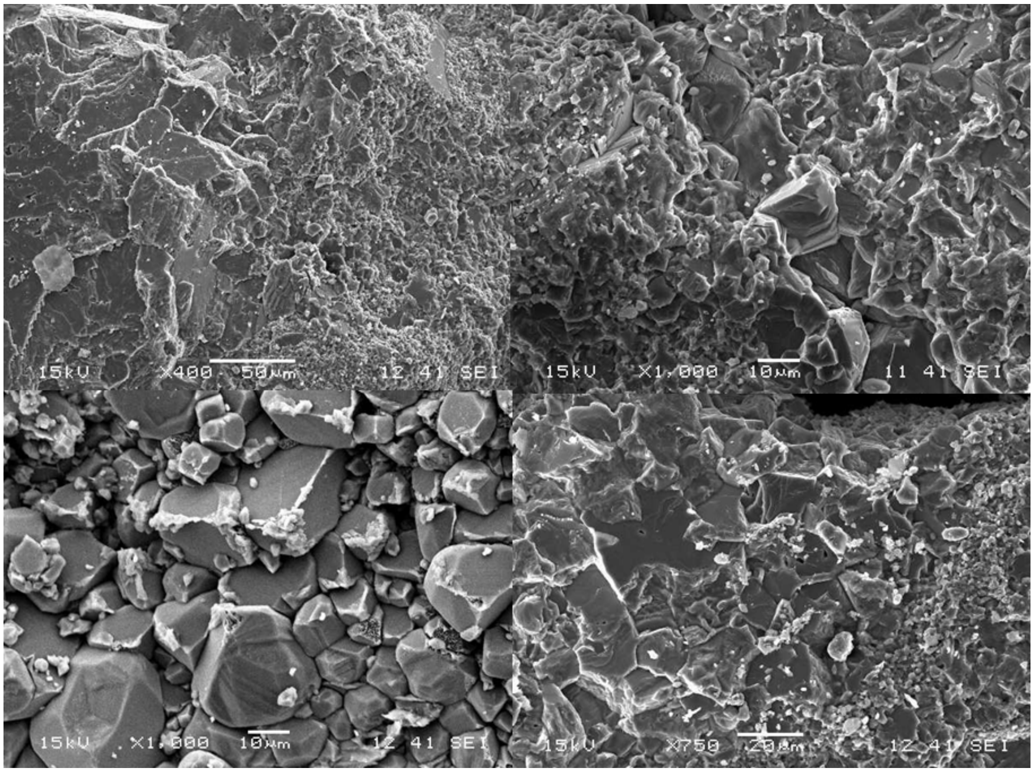
SEM/EDS analysis showing sealed surface topography with numerous Calcite crystals. The elemental profile is consistent with Calcite.

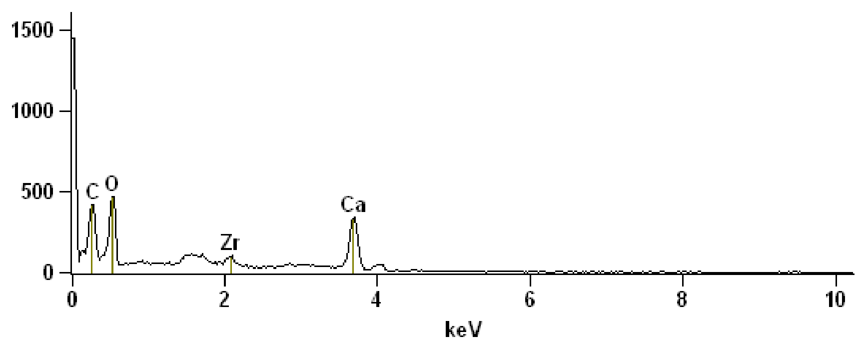


SEM/EDS analysis showing Calcite Crystals with pores in top two images. In the bottom images, EDS phase mapping is used to show a Quartz grain with a Calcium Carbonate crust. The Quartz is represented by the green color (silica) and the Calcium Carbonate crust is represented by the pink color (Calcium).

Rio Felix 1” Sample #2

The Rio Felix 1” Sample #2 shows a predominantly sealed surface topography, with blocky Calcite crystals present throughout. This should be consistent with a low porosity and good adhesion between the binder and aggregate.

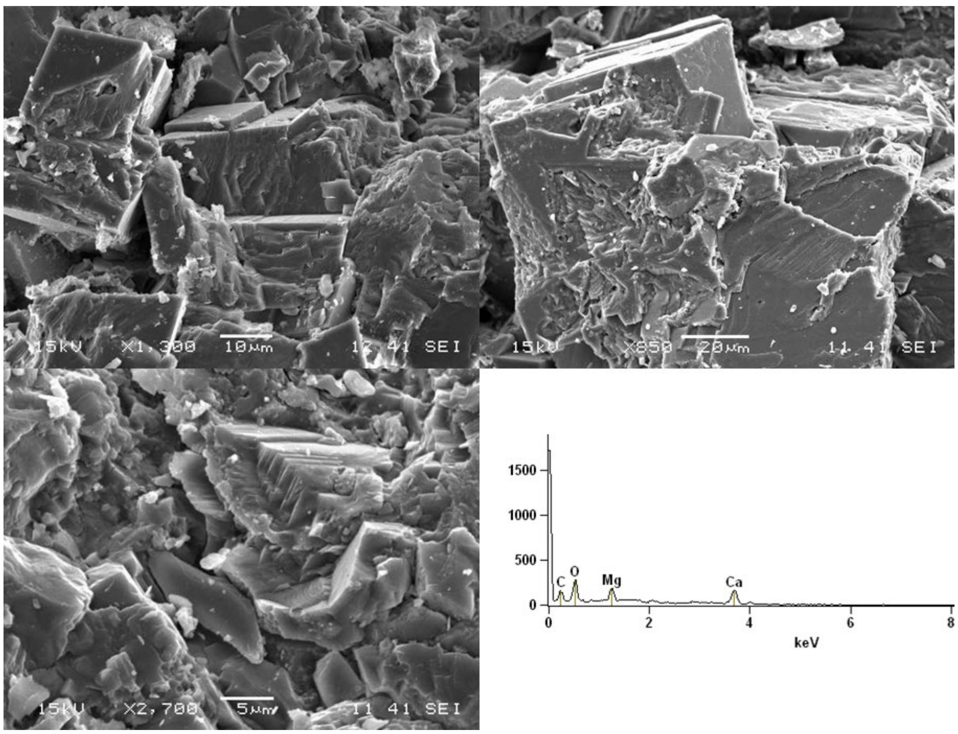




SEM/EDS analysis showing a sealed surface topography with numerous Calcite crystals present. The EDS elemental profile is consistent with Calcite with a trace concentration of Zirconium.

Rio Felix 3/8”

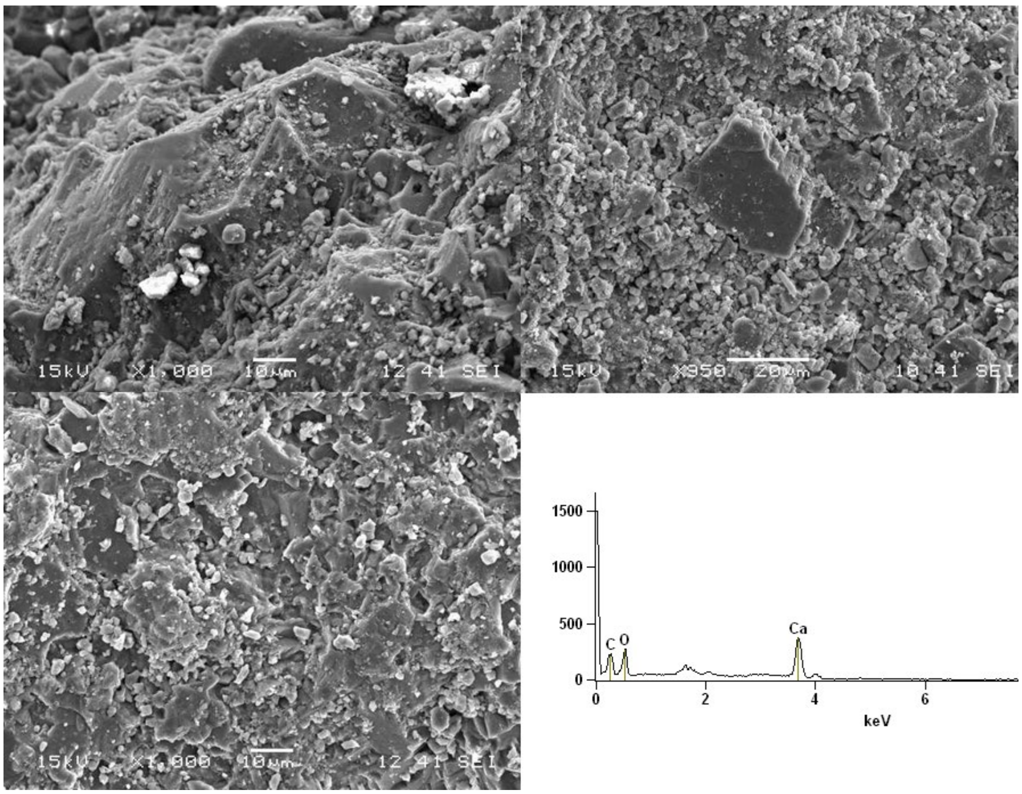
The Rio Felix 3/8” sample showed a sealed surface profile with numerous Dolomite and Calcite crystals prevalent. The EDS elemental profile analysis of the crystals was consistent with Dolomite.



SEM/EDS analysis showing blocky crystals of Dolomite. The EDS elemental profile is consistent with Dolomite.

Rio Felix Crusher Fines

The Rio Felix Crusher Fines showed a similar surface topography as seen in the 1” and 3/8” samples. Very few pores were seen in any of the samples indicating a low porosity. The elemental profile was consistent with Calcite.



CONCLUSIONS

Properties such as: mineral composition, hardness, porosity, surface texture, and trace element presence can greatly affect the quality of an aggregate for a project. This study evaluated some of these properties from aggregates obtained from these locations: Travelstead, Jal, Railroad Mountain, Boyd, and Rio Felix. The table below summarizes the findings of this study.

Location	Mineral Composition	Chemical Formula*	Mohs Hardness*	Specific Gravity*	Trace Elements/Minerals
Travelstead Quarry	Dolomite	$CaMg(CO_3)_2$	3.5-4	2.84-2.86	Zirconium, Kaolinite
	Calcite	$CaCO_3$	3	2.7102	
Jal Quarry	Dolomitic Calcite	$(Ca,Mg)CO_3$	3-3.5	2.7102	Zirconium, Hydrated Quartz (Opal)
	Quartz	SiO_2	7	2.65-2.66	
	Plagioclase Feldspar (Anorthite)	$CaAl_2Si_2O_8$	6-6.5	2.6-2.8	
Railroad Mountain Quarry	Basalt (primarily Plagioclase Feldspar)	$(Na, Ca) Al_2Si_2O_8$	6-6.5	2.6-2.8	Zirconium, Iron
Boyd Quarry	Dolomite	$CaMg(CO_3)_2$	3.5-4	2.84-2.86	Zirconium, Iron, Aluminum
	Calcite	$CaCO_3$	3	2.7102	
	Quartz	SiO_2	7	2.65-2.66	
Rio Felix Quarry	Dolomite	$CaMg(CO_3)_2$	3.5-4	2.84-2.86	Zirconium
	Dolomitic Calcite	$(Ca,Mg)CO_3$	3-3.5	2.7102	
	Quartz	SiO_2	7	2.65-2.66	

*https://www.mindat.org *http://geology.com/minera

FUTURE WORK

Porosity, mineral surface charge and percent mineral composition are all important variables in determining aggregate quality. Porosity, average pore distribution and surface area can all be determined using an ASAP 2020 (Accelerated Surface Area and Porosity 2020) instrument. Mineral surface charge can be determined using a Zeta Potential analyzer. Quantitative mineral composition analysis can be performed using a special technique on the XRD and through ICP-AES (Inductively Coupled Plasma-Automic Emission Spectroscopy) or ICP-MS (Inductively Coupled Plasma-Mass Spectroscopy) analysis. Sandia National Laboratories (Carlsbad) possesses the capability and expertise to complete these analyses. Another grant assistance can be requested in the future if this information presents to be necessary.

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