Summer 2014

Effects of indentation speed and water saturation level on the behavior of Roubidoux sandstone

Azupuri Ayerikujei Kaba

Follow this and additional works at: http://scholarsmine.mst.edu/masters_theses

Recommended Citation

This Thesis - Open Access is brought to you for free and open access by the Student Research & Creative Works at Scholars' Mine. It has been accepted for inclusion in Masters Theses by an authorized administrator of Scholars' Mine. For more information, please contact weaverjr@mst.edu.
EFFECTS OF INDENTATION SPEED AND WATER SATURATION LEVEL 
ON THE BEHAVIOR OF ROUBIDOUX SANDSTONE 

by 

AZUPURI AYERIKUJEI KABA 

A THESIS 

Presented to the Faculty of the Graduate School of the 
MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY 
In Partial Fulfillment of the Requirements for the Degree 

MASTERS OF ENGINEERING 
In 
GEOLOGICAL ENGINEERING 

2014 

Approved by 

Leslie S. Gertsch, Advisor 
Norbert H. Maerz 
J. David Rogers
ABSTRACT

The experiment conducted in this research was to determine the behavior of a porous rock under an indenter. To investigate this, medium-grained sandstone was subjected to a series of indentation tests. These tests were conducted under both dry and saturated conditions using a rounded conical indenter. In addition, tests were conducted at different indentation speeds. The test results were used to calculate the mechanical specific energy (SE) and specific penetration (SP). The porewater pressure evolution in the saturated sample was also monitored.

The tests and subsequent analyses reveal that saturation did not affect the specific energy when the indentation rate was 0.3 mm/sec. However, as the indentation rate increased to 20 mm/sec, a 32% decrease in specific energy was observed (significant at 80% confidence). The specific penetration, on the other hand, appeared not be affected by saturation at either indentation speed.

The variability in SE and SP was assumed to be controlled by three factors: saturation, loading rate, and rock properties. The water saturation was expected to be the major factor to affect the overall behavior of the rock beneath the indenter. However, the porewater pressure measurements showed that, though there was a statistically significant pore pressure buildup rate with increasing indentation rate, the maximum pore pressure magnitude was too small to affect the loading pressure. Variability in the rock properties could also cause this variation, but more data are required to separate the rock property effects from saturation and indentation speed effects.
ACKNOWLEDGEMENT

This project work would not have reached a successful completion without the help, support and encouragement of many individuals, to whom I am forever indebted. First, I thank God Almighty for grace and strength to carry out this work.

I would like to express my deep and sincere gratitude to my research advisor Dr. Leslie S. Gertsch who provided useful insights, laboratory resources, funds and excellent guidance throughout the project work. From the very beginning of the project work to the end, her doors were always opened to me. I greatly admire her patience and friendliness I enjoyed during my work with her. I would also like to thank my other committee members, including Dr. J David Rogers and Dr. Norbert H. Maerz for their constructive criticisms and concrete suggestions.

I am thankful to the technical support staff of Rock Mechanics and Explosives Research Center, especially, Mr. John Tyler, Sr. Research Engineer, and Mr. Mike Bassett, Sr. Research Technician. Their help was crucial for laboratory setups of my experimental work.

I am greatly indebted to my Parents, siblings for their encouragement, prayer and unwavering support throughout the course. To my dear uncle Mr. Farouk Kaba Asepaga, who has shared in every aspect of my career, this work is dedicated to you and all the family.

Finally, I would like to thank my colleagues and friends who knowingly or unknowingly, by their comments largely dictated the format of this report.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>SECTION</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xi</td>
</tr>
<tr>
<td>SECTION</td>
<td></td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1. BACKGROUND</td>
<td>1</td>
</tr>
<tr>
<td>1.2. AIMS/OBJECTIVES</td>
<td>2</td>
</tr>
<tr>
<td>1.3. STATEMENT OF THE PROBLEM</td>
<td>2</td>
</tr>
<tr>
<td>1.4. HYPOTHESIS</td>
<td>3</td>
</tr>
<tr>
<td>1.5. JUSTIFICATION OF THE STUDY</td>
<td>4</td>
</tr>
<tr>
<td>2. LITERATURE REVIEW</td>
<td>5</td>
</tr>
<tr>
<td>2.1. INTRODUCTION</td>
<td>5</td>
</tr>
<tr>
<td>2.2. SCOPE OF THE LITERATURE REVIEW</td>
<td>5</td>
</tr>
<tr>
<td>2.3. ON LOAD INDENTATION TESTS</td>
<td>6</td>
</tr>
<tr>
<td>2.4. SPECIFIC ENERGY</td>
<td>12</td>
</tr>
<tr>
<td>2.5. SATURATION EFFECTS STUDIES</td>
<td>15</td>
</tr>
<tr>
<td>2.5.1. Effect of Liquid on Mechanical Strength</td>
<td>16</td>
</tr>
<tr>
<td>2.5.2. Saturation Effects on Mechanical Excavation of Rocks</td>
<td>21</td>
</tr>
<tr>
<td>2.6. CLAY EFFECTS</td>
<td>24</td>
</tr>
<tr>
<td>2.7. CONCLUSION</td>
<td>25</td>
</tr>
</tbody>
</table>
3. EXPERIMENTAL AND CALCULATION PROCEDURES ........................................ 27

3.1. LOAD INDENTATION TESTS ........................................................................ 27
  3.1.1. Load Indentation Test Setup .................................................................... 28
  3.1.2. Indenter ................................................................................................. 29

3.2. SAMPLE PREPARATION ............................................................................. 32
  3.2.1. Dry Sample Preparation ....................................................................... 34
  3.2.2. Saturated Sample Preparation ............................................................. 37

3.3. POREWATER PRESSURE MEASUREMENT ............................................... 40

3.4. DATA ACQUISITION SYSTEM .................................................................... 42

3.5. TEST PROCEDURE .................................................................................... 44

3.6. CHIPS SIZE DISTRIBUTION MEASUREMENT ............................................ 45
  3.6.1. Volume of Chips and Dust .................................................................... 45

3.7. PERMEABILITY TEST ................................................................................ 46

3.8. DENSITY MEASUREMENT ......................................................................... 47

3.9. DERIVED PARAMETERS ........................................................................... 47
  3.9.1. Penetration at First Failure ................................................................... 48
  3.9.2. Load at First Failure ............................................................................. 48
  3.9.3. Indenter Footprint ................................................................................ 48
  3.9.4. Indenter Pressure ................................................................................. 48
  3.9.5. Work Done ............................................................................................ 48
  3.9.6. Specific Energy ..................................................................................... 49
  3.9.7. Specific Penetration ............................................................................. 49

3.10. Rock SAMPLE .......................................................................................... 50

4. RESULTS AND DISCUSSION ...................................................................... 52
4.1 PHYSICAL PROPERTIES TEST ............................................................ 52
4.2 FORCE .............................................................................................. 53
   4.2.1 Contact Point ........................................................................... 54
4.3 PRESSURE ......................................................................................... 56
   4.3.1 Porewater Pressure ................................................................. 56
   4.3.2 Indenter Pressure ..................................................................... 58
4.4 CHIPS AND DUST ............................................................................. 60
   4.4.1 Chips Volume .......................................................................... 62
   4.4.2 Cutting Shape Parameters ...................................................... 63
4.5 DERIVED PARAMETERS ................................................................. 64
   4.5.1 Effective Indenter Pressure .................................................... 65
   4.5.2 Specific Energy ....................................................................... 66
   4.5.3 Specific Penetration ............................................................... 66
4.6 SATURATION EFFECTS ................................................................. 69
4.7 SPEED EFFECTS .............................................................................. 74
4.8 EFFECTS OF PERMEABILITY ........................................................ 77
5. CONCLUSION AND FUTURE WORK .............................................. 80
   5.1 CONCLUSION ............................................................................... 80
   5.2 RECOMMENDEN FUTURE WORK ............................................. 81
APPENDIX .............................................................................................. 83
BIBLIOGRAPHY ..................................................................................... 105
VITA ......................................................................................................... 110
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1. Idealized model of the penetration of a wedge into rock (From Paul and Sikarskie, 1965)</td>
<td>7</td>
</tr>
<tr>
<td>2.2. Normal indentation of a wedge into rock (From Damjanac and Detournay)</td>
<td>10</td>
</tr>
<tr>
<td>3.1. Load indentation setup showing all connection</td>
<td>28</td>
</tr>
<tr>
<td>3.2. A schematic diagram of the load-indentation setup</td>
<td>29</td>
</tr>
<tr>
<td>3.3. Conical indenter used</td>
<td>30</td>
</tr>
<tr>
<td>3.4. Conical indentation geometry (not drawn to scale) (From Abu Bakar, 2012)</td>
<td>31</td>
</tr>
<tr>
<td>3.5. Forces acting on the indenter</td>
<td>31</td>
</tr>
<tr>
<td>3.6. Sample preparation procedure</td>
<td>33</td>
</tr>
<tr>
<td>3.7. Edging rock core sample</td>
<td>34</td>
</tr>
<tr>
<td>3.8. Sample casting procedure</td>
<td>36</td>
</tr>
<tr>
<td>3.9. A casted sample for the load indentation test</td>
<td>37</td>
</tr>
<tr>
<td>3.10. Rock sample prepared for saturation</td>
<td>39</td>
</tr>
<tr>
<td>3.11. Totally submerged rock samples</td>
<td>39</td>
</tr>
<tr>
<td>3.12. Bottom platen showing the pore pressure drainage channel with an attached pressure transducer</td>
<td>41</td>
</tr>
<tr>
<td>3.13. A sample coupled to two pressure transducers with the platen fixed to the bottom of sample</td>
<td>42</td>
</tr>
<tr>
<td>3.14. Data Acquisition Control System</td>
<td>43</td>
</tr>
<tr>
<td>3.15. A typical showing the major and minor axes</td>
<td>50</td>
</tr>
<tr>
<td>4.1. Load and Pore pressure versus displacement for a typical saturated sample</td>
<td>54</td>
</tr>
</tbody>
</table>
4.2. Load and displacement versus time for typical dry sandstone before choosing contact point ................................................................. 55

4.3. Load and displacement versus time for typical dry sandstone sample after choosing contact point ................................................................. 56

4.4. Typical test where P2 was greater than P1 ................................................................. 57

4.5. Typical test where P1 was greater than P2 ................................................................. 58

4.6. Load and Indenter pressure versus displacement for typical dry sandstone sample .. 60

4.7. A saturated sample indented at 3.8mm deep ................................................................. 61

4.8. Chips collected from a saturated sample under fast loading speed (20 mm/sec) ...... 62

4.9. Comparison of the experimental and theoretical volumes for all saturation level and speeds ........................................................................................................... 63

4.10. Images of samples and analyzed shapes ...................................................................... 64

4.11. A comparison of the IMAGEJ results for dry and saturated samples.......................... 64

4.12. Total load, Effective Indenter pressure and Indenter Pressure versus penetration for a typical saturated sample test ................................................................. 66

4.13. Box plots of SE values for dry and saturated samples at fast speed showing the median, highest, lowest, 1st and 3rd quartiles values ........................................ 72

4.14. Box plots of SE values for dry and saturated samples at slow speed showing the median, highest, lowest, 1st and 3rd quartiles values ........................................ 72

4.15. Box plots of SP values for dry and saturated samples at fast speed showing the median, highest, lowest, 1st and 3rd quartiles values ........................................ 73

4.16. Box plots of SP values for dry and saturated samples at slow speed showing the median, highest, lowest, 1st and 3rd quartiles values ........................................ 73

4.17. Box plots of SE values for saturated Roubidoux sandstone samples at two speeds showing the median, highest, lowest, 1st and 3rd quartiles values............... 75

4.18. Box plots of SE values for dry Roubidoux sandstone samples at two speeds showing the median, highest, lowest, 1st and 3rd quartiles values................. 75
4.19. Box plots of SP values for saturated Roubidoux sandstone samples at two speeds showing the median, highest, lowest, 1st and 3rd quartiles values.......................... 76

4.20. Box plots of SP values for dry Roubidoux sandstone samples at two speeds showing the median, highest, lowest, 1st and 3rd quartiles values............................ 77
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1. Some physical properties of the Roubidoux sandstone</td>
<td>52</td>
</tr>
<tr>
<td>4.2a. Summary of the dry Roubidoux sandstone test for slow indenter speed</td>
<td>67</td>
</tr>
<tr>
<td>4.2b. Summary of the saturated Roubidoux sandstone test for slow indenter speed</td>
<td>68</td>
</tr>
<tr>
<td>4.3a. Summary of the dry Roubidoux sandstone test for fast indenter speed</td>
<td>68</td>
</tr>
<tr>
<td>4.3b. Summary of the saturated Roubidoux sandstone test for fast indenter speed</td>
<td>69</td>
</tr>
<tr>
<td>4.4. Statistical comparison of specific energy and specific penetration for dry and saturated sandstone the slow and fast loading rates.</td>
<td>72</td>
</tr>
<tr>
<td>4.5. Statistical comparison of specific energy and specific penetration for dry and saturated sandstone under the maximum and minimum indentation speed</td>
<td>74</td>
</tr>
</tbody>
</table>
1. **INTRODUCTION**

1.1. **BACKGROUND**

Any rock mass which is to be mechanically reduced to fragments must first be penetrated or indented. Rocks offer some resistance, no matter how small, to the penetration of cutter tools, regardless of the shape of the tool. As rock is being indented, rock debris or cuttings are produced which can be analysis and combine with indentation parameters such as indenter force and indenter pressure, to characterize the behavior of the indented medium. The energy per volume of cuttings and other penetration parameters, if properly monitored and analyzed, can give an insight into the response of rocks to indentation. In this research, the behavior of Roubidoux sandstone is studied using specific energy (SE) (energy per unit volume of fragmented rock) and specific penetration (SP) (force per unit penetration of the rock, measured at the first failure as indicated by the sawtooth force trace) in dry and saturated conditions as the rock is been indented by a conical indenter at two different indentation rates.

Previous work on predicting rock behavior used such parameters as uniaxial compressive strength, tensile strength, and point load strength. In addition, indices such as indentation test have been variously employed. Each has shown utility in predicting the rock behavior. However, most of these studies did not evaluate the combined effect of saturation and loading rate on the behavior of porous rocks. The few works on the saturated conditions did not consider either the effects of speed or the effects of excess porewater pressure.
This current research focuses on the effects of saturation in the immediate near-field of an indenter under different cutter speed. This approach will provide new insights for a deeper understanding of excavation in saturated porous rock.

1.2. AIMS/OBJECTIVE

The objectives of the study are:

- Investigate the behavior of dry and saturated porous sandstone as it is indented at different indenter speeds.
- Add to the body of knowledge being built in an ongoing effort by academia and industry to understand and predict the effects of water on mechanical rock excavation.

1.3. STATEMENT OF THE PROBLEM

Factors such as rock properties, cutting speed, bit geometry, bit tip size, and moisture content that influence rock fragmentation under an indenter have each been a subject of extensive research, the results of which have led to a number of comprehensive texts (Damjanac and Detournay, 1995; Zhang et al, 2013; Boussinesq, 1885; Paul and Sikarskie, 1965). These works provided a great insight to understand the behavior of rock under several conditions and led to improvement of several mechanical rock cutting tools as well as the excavation process. Though many simplified models have also provided insight into the complex interaction of several factors in rock indentation process, much less effort has been made to understand saturated rock fragmentation under different indenter speed. A better understanding
of pore pressure evolution and how it correlates with the indentation force will help to fully appreciate the effects of saturation on rock indentation process.

The forces acting on rock cutting tools have also been extensively studied in different rock types from numerical, analytical and experimental perspective but in most cases, the testing has been performed under single cutter speed. Meanwhile, it is well established that rock behavior changes with cutting speed. It is also known that the presence of water affects the behavior of rocks. The combined effect of these parameters is therefore very important in understanding the full scale behavior of porous rocks. There could be a maximum cutting speed below which the rock-weakening effects of saturation increase the fragmentation of a rock, and above which the effective stress is decreased by undrained pore pressure. This speed threshold may increase with the permeability of the rock (all else constant); the higher the permeability, the faster the cutter can move without increasing the near-field pore pressure.

1.4. HYPOTHESIS

It is most certain that the porosity and permeability of rocks control the pore pressure evolution and that the pore pressure is the defining characteristic of the drained and undrained conditions. It is also known that the drained and undrained conditions are characteristics of the “slow” and “fast” loading rates during rock indentation. Therefore, to obtain the behavior of a given rock, its permeability and saturation conditions as well as the loading conditions must be well understood. In view of this, this research investigates if there is a distinctive trend in the behavior of
Roubidoux sandstone under two indentation speeds. There may be a distinctive trend between the loading rate and SE and SP of the dry and saturated Roubidoux sandstone under load-indentation that, once established, can be used to predictive the behavior of the porous sandstone.

1.5. JUSTIFICATION OF THE STUDY

With rock fragmentation as one of the fundamental activities that support civilization, this study will enhance understanding of the role that water saturation and indentation rate play in rock fragmentation process. The research also contributes to the database of experimental results to provide deeper understanding of excavation in saturated porous rock. This approach will provide new insights for a deeper understanding of saturated rock excavation
2. LITERATURE REVIEW

2.1. INTRODUCTION

The literature review in this section is limited to rock fragmentation, saturation effects, and the linkage that exists between them in connection with rock behavior predictions. It reveals some of the global views that people have shared particularly on the concept of rock fragmentation and the ideas expressed on the role that saturation plays in failure of porous sedimentary rock.

2.2. SCOPE OF LITERATURE REVIEW

Saturated rock fragmentation is a complex interaction of several factors, and successful study must encompass a variety of subjects and theoretical approaches. The interplay of the various factors in achieving rock breakage especially in saturated rock is not yet fully understood.

The literature review begins with definition of indentation and indentation process. A brief history of indentation as well as the current understanding of rock indentation is emphasized. The ultimate investigative tool for the present work is the rock indentation test.

The second main section focuses on chip formation and chip yield as products of indentation. Topics such as specific energy (SE) and specific penetration (SP) are also reviewed. Further, the section reviews the influence of water on the strength of rocks as presented by previous researchers. It continues with the linkage that exists
between water saturation and specific energy. This section ends with a review on the clay content effect on rock strength and how it may relate to the indentation process.

2.3. ON INDENTATION TESTS

There are two basic processes involved in the mechanical excavation of rocks: shearing or cutting for soft to medium strength rock, and indentation for medium strength to hard rocks (Fowell, 1993). This work is centered on indentation. The behavior of the rock under indentation has been widely studied by many researchers (for example, Boussinesq, 1885; Paul and Sikarskie, 1965; Lindqvist, 1982; Dollinger, 1998; Handewith, 1970). Studies on indentation processes have reached consensus in one way or other about the chip forming process under an indenter.

Figure 2.1 shows the indentation process of rock under an indenter. When an indenter is pressed against a rock surface, stresses are built up underneath the area of contact. The stresses increase with increasing load and the material is deformed elastically. At the contact surface irregularities deform and beneath the indenter a zone of crushed rock is developed (also referred to as hydrostatic core in other literature, such as Chiaia, 2000). This crushed zone behaves as a plastic zone. The plastic zone distributes the applied load as stresses to the surrounding rock, in all directions as the indenter penetrates deeper in the rock. This induces radial cracks which propagate outward from the crushed zone as the applied load and the stresses in the plastic zone increase. When the load reaches a sufficient level, a chip is formed and the stresses are released. The stored energy in the chip is released as the chip moves out of the way. Each time a chip is formed the load drops temporarily (in some
cases to zero) and must be built up to a new, higher level to achieve further chipping. The crushing and chipping create a crater.

![Diagram of a wedge indentation into rock](image)

Figure 2.1 Idealized model of the penetration of a wedge into rock (From Paul and Sikarskie, 1965).

To this end, it can be concluded that regardless of the indentation process, it starts with initiation of a stress concentration field. However, the details of the stress field generated vary according to tool shape geometry, direction of load or rate of loading, but principally a static or quasi-static indentation process causes rock fragments to be removed from the rock surface.

One of the earliest analytical solutions to the stress field generated beneath an indenter during indentation was introduced by Boussinesq (1885). He introduced the concept of the Boussinesq elastic field, in which he considered the stress situation in an elastic half-space subjected to a normal point load. He expressed the magnitude of
the stress as being proportional to the applied load and to the inverse squared of the radial distance from the point of contact, times some independent angular function (equation 2.1). This laid a direction to many later proposed failure models on force-indentation behavior of rocks (for example Lawn and Swain, 1975; Lindqivst, 1982).

\[ \sigma_{ij} = \left( \frac{p}{\pi R^2} \right) \left[ f_{ij}(\phi) \right]_v \]  

(2.1)

Where:

\( \sigma_{ij} = \) Stress under the indenter

\( p = \) Applied load

\( R = \) Radius of contact point

\( \left[ f_{ij}(\phi) \right]_v = \) Independent angular function, a function of the Poisson ratio

\( v = \) Poisson ratio

Analogous to the Boussinesq elastic field is the Hertzian elastic stress field theory. Hertz (1882) developed a theory to calculate the contact area and pressure beneath a smooth spherical indenter and predicted the resulting compression and stress induced in the object. He considered a smooth spherical indenter acting on an isotropic, linear elastic half-space.

Comprehensive reviews of the fundamental solutions for the evolution of stresses and displacements due to surface contact in an isotropic elastic half-space can be found in Gladwell (1980), Johnson (1985) and Hills et al. (1993). The urge to understand the stress and deformation fields beneath indenters grew even stronger and stronger among investigators. Tandanand and Hartman (1961) showed that the stresses produced beneath a wedge indenter are similar to those stresses produced by a line load on a semi-infinite plate. They noticed that the geometry of the chips
produced was much dependent upon the cutter’s wedge angle and the amount of applied load.

In recent studies, Zhang et al (2013) conducted an experiment to study the evolution of deformation and failure of Yunnan sandstone under cyclic indentation. They investigated the deformation fields on the sample surface using a digital imaging correlation (DIC) technique. They found that tensile strains concentrate beneath the indenter right before cracking and that cracks nucleate when the indentation load exceeds a critical value. They also indicated digital imaging correlation (DIC) is an efficient method in tracing the evolution of cracks in rocks.

Parallel to the ongoing experimental work on indentation are series of theoretical studies that also investigated the indentation of rock. Paul and Sikarskie (1965) modeled a wedge as it penetrates a brittle material, with the stresses generated by the wedge governed by Mohr-Coulomb failure criterion. The basic geometry assumed a zone of crushed material and a median vent crack, both directly underneath the indenter, and chips that formed at the sides of the indenter. As the indenter penetrates the rock, the model assumed that the forces on the indenter are transferred to the side of the incipient chip (Figure 2.1). Thus the model postulated that the wedge pushes the chip out along a fracture plane and this action is responsible for the reaction force on the indenter. As the wedge penetrates the rock surface, the load builds until a chip forms, then the force drops off quickly. The force change on the indenter during this process was modeled by a sawtooth function. After a chip forms, the indenter continues to penetrate the rock until a larger chip forms, which is accompanied by a larger sawtooth force function. Increasing indenter penetration was
assumed to cause larger and larger chips and larger force variations. Of interest are the concept of chip formation and the sawtooth model of the force change during the indentation.

Damjanac and Detournay (1995) simulated a wedge indentation into an elasto-plastic half-plane (Figure 2.2) using finite difference code (FLAC). The study focused on the initial regime of the indentation process (prior to the initiation of a tensile fracture). They found that the indentation process is predominantly described by a single number, which is a function of the wedge angle, the unconfined compressive strength of the rock, and its elastic modulus.

Liu et al. (2002) studied a simulated quasi-photoelastic stress fringe pattern induced by a single indenter when the rock is considered as a homogeneous material. Though the observed stress field was not uniform, it was symmetrical. The stresses

Figure 2.2 Normal indentation of a wedge into rock (Damjanac and Detournay, 1995).
were extremely high close to the loading point and decreased rapidly with increasing distance from the loading point. They observed a fan-shaped stress field that radiated outside the highly stressed zone. The stress field looked like water-waves far from this highly stressed zone, which they attributed to rock heterogeneities.

The indentation (punch) test was originally developed as a method for directly determining normal loads on rock cutting tools during raise boring and tunnel boring. One of the first indentation tests conducted for this purpose was by Handewith (1970), to predict the performance of disc cutters. For this purpose, he casted a rock sample in a 4inch (102mm) outside diameter tapered steel confining cylinder using 12,000 psi (83 MPa) UCS gypsum plaster (commercially known as hydrostone). The cylinder was 4inches high and the rock was placed so that the diamond-sawed flat rock surface faced upward. The test was conducted on the flat surface though the rocks had variable shapes. A 0.5 inch diameter tungsten carbide indenter with a 30º taper was then forced into the flat surface. Force and penetration were measured during the indentation. The tapered cylinder provided increasing confinement to the sample during the test, which the author calculated to be approximately 100psi (0.69MPa). The force was applied until displacement of 0.02, 0.04, 0.0, 0.08, 0.10 inch were reached. At each of these levels of penetration, the applied force was relaxed and the permanent deformation was measured. Each test was terminated when a maximum force of 16,000 pounds (71KN) or penetration of 0.1inches (2.5mm) was reached. The index relied on determining the permanently deformed penetration of the indenter (i.e. the depth to reach by the indenter when load was relaxed), and comparing it to the load needed to reach the several permanently deformed points.
For the purpose of the present study, the penetration index developed by Handewith, which is the slope of the set of forces as a function of the permanent deformation penetrations induced, is of great concern.

Moving from stress field and fracture nucleation to chip production, there exists a certain critical load above which the induced fractures (discussed previously) propagate back to the surface of the sample, resulting in stress release, forming a chip. At this point the indenter load drops to zero and begins to build up with further penetration. Various investigators have presented several experimental based views on this topic; for example, Abu Bakar (2012) conducted an indentation test in the same rock as this study and indicated that chips produced during the dry rock indentation differed from chips produced from the saturated rock. Saturated rock produced more fine fragments than dry rocks, though the difference was statistically insignificant. Mammen et al, (2009) also observed a difference in chip size between the two conditions.

Regardless of the reasons attributed to the findings pertaining to the chip size and volume, chip parameters affect the specific energy and hence indicate the behavior of the indented medium.

2.4. SPECIFIC ENERGY

This section reviews specific energy (SE), an idea that has shed significant light on rock failure, and has given direction to research efforts over several decades. Specific energy is the amount of energy required to fragment a unit volume of rock. It is one of the fundamental measures in rock fragmentation. The term was first defined
by Teale (1965) and subsequently showed its importance for evaluating and comparing alternative methods of rock cutting. Since then, determination of specific energy has become part and parcel of many investigations and reduction of the specific energy is a fundamental goal of rock excavation.

Specific energy is a function of both the rock properties and the rock failure processes, which combined to yield rock cuttings of a certain size distribution (Gertsch 2000). Generally, the smaller the cuttings produced, the higher the specific energy of the cuttings, because smaller cuttings have larger surface area per volume than larger cuttings. Increasing the rock fragment size by cutting process lowers the specific energy required (Gertsch and Ozdemir, 1991). Since the size of the cuttings is a major controller of the SE, which is a function of the rock strength, SE can be used to study the behavior of porous rock as is being indented.

Even though the initial concept of specific energy evolved in drilling, investigators (e.g. Teale) imagined drilling as an indentation process that crushes the rock and then produces small cuttings at the sides of the indenter after intense crushing. It is therefore a useful concept in any indentation process.

One of the latest laboratory indentation studies performed to predict the effects of saturation on rock excavation observed the energy required to fragment a unit volume of rock. During indentation test, Abu Bakar (2012) subjected a core sample, 25.4mm (1.0in) diameter and 38.1mm(1.5in) long, to a conical indenter (Section 3, Figure 3.4) under a single indenter speed (~100mm/sec). Note the tests were performed at a single indenter penetration rate, which leaves us with the question, would the experimental outcome be the same at lower or higher indenter
speeds? Notwithstanding, his work provided a fundamental understanding on the effects of saturation on Roubidoux sandstone. He noticed a 25% increase in cutting saturated sandstone versus dry sandstone. Though the difference was statistically insignificant, he attributed the increase in specific energy to the small chip size coupled with large amount of fines due to the water weakening the clay cement present between the quartz grains in the sandstone. Thus, quantitatively, the amount of energy required to break a unit volume of saturated sandstone (using a conical indenter) is greater than that required in dry sandstone fragmentation.

The energy discrepancies between cutting saturation and dry rock are similar to an effect noted in an empirical study of drilling by Mammen et al. (2009), who found a 38% reduction in specific energy between cutting a saturated sandstone and a dry one. They, however, related the reduction entirely to the cutting force reduction, explaining that there was no significant difference in yield (cuttings) between the two conditions. For the purpose of the present study, the decrease in specific energy between the two conditions could be a useful indicator of rock behavior (strength).

Sengun and Altindag (2011) conducted a specific energy measurement on 12 different carbonate rocks in industrial stone cutting process using saws. They found that the SE values of rocks in cutting process was highest for those rock having the high density, compressive strength, flexural strength, point load strength index and p-wave velocity. While these properties are not considered in this thesis, they are shown to emphasize the fact that several rock properties control the specific energy.

Tiryaki and Dikmen (2006) performed linear cutting tests on different types of sandstones collected from Ankara, Turkey using chisel type picks. The sandstones
were cut in air dry condition. They noted a decrease in specific energy of drag pick cutting with increases in effective porosity and pore volume, both parameters being directly related to bulk rock strength along with the strength of the intact rock.

2.5. SATURATION EFFECT STUDIES

It is important at this point to define “saturation”. Due to the many different professions that deal with the water content of soil and rock, a variety of terms have evolved to describe it (water content): saturated, fully wetted and so on. The bearing capacity and other aspects of soil behavior are controlled in great measure by the water that exists between the soil grains. Significant differences in soil behavior can arise from subtleties in the mix of soil water and soil gases in the pores between grains. Being consolidated and stiffer than soil, detrital sedimentary rock is much less sensitive (though not wholly insensitive) to those subtleties. The term “fully wetted” is used in numerous applications, including soil engineering, to describe a material where its pores are filled partly with gases, but its solid grains are completely coated with water. Thus a fully wetted material is not necessarily fully saturated. Fully saturated means that the pores are filled completely with water and contains no gas phases. The distinction was not considered significant for this study.

The literature review in this section is subdivided into two parts:

- Effect of liquids on mechanical strength
- Saturation effects on mechanical excavation of rock
2.5.1. Effect of Liquids on Mechanical Strength. Considerable research has been carried out over the past decades to investigate strength of rocks under varying degrees of saturation conditions. The results indicated various rock responses to moisture. Nevertheless, they all agree that moisture has a significant effect on the behavior (strength) of rocks (Hawkins and McCounell, 1992; Roxborough and Rispin 1973; Burshtein, 1969; Vutukuri, 1974). In most of these studies, it was reported that the strength of rock decreased under saturated conditions. This section reviews some of the effects of saturation on the strength of rocks from previous studies.

The effect of moisture content on the compressive, tensile and point load strength of sandstone was examined by Ojo and Brook (1990). They observed that both compressive and tensile strength of sandstone decreased, but the effect of moisture on the tensile strength was greater than that on compressive strength. They also found a decrease in point load strength of 79% from air dried to water saturated.

Similar observations were made by Barefield and Shakoor (2006). They performed a uniaxial compressive strength test on a wide range of sandstones rocks in varying degrees of saturation conditions. The tested rocks were collected from central Ohio through to central Pennsylvania. They found up to 72% reduction in strength between dry and saturated states. Much of the strength reduction was reported to have occurred between 0-20% saturation with minimal to indiscernible strength reduction at high saturation levels and these effects were more pronounced in the stronger rocks. A similar trend was observed in dry density and porosity.

The decrease in strength and other properties with saturation is similar to the findings of many other investigators. Examples include Wu and Tan (2001) and
Yilmaz (2010). Yilmaz (2010) performed a series of tests to determine the influence of water content on the UCS and elasticity modulus of natural gypsum from the Hafik Formation in Sivas Basin, Turkey. Both the UCS and elastic modulus of the samples were determined under air-dried conditions as well as near-saturated conditions. He found that the strength loss of gypsum was about 60% after being immersed in water for one week and reached about 65% loss after sixteen days. The best-fit relationship between the UCS and water content was found to be exponential and it indicated that even very small increase water content (1-2%) could cause a considerable loss in strength of gypsum. A similar trend was observed for elastic modulus, which decreased by about 55% when saturated.

Zhang et al (2012) performed a series of micro-indentation and mini-compression tests on Cox claystone to determine the effects of water content and structural anisotropy on its behavior. The samples were tested under varying relative humidity in both parallel and perpendicular directions with respect to bedding planes. They found that the elastic modulus and failure strength decreased with increasing relative humidity in both directions, parallel and perpendicular. They also observed that the elastic modulus and failure stress as well were affected by the bedding planes.

Torok and Vasarhelyi (2010) investigated the influence of fabric and water on some mechanical parameters of travertine and asserted that rocks with high porosity such as travertine behave in a completely different way under dry and saturation condition. They reported a significant reduction in strength of travertine with increasing water content.
In a recent work, Wong and Jong (2013) reported reduction up to 50% in tensile strength with increasing water content. Samples of artificial gypsum were prepared and tested under both dry and saturated conditions. The samples were saturated for one, three, and ten weeks while the dry samples were oven dried at 40°C. Their tests indicated a significant reduction in strength within the first week of saturation between water content 0-16.6 percent. They however reported a slight decrease in tensile strength with increasing time of soaking the gypsum samples (three and ten weeks).

Alongside these experimental works were theoretical attempts to model the relationship between water and the strength of rocks. Hawkins and McConnell (1992) investigated the influence of water content on the strength of fifteen sandstones. They found that the relationship between water content and uniaxial compressive strength could be expressed by an exponential form (Equation 2.2).

\[ \sigma_c(w) = ae^{-bw} + c \quad (2.2) \]

Where:

- \( \sigma_c(w) \) = Uniaxial Compressive Strength (MPa)
- \( w \) = water content (%)
- \( a, b, \text{ and } c \) are constants.

They measured uniaxial compressive strength of the sandstone under dry and fully saturated conditions. Vasarhelyi and Van (2005) analyzed the published data of Hawkins McConnell and developed a method for estimating the sensitivity of sandstone strength to water content. They redefined the Hawkin and McConnell
equation with special emphasis on the material constant “b” and the water content expressed using an absolute measure like degree of saturation, S.

\[
\sigma_c(w) = a^* + C^* e^{-b^* w} = \sigma_{c0} - \frac{\sigma_{c0} - \sigma_{csat}}{1 - e^{-b^*}} + \frac{\sigma_{c0} - \sigma_{csat}}{1 - e^{-b^*}} e^{-b^* w}
\]  

(2.3)

Where:

\[
b = \frac{b^*}{n_{eff}}
\]  

(2.4)

\[
b^* = -\ln \left( \frac{0.1}{\sigma_{c0} - \sigma_{csat}} \right)
\]  

(2.5)

\[
c^* = \frac{\sigma_{c0} - \sigma_{csat}}{1 - e^{-b^*}}
\]  

(2.6)

\[
\sigma_{c0} = \text{Dry Compressive strength}
\]

\[
\sigma_{csat} = \text{Saturated compressive strength}
\]

\[
n_{eff} = \text{Effective porosity}
\]

The best-fit relationship between “b” and \( n_{eff} \) was found (Equation 2.7). They conclude that Equation 2.7 describes the sensitivity of their sandstone to its water content.

\[
b = \frac{6.0259}{n_{eff}}
\]  

(2.7)

While these equations may not be directly useful in the present study, they are meant to show some of the established relationships that exist between water and rock strength.

In recent studies, Celik et al. (2013) evaluated the effects of water absorption processes on the strength and other physical and mechanical properties of the Ayazini tuff under saturated, freeze and thaw conditions. They reported a 32% decrease in
uniaxial compressive strength of Ayazini tuff after immersion in water for one hour. After 48 hours of water immersion time period, the value of compression strength decreases by about 44%. They therefore concluded that mass water absorption over time leads to a rapid decrease in the strength of the Ayazini tuffs. A similar trend was observed for the freeze and thaw conditions: flexural strength about 34% and 26-43% reduction in freeze and thaw conditions respectively were reported.

Among the investigators are others authors who studied the effects of saturation due to different types of fluids. Saturated effect test was performed by Wu and Tan (2001) to determine how the strength of sandstone varied under water and oil saturation conditions. Water and oil saturated sandstone collected from outcrops and downhole sandstones were tested using UCS and triaxial tests. Their results indicated that strength reduction is more significant for water saturation than oil saturation. They also observed that the degree of strength reduction in water saturation was proportional to the quantity of clay present in the sandstone.

In addition to many follow-on studies on water saturation effects on the strength of rocks under an indenter, the efforts to quantify rock strength and to use these quantities to estimate the degree of the effect between saturation due to different types of fluids started long before this time. Vutukuri (1972, 1974) determined the effect of AlCl3 solutions on the tensile strength of quartzite. He observed reduction in strength up to about 11%. He also studied the effect of liquids on tensile strength of limestone. The liquids used were water, glycerine, ethylene glycol, nitrobenzene, ethyl alcohol, benzaldehyde, and n-butyl alcohol. He stated that since the surface free energy of a solid saturated with a liquid is a function of the properties (such as surface
tension, dielectric constant) of the liquid, it can be postulated that the influence of the saturated liquid is to alter the surface free energy of the rock and hence its strength. He found that as the dielectric constant and surface tension of the liquid increased, the tensile strength of the limestone decreased. The greater the surface tension and dielectric constant of the saturating liquid, the lower the cohesion, and hence the strength, between the particles making up the solid. He therefore concluded that increases in dielectric constant and surface tension of the saturating liquid decrease the tensile strength of rock.

Although most authors reported that the strength of various rocks decreased when saturated with liquids, an increase in the strength of several rock types was also reported. Ruiz (1966) conducted tests on various types of rocks and observed that the strength of some of the basalt, diabase, granite, porphyritic granite, gneiss and limestone samples in saturated conditions were higher than in dry conditions. This was attributed to the heterogeneity of the rocks and to the small number of specimens of each rock type tested.

**2.5.2. Saturation Effects on Mechanical Excavation of Rocks.** Fluids can affect the strength, deformation and general behavior of porous rocks by different physico-chemical processes. Physical processes refer to the effects of build-up of pore pressure of the fluid in the rock pores, micro-cracks, and voids.

Chemical effects, on the other hand, refer to molecular adsorption and stress corrosion cracking (Atkinson, 1984). Stress corrosion cracking is known to be a rate-
dependent phenomenon. In the adsorption process, water interacts with the exposed molecules of the solid, lowering the surface energy.

High cutting strain rate coupled with low enough rock permeability should prevent drainage of excess pore pressure and thus reduce the effective stress, making the rock appear stronger. On the other hand, low cutting strain rate coupled with high enough rock permeability should dissipate excess porewater pressure buildup due to passage of the cutting tool. Abu Bakar (2012) concluded from preliminary tests on the same sandstone as the present study that no mechanical effect exists. This means that saturation did not affect the rock indentation at the indentation speed used. Others have investigated possible effects of saturation on various characteristic of rocks, including capillary pressure (Schmitt et al, 1994) and pore fluid movement under indenter (Thiercelin and Cook, 1988; Cook and Thiercelin, 1989).

Mammen et al (2009) found reduction of up to 40 and 49% in cutting and normal forces during an experiment to study the effects of moisture on rock cutting performance. Triassic argillaceous quartz sandstone, dry UCS=57MPa, wet UCS=22MPa, were tested. They also observed up to 38% percent reduction in specific energy. They concluded that there is a significant reduction of the rock cutting performance parameters with moisture. They conclude that the difference was pronounced between the dry and saturated samples.

Kaitkay and Lei (2005) conducted an experiment to investigate the effects of hydrostatic pressure on rock cutting. They found increases in the cutting forces and in the length of the rock chips produced by a polycrystalline diamond compact (PDC) bit with increase in external hydrostatic pressure. The external hydrostatic pressure
can transform the cutting process from a dominantly brittle fracture to an intermediate ductile-brittle mode in case of rocks. The chip length increase was attributed to the formation of small cracks and pressure-induced plastic deformation ahead of the cutting tool. When an external pressure is applied, failure in shear increases, resulting in more shear flow during chip formation. The longer chips may be assumed to be made up of small rock particles with internal fractures suppressed by the external pressure.

Abu Bakar and Gertsch (2011) conducted a series of full scale laboratory linear cutting experiments with an 11mm wide constant cross section blade, 292mm in diameter. They reported reductions in cutting force and specific energy between the dry and saturated sandstone samples. They noted a reduction of up to 10 and 8% in the nominal SE (based on theoretical excavated volume) and actual SE (based on mass of broken chips) when cutting in saturated rock against dry rock cutting. They also observed a reduction of 28%, 44% and 48% in the normal, rolling and side forces respectively, when cutting in saturated rocks as compared to cutting in dry rocks.

If the rock is saturated, very high porewater pressures can be expected in this highly confined crushed rock zone due to reduction in the rock’s permeability there by the crushing. These elevated porewater pressures can dissipate local stress concentrations in the highly confined crushed rock zone ahead of the drag pick (Hood and Roxborough, 1992). Increased cutting forces in saturated drag pick tests were hypothesized to have been affected by this excess porewater pressure build-up in the confined crushed rock zone underneath and ahead of the drag pick. It is believed that the excess porewater pressure may have caused reduction in the effective stress
imposed by the drag pick, thereby increasing the drag and normal forces required to fail the rock under the cutters.

2.6. CLAY EFFECTS

The behavior of a rock depends on the composite effects of several interacting factors, namely composition and environmental factors. Compositional factors may include but are not limited to: the amount and type of minerals, while environmental factors may include loading condition and water content. Clay minerals (composition factor) are as important as saturation and have been known for their dominating influence on the behavior of the entire rock mass even if they exist only in small fraction of its constituents. This is because water tends to weaken the covalent bonds between the clay molecules. Though the type of clay mineral (kaolinite) in the tested sample does not react significantly with water, clay effect is still worth mentioning because similar rock with different clay minerals can make a great difference in the results. Erguler and Ulusay (2008) carried out a series of laboratory tests to quantify the effects of water content on the mechanical properties of clay-bearing rocks. Different clay-bearing rocks collected from various parts of Turkey were used for this experiment. Their results indicated a 90%, 93% and 90% reduction in UCS, modulus of elasticity; tensile strength respectively, from oven-dried to saturated conditions. They developed a method for estimating the rock strength based on their results.

Hawkins and McConnell (1992) found that an increase in moisture content of as little as 1% from dry state can have a marked effect on both strength and deformability of sandstones. They reported a 78% reduction in uniaxial compressive
strength of clay rich sandstones upon saturation, whereas siliceous sandstones reduced their strength by 8% upon saturation. Their research also indicated that development of pore pressure during loading is negligible especially in pure sandstones and hence does not play a significant role in moisture related strength reduction. They concluded that the degree of sensitivity to moisture content is controlled primarily by the proportions of quartz and clay minerals present and to a lesser extent by the rock microfabric.

Wu and Tan (2001) performed a test to determine the effects of saturation on the strength of sandstone. Water- and oil-saturated sandstones collected from outcrops and downhole were tested using UCS and triaxial tests. Their results indicated that strength reduction is more significant for water saturation than oil saturation and that the degree of strength reduction in water saturation was proportional to the quantity of clay present in the sandstone.

The clay effect review is important because the sandstone tested in this work has a certain amount of clay (6% kaolinite). The 6% kaolinite and iron oxides are the sparse material that fills and holds the sand (quartz) grains together (Gertsch and Summers, 2006). Clay content, however small, has been proven to have a significant effect on rock strength especially when wet (Hawkins and McConnell, 1992; Erguler and Ulusay, 2008).

2.7. CONCLUSION

From the foregoing review of literature, it is clear that water, however minor a constituent, can significantly affect the behavior of rocks. It is also clear that
understanding the influence of water on the behavior of rock will be the way forward to better understanding rock fragmentation process. Established literature has shown the numerous ways in which water reduces the strength of rocks and if these factors are taken into account, rock behavior under an indenter should be predictable.

The pore pressure evolution as a function of rock permeability and tool indentation rate is a crucial aspect for understanding saturated rock.

The research will further attempt to identify shortcomings related to the present study and mitigating measures be recommended to ensure the full utilization and application of the study conclusions.
3. EXPERIMENTAL AND CALCULATION PROCEDURES

This section describes the test apparatus and setup used in this project. It further discusses testing procedure, data acquisition and some calculation procedure.

3.1. LOAD-INDENTATION TESTS

The load-indentation test, also known as the punch-penetration test, is a nonstandard laboratory test that was originally designed to provide a direct method for estimating the normal loads on button and disc cutters during mechanical excavation of rocks. It was developed in the late 1960s and the first punch test apparatus was designed by Handewith (1970). Since its initial development, the test has undergone several modifications and improvement; at the Missouri S&T Rock Mechanics and Explosives Research Center, these improvements include automation of data collection system, increasing the load capacity, increasing the size of the indenter used, depth of penetration has also been changed from Handewiths first setup, with the most recent being the introduction of pore pressure measurement facilities. The test belongs to the same class of laboratory test as the linear cutting and rotary cutting tests since it directly determines the cutter normal loads during TBM and RBM (Raise Boring Machine) excavation. Like every method, this test method also has its ups and downs. On the upside, it is simpler to perform and much less expensive to own and operate. Furthermore, it is more practical than other direct method because it uses much smaller test samples which allows for many tests to be run in a limited budget (Dollinger et al., 1998). On the downside, the smaller sample size cannot take rock discontinuities or fractures into account. Moreover, in a load-
indentation test, variation of spacing to incorporate effect of interaction between adjacent cuts is not possible.

3.1.1. Load-Indentation Test Setup. The load-indentation setup used to perform the test consisted basically of the following parts: the hydraulic ram, indenter, sensor for measuring displacement (LVDT), pressure transducer, load cell, and a toggle switch to control the depth of penetration. Figure 3.1 shows the setup itself whereas Figure 3.2 shows its schematic drawing. The hydraulic ram is fixed to the load frame and is actuated by a hydraulic pump. The hydraulic ram presses an indenter perpendicularly into a saw-cut rock surface.

![Load-indentation setup showing all connections.](image_url)

Figure 3.1 Load-indentation setup showing all connections.
3.1.2 **Indenter.** The indenter used in the indentation test was a conical shape indenter (Figure 3.3) with varying cone angles, sometimes called a truncated or rounded indenter. It is made of tungsten carbide. Figure 3.4 shows the geometry of the indenter. Conical indenter was selected because many current-art rock cutting
tools use conical inserts (Gertsch, 2000). Figure 3.5 shows the force reaction on the indenter.

Figure 3.3 Conical indenter used.
Figure 3.4 Conical indenter geometry (not drawn to scale, from Abu Bakar, 2012).

Figure 3.5 Forces acting on an indenter.
3.2. SAMPLE PREPARATION

The rock samples for the experiment were obtained from a commercial quarry located 15 miles from the campus of Missouri University of Science and Technology (MS&T). They were obtained in blocks of approximately 1270mmX 635mmX 279.4mm (50in X 25inX11in) from the quarry. Once delivered, the blocks were further subdivided into smaller blocks that could be taken into the rock core room at Rock Mechanics and Explosive Center, MS&T. They were then cored and subsequently sawed at both ends to obtain core samples with which to determine the rock strengths parameters (Figure 3.6). The rock cores with rough surface were smoothened with a diamond grinding wheel in a surface grinder (Figure 3.7) to obtain surfaces that were flat, parallel and perpendicular to the axis of the core. Each core sample was nominally 152.4mm (6 inches) in diameter and 88.9mm (3.5 inches) long. These dimensions were selected following a preliminary test, which indicated that the sample thickness was appropriate enough to prevent induced fractures (breakthrough) to a greater extent. The core samples were then divided randomly into those to be used for the air-dry cutting tests and those to be used for the saturated indentation tests.
Figure 3.6 Sample preparation process. (a) Cutting blocks into size for easy handling and coring; (b) Coring of rock sample using the core drill; (c) Sawing drilled cores into the desired thickness; and (d) Rock core samples.
3.2.1. **Dry Sample Preparation.** The part of the core samples described in the previous section which are to be used for the dry cutting test, were casted in plastic pipe measuring 114.3 mm (4.5 in) long and 165.2 mm (6.504 in) outside diameter, using hydrostone (a high strength plaster of Paris) and allowed to cure for at least two days before testing. During casting the rock core was centered in the plastic pipe with one end of the sample—the end to be indented—flush with the end of the pipe, then annulus between the pipe and the core was filled with hydrostone. A conical funnel placed on the top of core to help direct the mixed hydrostone into the annulus (Figure 3.8). The purpose of the funnel was to direct and prevent trapping of air bubbles as
well as ensuring even distribution of hydrostone within the annulus. On the other end of the sample, the plastic pipe protruded 25.4mm (1inche) from the end of the sample to ensure that it properly fits onto a steel platen, yet to be discussed. The Hydrostone confined the rock specimen within plastic pipe. The confinement provided by the hydrostone is required to simulate the partially confined rock condition at the tunnel face and to prevent the samples from failing prematurely due to tensile splitting. Hydrostone swells as it sets and provides a small confining pressure on the sample (Dollinger et al., 1998). Dollinger (1978) indicates that this material has an expansion factor of 0.002-0.003% and produces a confining pressure of approximately 100 psi on standard NX core size. Figure 3.9 shows a casted sample.
Figure 3.8. Sample casting procedure (a) Centering the rock samples in the plastic sleeve; (b) Funnel centered on rock sample; (c) Pouring the hydrostone over the funnel into the annulus between the rock and the plastic sleeve; and (d) Casted sample with the funnel.
3.2.2. Saturated Samples Preparation. The second portion of the rock core samples were saturated for the saturated indentation test. They were saturated in accordance with the method suggested by US Army Corp of Engineers for dredging research (1995). By this method, water rises by capillary force to saturate the core sample progressively. The rock samples were placed carefully in a container containing several thin strips of Styrofoam (Figure 3.10) to prop up the sample bottoms and prevent partial saturation. Water and dye were gently poured into the container to cover the bottom of the samples. The purpose of the dye was to monitor the capillary rise but the dye molecules were larger than water molecules and were observed to be rising slower than the water molecules. The rising of the water upward is controlled by the rock permeability as well as its mineralogy. The water level was
increased at a regular interval to no more than half the additional vertical distance gained by the wetting front during the preceding time interval.

The method used to saturate the rock samples in this study was selected to maximize the amount of water in the pores of the rock without damage to the solid grains. As mentioned as earlier, the method relies on the wicking ability of even low-permeability rock to draw water up into pores through capillary action from a nearby reservoir. The greater the distance from the reservoir (often the groundwater table), the lower the saturation level of the rock, with saturation greater than 85% achieved only within a few centimeters (Al-Samahij et al., 2000). This method deals with that issued by continually raising the reservoir water level so that it is always within a few centimeters below the wetting front until the samples are completely submerged (Figure 3.11). This ensures that the water content of the rock pores is sufficiently close to full saturation.

The saturated rock samples were then cast in hydrostone in plastic sleeves by using the same method as described for dry rock core samples.
Figure 3.10 Rock samples (3.5in long and 6in diameter each) placed in soaking container and propped up by styrofoam spacers, ready to undergoing saturation procedure.

Figure 3.11 Rock samples totally submerged after the wetting front has reached their top.
3.3. PORE PRESSURE MEASUREMENT

To evaluate the potential effects of porewater pressure on the indentation, the porewater pressure generated during the indentation of saturated rock samples was measured during each test. To achieve this, a hardened steel platen with a set of drainage channels connected to a central drainage hole was attached to the bottom of the plastic pipe containing the rock sample as described in section 3.2.2 (Figure 3.12). The drainage hole had an inner diameter of 2 mm (0.079 in). The steel platen was necked with a groove and fitted with a rubber O-rings that provided the necessary sealing against leakage of water. The drainage hole of the platen was attached to a 50 psig pressure transducer with appropriate couplings. Two 5 psig pressure transducers were coupled to the sample at 12.7mm (0.5in) and 44.45mm (1.75in) below the indented surface to monitor the pressure evolution with depth (Figure 3.13), an addition which was not considered by other researchers (for example Abu Bakar, 2012).
Figure 3.12 Bottom platen showing the pore pressure drainage channel with an attached pressure transducer.
3.4. DATA ACQUISITION SYSTEM

The schematic diagram of the data acquisition system for the experiment is shown in Figure 3.14. The displacement of the indenter into the rock sample was monitored by a linear variable differential transducer (LVDT) attached to the hydraulic ram. The load transmitted through the test sample was monitored by a load cell placed under the platen. The output voltages from the LVDT, load cell and pressure transducers were converted by convertor box from analog to digital form and were recorded using a computer based data acquisition system. The data logging software (National Instruments Labview 8.5) was programmed to scan each force,
displacement and pressure channels at 1000 samples per second, providing several thousand readings for each indentation made. The data acquired from the software is processed using calibration constants derived to obtain average, specific energy of cutting and other relevant data.

Figure 3.14 Data Acquisition Control System.
3.5. TEST PROCEDURE

First, the test machine was turned on, warmed and checked prior to any testing session. The data acquisition software was also activated. This procedure gets all the hydraulics warmed and flushes out bubbles in the hydraulic cylinder. These tasks were performed at the start of every testing session.

The protruding end of the plastic sleeve of the prepared rock sample, dry or saturated, was lubricated with grease and carefully seated on the platen. The grease ensured smooth slipping of the plastic sleeve over the O-ring around the platen and made easier the removal of the platen after each test. The pressure transducers were then attached to the sample with the appropriate couplings as shown in Figure 3.13 above. The sample with its pressure transducers is then placed in the sample holder and the load cell is placed beneath the platen to measure the indenter load during the test.

For each test, the whole assemblage described above was then centered symmetrically beneath the indenter, which had been fixed to the hydraulic ram. The test frame was designed to clamp the sample holder frame so that sample displacement in response to indentation was minimized. Once the sample was centered, a camera was set to capture the failure process.

When all was ready, the pre-programmed loading rate was initiated. Following a monotonically increasing displacement function, it forced the indenter into the sample to a preset penetration depth controlled by a toggle switch. The output from the LVDT, load cell, and the porewater pressure transducers were recorded using the LabView 8.5 data acquisition system. After the data were recorded and
archived, calibration constants were used to calculate the load, the indenter displacement and the porewater pressure generated during the indentation; the penetration energy, specific penetration and other parameters were calculated from these measurements.

3.6. CHIPS SIZE DISTRIBUTION MEASUREMENT

The chips collected during the tests were analyzed to determine the chip size distribution. The problem was that the chips and dust collected were very small to undergo the conventional mechanical sieve analysis. Besides, using the conventional method would further break the chips. For these reasons, an image analysis package (IMAGEJ) was used to determine the size distribution without sieving. The shape descriptors obtained from the IMAGEJ were: roundness, and aspect ratio. These were then used to formulate the size distribution of the chips larger than individual quartz crystals.

3.6.1. Volume of Chips and Dust. Another important parameter that was measured was the volume of chips and dust (volume of the crater formed during the indentation). The problem encountered was that the volume of the chips and dust collected was less than the volume of the crater formed due to fly chips and too fine dust that could not be collected. For this reason, play-doh was used to determine the volume of the crater (NOTE: this volume doesn’t include the entire disturbed volume). The crater was completely filled with play-doh. The play-doh was subsequently removed and its volume determined using Archimedes’ fluid
displacement principle. By this principle, the play-doh is placed into a graduated cylinder with an initial known volume of water $H_1$ and the water level rises to $H_2$. The final water level minus the initial water level ($H_2 - H_1$) shows the amount of water displaced by the volume of the play-doh. Play-doh seems to dissolve few minutes after dropping in water. Because of this, all the volume readings were taken few seconds after the play-doh has totally submerged.

The nominal volume of the chips was also calculated for comparison purposes. It was calculated as the volume of the indenter for a given penetration. Since the indenter was a truncated cone, the volume of a cone was used for the first portion of the indenter (lower segment) and formula for frustum was used for the remaining section (where necessary) until the penetration was fully accounted for.

### 3.7. PERMEABILITY TEST

The second type of test conducted was the permeability test. The permeability test was conducted using brine in one of the Petroleum Engineering laboratories of the Missouri University of Science and Technology. The permeability was calculated using the equation:

$$Q = \frac{K \Delta P}{\eta \Delta L} A$$

(3.1)

Where:

- $Q$ = flowrate
- $K$ = permeability
- $\Delta P$ = pressure difference
- $L$ = thickness of test sample
A = area of cross-sectional area to flow

\( \eta \) = fluid viscosity

### 3.8. DENSITY MEASUREMENT

In determining the dry density of the tested rock, the mass of rock core with known diameter and thickness was measured using a beam balance. The dry density was then calculated using equation 3.2. The saturated bulk density was also measured by measuring the saturated rock core weight and divides it by the volume using equation 3.3.

\[
\text{Dry density} = \frac{\text{Mass of dry core}}{\text{Volume of dry core}} 
\]

\[ (3.2) \]

\[
\text{Saturated bulk density} = \frac{\text{mass of saturated core}}{\text{volume of core}} 
\]

\[ (3.3) \]

### 3.9. DERIVED PARAMETERS

A series of parameters were calculated from the force-penetration data obtained during the test and the rock cuttings (chips) data measured after the test. These parameters provided a means of evaluating and understanding the physical characteristics of the sandstone in both dry and saturated conditions under the indenter. The indentation test parameters were measured at both first failure and peak load. On load-displacement plots, these are the first peak load, or first “sawtooth” and the “sawtooth” where the maximum load is observed. Further, parameters such as
chip roundness, and aspect ratio were calculated and measured using IMAGEJ. The following terms were employed in subsequent analysis.

### 3.9.1. Penetration at First Failure
This is the measured penetration depth of the indenter into the rock when the first major failure occurs.

### 3.9.2. Load at First Failure
This is the measured load acting on the indenter when the first failure occurs. It is the first peak on the load indentation curve.

### 3.9.3. Indenter Footprint
This is the horizontal areal projection of the buried portion of the indenter. Since the indenter is conical, the footprint is a circle. For ease of calculation, the size of the circle was assumed to be a direct function of the indenter penetration; that is, rock bulking and other crater irregularities around the indenter was not accounted for. The formula for indenter footprint is discussed later in this report.

### 3.9.4. Indenter Pressure
The indenter pressure, $P_{\text{indenter}}$, was calculated by dividing the maximum indenter load by the indenter footprint as defined above:

### 3.9.5. Work done.
This is the total energy consumed by the indenter in order to reach a given penetration and was determined by calculating the total area under the force-penetration curve:

$$ W_d = \int_{x_0}^{x_1} F(x) \, dx $$  \hspace{1cm} (3.4)

Where:

- $W_d$ = Work done (energy); the area under the force-penetration curve
- $F(x)$ = indenter load
\[ x = \text{indenter displacement downward} \]

### 3.9.6. Specific Energy

It is defined as the amount of work required breaking a unit volume of rock. It is accepted that, to break a given volume of rock, a certain theoretically attainable minimum quantity of energy will be required. Its amount will depend entirely on the nature of the rock. Equation 3.2 defines the SE. The integration was used to incorporate the fluctuating force and to smooth the data (Asaf et al. 2007) and is the work done as defined above. The force traces, \( F(x) \), were integrated over the depth of penetration to calculate the total energy consumed for indentation to that point. Then the energy values were divided by the volume of chips and dust collected to give the specific energy; see section 4, subsection 4.5.2 for details.

### 3.9.7. Specific Penetration

This parameter describes the force required to penetrate a unit depth into the rock, at first failure. It is obtained from the force-displacement data as the first failure point.

The aspect ratio measured using the IMAGEJ software is defined as the ratio of the major chip axis to the minor chip axis (Figure 3.15).

\[
AR = \frac{\text{major_axis}}{\text{minor_axis}} \tag{3.5}
\]

Where:

\( AR = \text{Aspect ratio} \)

\( major_{axis} = \text{Maximum chip diameter (the longest distance between any two points along the boundary of the chip)} \)
\( \text{minor}_{\text{axis}} = \) Minimum chip diameter (the shortest distance between any two points along the boundary of the chip)

An aspect ratio of 1 indicates a perfect circle or square but as the value approaches zero, it shows increasing elongated shape. Figure 3.15 indicates the aspect ratio parameters on a typical chip sample. The roundness is the inverse of the aspect ratio and is calculated using the equation:

\[
\text{Roundness} = \frac{1}{\text{aspect ratio}}
\]  

(3.6)

Figure 3.15 A typical chip showing the major and minor axes

3.10. ROCK PROPERTIES

The rock sample used in this research is an Ordovician-age Roubidoux sandstone, medium grained, laminated to thinly bedded quartz sandstone that is
porous and somewhat friable. It is usually found in white or red varieties, occasionally, with patches of iron concretions. According to Dake (1918), the Roubidoux Sandstone has a larger surface outcrop than any other sandstone in Missouri, and the formation is widely variable in its characteristics from point to point. It has been reported to have uniaxial compressive strength (UCS) of 51MPa when dried and 43MPa when saturated (Abu Baka 2012). It has a porosity of 18% and a dry density of 2150kg/m$^3$ (Gertsch and Abu Bukar, 2011). The sand grains are nearly euhedral double-ended quartz prisms that show little wear or abrasion (Gertsch and Summers, 2006). X-ray diffraction of this sandstone shows that it comprises almost 94% quartz and 6% kaolinite. The clay and trace amounts of iron oxides are the sparse cement that holds the grains together.

Indentation test is not a standardized tests and hence has not be used in most cases as a lone test. It is however used as an index test in connection with other test-linear cutting test in most rock-works prediction.
4. RESULTS AND DISCUSSION

This section contains and discusses the results of the various experiments performed, beginning with the physical characteristics (properties) of the tested rock.

4.1. PHYSICAL PROPERTIES TEST

The measured physical properties of the tested rock include: saturated density, dry density, porosity and permeability. The details of the test are in section three. The physical properties measured in this project are slightly lower than those obtained by Abu Bakar (2012). It is important to know that Roubidoux sandstone is widely variable in characteristics (Dake, 1918). Table 4.1 shows the results of the physical property tests. The mineralogical composition, strength test results and structure of the rock were obtained from previous investigations (Gertsch and Summers, 2006 and Abu Bakar 2012).

Table 4.1 Some physical properties of the Roubidoux sandstone.

<table>
<thead>
<tr>
<th>Rock properties</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniaxial compressive strength (dry)</td>
<td>51 MPa</td>
</tr>
<tr>
<td>Uniaxial compressive strength (saturated)</td>
<td>43 MPa</td>
</tr>
<tr>
<td>Brazilian tensile strength (dry)</td>
<td>1.10 MPa</td>
</tr>
<tr>
<td>Brazilian tensile strength (saturated)</td>
<td>1.00 MPa</td>
</tr>
<tr>
<td>Bulk saturated density</td>
<td>597kg/m³</td>
</tr>
<tr>
<td>Dry density</td>
<td>567kg/m³</td>
</tr>
<tr>
<td>Porosity</td>
<td>3%</td>
</tr>
<tr>
<td>Permeability</td>
<td>2.087mD</td>
</tr>
<tr>
<td>Constituents</td>
<td>Quartz 94%, Kaolinite 6%</td>
</tr>
<tr>
<td>Structure</td>
<td>Medium grained, laminated to thinly bedded.</td>
</tr>
</tbody>
</table>
4.2. FORCE

The normal force was recorded continuously for each test. The force traces for dry and saturated samples exhibited the same characteristic shape. For each force trace, the load increases linearly and drops significantly after a certain peak load. This peak load varied from sample to sample. With further penetration, the load builds up again and increases more-or-less linearly until a sufficient load level when a significant drop of the load occurs. The explanation for this behavior was attributed to the fact that as the indenter loads the rock; stresses are building up beneath the indenter. Beneath the contact zone, a zone of crushed rock is formed. The crushed zone behaves plastically and distributes the buildup stress to the surrounding rock in all directions as the indenter penetrates further (deeper). When the load reaches a sufficient level, a chip is formed and the stresses are released. This causes a temporary drop in the indenter load as shown in Figure 4.1. Each time a chip is formed the load drops temporarily and builds up again to a new, higher level to achieve further chipping. This accounts for the sawtooth nature of the load-indentation curve (Figure 4.1). This behavior was identified by numerous investigators (Dolinger 1978; Thiercelin and Cook, 1988) and is believed to be characteristic of the failure of brittle material. The point where the load first builds up and drops is the first failure. The parameters measured at this location are used in subsequent calculations and discussions.
4.2.1. Contact Point. During the indentation, the indenter moves through air before making contact with the sample. When the indenter makes contacts, there is a significant increase in the load (Figure 4.2). It is evident also the change in gradient of the displacement curve in Figure 4.3 that the LVDT also responds to contact of the indenter with the rock surface. This is because the rock resists the penetration of the indenter and slows down its penetration rate. The displacement slope change was
used to choose the point at which the indenter made contact with the sample (Figure 4.3).

Figure 4.2 Load and displacement versus time for a typical dry sandstone sample, before choosing contact point.
4.3. PRESSURE

Two types of pressure were measured during the indentation: porewater pressure and indenter pressure.

4.3.1. Porewater Pressure. The three pressure transducers described in section 3; Figure 3.1 measured the pressure variation along the length of each sample. The results indicated that although there was a pressure response on all transducers, no predictive relationship could be inferred, as the responses varied for the same transducer location in different samples and from point to point for the same sample. In some of the tests, the middle pressure transducer (P2) showed higher...
values while the upper pressure transducer indicated a lower value; in other tests the opposite was true. Generally, however, the bottom pressure transducer showed the lowest pressures. Fracture growth may explain this observation. During chip formation different fracture networks are formed in different directions. If a fracture is favorably oriented in the direction of any transducer, such transducer will detect and record high pressure. This could account for the larger variability in the porewater pressure values at the upper and middle pressure transducers. Figures 4.4 and 4.5 show samples where the upper (P1) and middle (P2) pressure measurements varied in magnitude for the same indenter speed. Because of this variability in upper (P1) and middle (P2) pressure measurements, only the bottom (P3) data are discussed here. Besides, the upper (P1) and middle (P2) pressure values are point measurements whereas the bottom (P3) pressure values are volume-averaged pressures.

![Figure 4.4 Typical sample where P2 was greater than P1.](image-url)
4.3.2. **Indenter Pressure.** Indenter pressure is the pressure induced by the indenter. Indenter pressure provides a first insight into the failure mechanism, because the magnitude of the pressures involved reflects the energy required to achieve failure (Gertsch, 2000). Indenter pressure was calculated as the maximum indenter load divided by the area of indenter footprint. The indenter pressure was calculated as:

\[
P_{\text{indenter}} = \frac{F_{\text{max}}}{A} \tag{4.1}
\]

Where:

\[F_{\text{max}} = \text{maximum indenter load}\]
A = area of indenter footprint

\[ A = \pi R^2 \]  \hspace{1cm} (4.2)

Where:

\[ R = \text{radius of the horizontally projected surface (mm)} \]

It is important to mention that the footprint area is the horizontal projected area of the indenter, measured at the intersection of the indenter and the free surface. Since the used indenter was of conical shape with varying cone angles, the footprint area varied with the indentation into the rock sample. This was accounted for by calculating the indenter area as a direct function of the indenter penetration.

Depending on the depth of penetration (d), the radii were calculated using the formulae below

0 \leq d < 0.8:

\[ R = 3.125d \]  \hspace{1cm} (4.3)

0.8 \leq d < 2.8:

\[ R = 1.7 + d \]  \hspace{1cm} (4.4)

2.8 \leq d < 7.0:

\[ R = 3.374 + 0.404d \]  \hspace{1cm} (4.5)

\[ d \geq 7.0: \]

\[ R = 6.2 \]  \hspace{1cm} (4.6)

Where:

\[ d = \text{Depth of penetration} \]

It can be seen from Figure 4.6 that the indenter pressure increases with increasing load. This explains the nature of the stress buildup in the crushed zone beneath the
indenter discussed previously. It can also be seen that beyond the crushed zone, the shape of the indenter pressure curve follows the shape of the indenter load though both quantities are very different. This behavior is true for all tested samples.

![Graph showing load and indenter pressure versus displacement](image)

Figure 4.6 Load and indenter pressure versus displacement for typical dry sandstone sample.

### 4.4. CHIP AND DUST

During each indentation, chips and dust were collected and their properties determined. The indentation was accompanied by airborne chips and dust, resulting in fewer cuttings being collected than produced. In some cases, no cuttings could be
collected, especially in the dry samples. Figure 4.7 shows an indented sample (sample code aak2_sator sample No. 2 for fast indentation speed) and Figure 4.8 shows the cuttings obtained from sample No. 2 or aak2_sat at slow indentation speed.

Figure 4.7 A saturated sample indented at 3.8mm deep.
Figure 4.8 shows the image of the cuttings obtained from the (sampleaak2_sat) at fast indentation speed.

4.4.1. Chips Volume. The experimental volume of the crater was measured after each test, and the theoretical volume was also calculated using the volume of the indenter. The theoretical volume assumed that the volume of the indenter imbedded in the sample was equal to the volume of material (cuttings) displaced. The experimental and theoretical volumes of cuttings reveal more clearly the relative efficiency of the indentation process (Figure 4.9). Example the average experimental volume of cuttings (crater) for dry sandstone at a fast loading rate was about three times the its corresponding theoretical volume calculated from the shape of the indenter (see Tables 4.2 and 4.3 for details).

Statistically, this difference in volume in the above example is significant (p-value = 0.021; t-test at α=0.05). The experimental volumes of the craters were larger than the theoretical volumes. This observation was expected, since the volume of the
crater must be greater than the volume of the tool that created it. This was observed in all samples.

Figure 4.9 Comparison of the experimental and theoretical volumes for all saturation levels and speeds

4.4.2. Cuttings Shape Parameters. The cuttings collected were analyzed with IMAGEJ software to determine their shape parameters. Some representative particles are shown in Figure 4.10. Particles were classified as rounded to angular.

The software also allowed measurement of the particle aspect ratio. Figure 4.11 compares the average chip shape for dry and saturated samples. These results indicate the average chip shape is not affected by saturation level since there was no significant difference in the shape parameters.
4.5. DERIVED PARAMETERS

These parameters include effective indenter pressure, specific energy and specific penetration. These are discussed below.
4.5.1. **Effective Pressure** The indenter pressure calculated in section 4.4 was used to compute the effective indenter pressure. This was computed according to the Terzaghi’s principle of effective stress as:

\[
P_{\text{eff. indenter}} = P_{\text{indenter}} - P_{\text{pw}}
\]  

(4.7)

Where:

- \( P_{\text{eff. Indenter}} \) = effective indenter pressure
- \( P_{\text{indenter}} \) = indenter pressure
- \( P_{\text{pw}} \) = porewater pressure (bottom pressure)

This was used as a means of determining the effects of porewater pressure on the behavior of Roubidoux sandstone.

Analysis of the indenter pressure and the effective indenter pressure indicated that the curves coincide with each other (Figure 4.12). This means that the excess porewater pressure generated under the indenter is not high enough to affect the behavior of the tested rock. The possible explanation for this observation may be that the indentation speeds were too low to affect the rock behavior beyond the crushed zone and hence did not reduce the rock’s permeability. This would have been required to result in an undrained condition. This observation was reported also by Abu Bakar (2012). The pore pressure during loading was thus negligible during indentation of Roubidoux sandstone in this study and hence did not play a significant role in the behavior of the rock during these tests.
Specific Energy

The specific energy (SE) of fragmentation is the energy required to fragment a unit volume of rock. It is the total energy expended divided by the volume of dust and fragments collected.

Normalization of the energy (work done) with the volume of cuttings is important to account for the varied penetration depth. It was observed that higher indentation produced more cuttings.

Specific Penetration

The specific penetration (SP) is the force required to penetrate a unit depth into a rock. This parameter was calculated for the
point where the first major failure occurred. The SP has been observed to be a function of the strength of the rock and the dullness of the indenter (Gertsch, 2000). A total experimental depth of 0.5m was achieve and so it was assumed that the change in sharpness or dullness of indenter was insignificant in this work.

SE and SP are used as a basis to understand the response of Roubidoux sandstone to saturation and varying indenter (cutter) speed. Table 4.2 and table 4.3 summarize the load indentation tests results for dry and saturated conditions.

Table 4.2a. Summary of the dry Roubidoux sandstone test for slow indenter speed.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Fmax (KN)</th>
<th>Avg Indent Rate (mm/sec)</th>
<th>Specific Energy (J/cm^3)</th>
<th>Grain Roundness (Avg)</th>
<th>Grain Aspect Ratio (Avg)</th>
<th>Specific Penetration (N/mm)</th>
<th>Experimental Volume of chips (cm^3)</th>
<th>Theoretical Volume of Chips (cm^3)</th>
<th>Pindenter (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.8</td>
<td>0.32</td>
<td>62.33</td>
<td>1.26</td>
<td>0.80</td>
<td>7821</td>
<td>0.30</td>
<td>0.13</td>
<td>291.3</td>
</tr>
<tr>
<td>2</td>
<td>56.5</td>
<td>0.31</td>
<td>160.82</td>
<td>1.66</td>
<td>0.64</td>
<td>10169</td>
<td>0.40</td>
<td>0.21</td>
<td>668.4</td>
</tr>
<tr>
<td>3</td>
<td>28.5</td>
<td>0.32</td>
<td>139.44</td>
<td>1.58</td>
<td>0.74</td>
<td>6868</td>
<td>0.45</td>
<td>0.20</td>
<td>343.3</td>
</tr>
<tr>
<td>4</td>
<td>28.7</td>
<td>0.32</td>
<td>23.49</td>
<td>1.35</td>
<td>0.76</td>
<td>6112</td>
<td>1.55</td>
<td>0.13</td>
<td>399.0</td>
</tr>
<tr>
<td>5</td>
<td>23.8</td>
<td>0.31</td>
<td>99.21</td>
<td>1.42</td>
<td>0.73</td>
<td>8555</td>
<td>0.20</td>
<td>0.04</td>
<td>786.7</td>
</tr>
<tr>
<td>6</td>
<td>26.5</td>
<td>0.31</td>
<td>116.35</td>
<td>1.64</td>
<td>0.66</td>
<td>4200</td>
<td>0.22</td>
<td>0.16</td>
<td>345.4</td>
</tr>
<tr>
<td>7</td>
<td>29.5</td>
<td>0.32</td>
<td>51.00</td>
<td>1.65</td>
<td>0.65</td>
<td>7604</td>
<td>0.82</td>
<td>0.16</td>
<td>382.8</td>
</tr>
<tr>
<td>8</td>
<td>33</td>
<td>0.31</td>
<td>45.23</td>
<td>1.76</td>
<td>0.62</td>
<td>12411</td>
<td>1.30</td>
<td>0.19</td>
<td>403.3</td>
</tr>
<tr>
<td>9</td>
<td>36</td>
<td>0.30</td>
<td>135.26</td>
<td>1.57</td>
<td>0.66</td>
<td>12131</td>
<td>0.40</td>
<td>0.14</td>
<td>493.3</td>
</tr>
<tr>
<td>Mean</td>
<td>31.5</td>
<td>0.31</td>
<td>92.57</td>
<td>1.54</td>
<td>0.70</td>
<td>8430.06</td>
<td>0.63</td>
<td>0.15</td>
<td>457.06</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>10.4</td>
<td>0.00</td>
<td>48.66</td>
<td>0.16</td>
<td>0.06</td>
<td>2723.72</td>
<td>0.49</td>
<td>0.05</td>
<td>165.57</td>
</tr>
</tbody>
</table>
Table 4.2b. Summary of the saturated Roubidoux sandstone test for slow indenter speed.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Fmax (KN)</th>
<th>Avg Indent Rate (mm/sec)</th>
<th>Specific Energy (J/cm^3)</th>
<th>Grain Roundness (Avg)</th>
<th>Grain Aspect Ratio (Avg)</th>
<th>Specific Penetration (N/mm)</th>
<th>Experimental Volume of Chips (cm^3)</th>
<th>Theoretical Volume of Chips (cm^3)</th>
<th>Pindenter (MPa)</th>
<th>Porewater pressure (P3) (Pa)</th>
<th>Change in P3 (Pa/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.8</td>
<td>0.32</td>
<td>50.4</td>
<td>1.58</td>
<td>0.65</td>
<td>4762</td>
<td>0.9</td>
<td>0.25</td>
<td>283.6</td>
<td>102.7</td>
<td>9.77</td>
</tr>
<tr>
<td>2</td>
<td>18.2</td>
<td>0.31</td>
<td>37.6</td>
<td>1.45</td>
<td>0.71</td>
<td>7225</td>
<td>0.58</td>
<td>0.08</td>
<td>291.8</td>
<td>87.9</td>
<td>10.67</td>
</tr>
<tr>
<td>3</td>
<td>14.8</td>
<td>0.32</td>
<td>168.6</td>
<td>0.76</td>
<td>0.69</td>
<td>9632</td>
<td>0.2</td>
<td>0.14</td>
<td>200.3</td>
<td>46.7</td>
<td>14.62</td>
</tr>
<tr>
<td>4</td>
<td>23.1</td>
<td>0.31</td>
<td>152.3</td>
<td>1.51</td>
<td>0.69</td>
<td>9453</td>
<td>0.2</td>
<td>0.08</td>
<td>372.9</td>
<td>107.9</td>
<td>11.47</td>
</tr>
<tr>
<td>5</td>
<td>27.2</td>
<td>0.31</td>
<td>157.7</td>
<td>1.61</td>
<td>0.73</td>
<td>8001</td>
<td>0.2</td>
<td>0.09</td>
<td>416.7</td>
<td>157.9</td>
<td>13.10</td>
</tr>
<tr>
<td>6</td>
<td>27.1</td>
<td>0.31</td>
<td>82.4</td>
<td>1.64</td>
<td>0.66</td>
<td>8455</td>
<td>0.35</td>
<td>0.08</td>
<td>446.2</td>
<td>140.7</td>
<td>14.84</td>
</tr>
<tr>
<td>7</td>
<td>7.5</td>
<td>0.31</td>
<td>49.7</td>
<td>0.76</td>
<td>0.69</td>
<td>4498</td>
<td>0.2</td>
<td>0.06</td>
<td>147.2</td>
<td>44.8</td>
<td>6.06</td>
</tr>
<tr>
<td>8</td>
<td>28.5</td>
<td>0.30</td>
<td>110.4</td>
<td>1.68</td>
<td>0.67</td>
<td>13542</td>
<td>0.3</td>
<td>0.08</td>
<td>459.8</td>
<td>147.6</td>
<td>14.98</td>
</tr>
<tr>
<td>9</td>
<td>13</td>
<td>0.32</td>
<td>21.9</td>
<td>1.47</td>
<td>0.70</td>
<td>6472</td>
<td>0.8</td>
<td>0.15</td>
<td>174.5</td>
<td>41.9</td>
<td>6.01</td>
</tr>
<tr>
<td>10</td>
<td>24</td>
<td>0.35</td>
<td>69.4</td>
<td>1.59</td>
<td>0.68</td>
<td>10002</td>
<td>0.58</td>
<td>0.13</td>
<td>336.1</td>
<td>74.2</td>
<td>16.05</td>
</tr>
<tr>
<td>11</td>
<td>20.6</td>
<td>0.31</td>
<td>161.8</td>
<td>1.64</td>
<td>0.66</td>
<td>7929</td>
<td>0.19</td>
<td>0.10</td>
<td>309.7</td>
<td>84.5</td>
<td>12.07</td>
</tr>
<tr>
<td>Mean</td>
<td>20.9</td>
<td>0.32</td>
<td>96.6</td>
<td>1.57</td>
<td>0.69</td>
<td>8179</td>
<td>0.4</td>
<td>0.1</td>
<td>312.6</td>
<td>94.3</td>
<td>11.8</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>6.8</td>
<td>0.01</td>
<td>55.5</td>
<td>0.08</td>
<td>0.03</td>
<td>2550</td>
<td>0.3</td>
<td>0.1</td>
<td>107.2</td>
<td>41.6</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table 4.3a Summary of the dry Roubidoux sandstone test for fast indenter speed.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Fmax (KN)</th>
<th>Avg Indent Rate (mm/sec)</th>
<th>Specific Energy (J/cm^3)</th>
<th>Grain Roundness (Avg)</th>
<th>Grain Aspect Ratio (Avg)</th>
<th>Specific Penetration (N/mm)</th>
<th>Experimental Volume of Chips (cm^3)</th>
<th>Theoretical Volume of Chips (cm^3)</th>
<th>Pindenter (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30.4</td>
<td>21.90</td>
<td>42</td>
<td>1.62</td>
<td>0.63</td>
<td>5578.9</td>
<td>1.3</td>
<td>0.27</td>
<td>322.8</td>
</tr>
<tr>
<td>2</td>
<td>24.3</td>
<td>19.74</td>
<td>255.8</td>
<td>1.93</td>
<td>0.52</td>
<td>8104.0</td>
<td>0.1</td>
<td>0.08</td>
<td>402.4</td>
</tr>
<tr>
<td>3</td>
<td>21.3</td>
<td>21.75</td>
<td>151.9</td>
<td>1.62</td>
<td>0.67</td>
<td>3877.9</td>
<td>1.2</td>
<td>0.44</td>
<td>243.6</td>
</tr>
<tr>
<td>4</td>
<td>28.5</td>
<td>19.51</td>
<td>64.0</td>
<td>1.62</td>
<td>0.67</td>
<td>3877.9</td>
<td>1.2</td>
<td>0.44</td>
<td>243.6</td>
</tr>
<tr>
<td>5</td>
<td>6.9</td>
<td>20.93</td>
<td>52.6</td>
<td>1.62</td>
<td>0.67</td>
<td>4863.9</td>
<td>0.1</td>
<td>0.05</td>
<td>152.9</td>
</tr>
<tr>
<td>6</td>
<td>26.1</td>
<td>20.58</td>
<td>67.5</td>
<td>1.64</td>
<td>0.68</td>
<td>10087.7</td>
<td>0.7</td>
<td>0.16</td>
<td>337.4</td>
</tr>
<tr>
<td>7</td>
<td>14.1</td>
<td>17.84</td>
<td>85.2</td>
<td>1.47</td>
<td>0.70</td>
<td>8552.0</td>
<td>0.15</td>
<td>0.04</td>
<td>359.2</td>
</tr>
<tr>
<td>8</td>
<td>26.4</td>
<td>19.58</td>
<td>67.4</td>
<td>1.68</td>
<td>0.63</td>
<td>11505.8</td>
<td>0.5</td>
<td>0.11</td>
<td>387.5</td>
</tr>
<tr>
<td>9</td>
<td>30.3</td>
<td>19.79</td>
<td>221.7</td>
<td>1.94</td>
<td>0.60</td>
<td>13508.8</td>
<td>0.4</td>
<td>0.23</td>
<td>349.1</td>
</tr>
<tr>
<td>10</td>
<td>24.9</td>
<td>18.66</td>
<td>148.8</td>
<td>1.76</td>
<td>0.58</td>
<td>9967.2</td>
<td>0.25</td>
<td>0.10</td>
<td>377.8</td>
</tr>
<tr>
<td>Mean</td>
<td>23.3</td>
<td>20.0</td>
<td>115.7</td>
<td>1.7</td>
<td>0.6</td>
<td>8009.5</td>
<td>0.5</td>
<td>0.2</td>
<td>317.6</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>7.5</td>
<td>1.3</td>
<td>75.2</td>
<td>0.2</td>
<td>0.1</td>
<td>3324.6</td>
<td>0.4</td>
<td>0.1</td>
<td>79.5</td>
</tr>
</tbody>
</table>
4.6. SATURATION EFFECTS

The discussion of the results in this section is limited to the specific energy (SE) and specific penetration (SP) for dry and saturated samples. Table 4.4 statistically compares dry and saturation rock indentation with the loading rate “held constant” (accounted for) by hypothesis testing to compare the means. A one-tailed t-test, assuming normal distribution, was applied to the difference in the means. The significance level (α-value) of the t-test was set at 0.2 (80% confidence).

Table 4.4 indicates that saturation appeared not to affect the SE and SP of the rock at the slow indentation speed. However, at the fast indentation speed, saturation decreased the specific energy by 32%, which is significant at 80% confidence. The specific penetration was not significantly affected by the saturation level at either the fast or the slow indentation speeds.

These results are expressed graphically by boxplots displayed in Figures 4.13-4.16. The boxplots provide a five-part summary of the data distribution: minimum,
first quartile, median, third quartile, and maximum values. These represent the range, distribution and variability in the data for a given saturation level.

The decrease in specific energy with saturation at the fast loading rate (Table 4.4 and Figure 4-13) was the result expected if the permeability of the Roubidoux sandstone is high enough that even the higher indentation rate does not induce pore pressure buildup, given that the other effects of saturation have been shown to weaken rock (Abu Bakar, 2012; Hood and Roxborough, 1992).

The specific penetration, on the other hand, increased 6% with saturation (Table 4.4 and Figure 4-15). Though statistically insignificant at 80% confidence, this was not expected, especially since the specific energy decreased in the same circumstances. Figure 4.12 indicates that the generated porewater pressure was not high enough to affect the indenter pressure and hence could not validate the idea of the pore pressure affecting the strength.

Under the slow indentation rate (Table 4.4 and Figures 4.13 and 4.16), the medians and variances for the SE and the SP are not significantly different for the saturated samples than for the dry samples. This supports the conclusion that the slow indentation speed is below the minimum speed required to generate an undrained condition in the rock beneath the indenter.

The difference in response of two such highly related indicators as specific energy and specific penetration cannot be explained fully from the results of this study. There are two possibilities: Rock property variability and the inherent limitations of these two index properties. The variability of the Roubidoux sandstone has been noted previously (Dake, 1918) and was confirmed by observation in this
study to consist of variable iron oxide and clay cementation as well as minor sedimentary structures such as non-separated bedding planes. This variability cannot be laid either for or against this unexpected difference, however. It is as likely to obscure the difference as to enhance it. That leaves the properties of the SE and SP indexes themselves. Specific energy is a property of all three dimensions (volume) whereas specific penetration is only one-dimensional (displacement). It is reasonable that a volume-averaged property would more accurately reflect the behavior of the rock than a simpler distance-averaged property.

Table 4.4 Statistical comparisons of the specific energies and specific penetrations for dry and saturated sandstone at the slow and fast loading rates. The only statistically significant difference is highlighted.

<table>
<thead>
<tr>
<th></th>
<th>Fast</th>
<th>Slow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg. SE</td>
<td>Avg. SP</td>
</tr>
<tr>
<td></td>
<td>(J/cm^3)</td>
<td>(N/mm)</td>
</tr>
<tr>
<td>Dry Sandstone</td>
<td>115.68</td>
<td>8009.55</td>
</tr>
<tr>
<td>Saturated Sandstone</td>
<td>78.81</td>
<td>8491.21</td>
</tr>
<tr>
<td>Percent change (%)</td>
<td>31.9</td>
<td>5.7</td>
</tr>
<tr>
<td>t-value (α=0.2%)(critical)</td>
<td>0.862</td>
<td>-0.862</td>
</tr>
<tr>
<td>t-value (calculated)</td>
<td>1.279</td>
<td>-0.345</td>
</tr>
</tbody>
</table>

SE-Specific Energy, SP-Specific Penetration
Figure 4.13 Boxplots of SE values for dry and saturated samples at fast speed showing median, highest, lowest, and the 1st and 3rd quartile values.

Figure 4.14 Boxplots of SE values for dry and saturated samples at slow speed showing median, highest, lowest, and the 1st and 3rd quartile values.
Figure 1.15 Boxplots of SP values for dry and saturated samples at fast speed showing median, highest, lowest, and the 1st and 3rd quartile values.

Figure 4.16. Boxplots of SP values for dry and saturated samples at fast speed showing median, highest, lowest, and the 1st and 3rd quartile values.
4.7. SPEED EFFECTS

Statistical analysis of the effects of indentation rate was conducted separately for each saturation level. Comparison of the specific energy and specific penetration values (Table 4.5 and Figures 4.17-4.20) for dry rock shows mixed results, with a 20% increase in specific energy and a 5% decrease in specific penetration with increasing indentation rate. In saturated rock, the specific energy decreased by 18.4% while the specific penetration increased by 3.7% with increasing indentation rate. Although none of these trends are statistically significant at 80% confidence, they do not contradict the well-known strengthening effect of increasing strain rate (Gladwell 1980; Johnson, 1985 and Hills et al., 1993).

This is likely to be due to both speeds being too low to cause undrained conditions beneath the indenter. Since the differences in SE and SP are insignificant for both dry and saturated rocks, it can mean that the speed magnitude was not significant enough to cause a noticeable change in the rock behavior. More load indentation data will be required to verify the current observations.

Table 4.5 Statistical comparison of specific energy and specific penetration for dry and saturated sandstone under the maximum and minimum indentation speeds.

<table>
<thead>
<tr>
<th></th>
<th>Dry Avg. SE (J/cm³)</th>
<th>Dry Avg. SP (N/mm)</th>
<th>Saturated Avg. SE (J/cm³)</th>
<th>Saturated Avg. SP (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast speed</td>
<td>115.68</td>
<td>8009.55</td>
<td>78.81</td>
<td>8491.21</td>
</tr>
<tr>
<td>Slow Speed</td>
<td>92.57</td>
<td>8430.06</td>
<td>96.6</td>
<td>8179.31</td>
</tr>
<tr>
<td>Percent change (%)</td>
<td>20.0</td>
<td>5.0</td>
<td>18.4</td>
<td>3.7</td>
</tr>
<tr>
<td>t-value (α=0.2%)(critical)</td>
<td>0.863</td>
<td>-0.863</td>
<td>-0.861</td>
<td>0.861</td>
</tr>
<tr>
<td>t value (calculated)</td>
<td>0.784</td>
<td>-0.299</td>
<td>-0.759</td>
<td>0.262</td>
</tr>
</tbody>
</table>

SE-Specific Energy, SP-Specific Penetration
Figure 4.17 Boxplots of SE values for saturated Roubidoux sandstone at two speeds showing the median, highest, lowest, and the 1st and 3rd quartile values.

Figure 4.18 Boxplots of SE values for dry Roubidoux sandstone at two speeds showing the median, highest, lowest, and the 1st and 3rd quartile values.
In Figure 4.17, the statistics (median, 1st, 3rd) of the data for the fast speed is generally lower than the SE for the slow speed but has a larger mean due to the outliers. The box graphs overlap at the upper quartiles and lower quartiles but the slow data is widely spread. It appears that slow speed require less energy to excavate rock than fast speed but the hypothesis testing showed no significant different under the two speeds.. In the dry rock (Figure 4.18), there is less variability in the SE for both speeds and their medians are not significantly different. However, the fast speed data shows negatively skewedness.

Figure 4.19 Boxplots of SP values for saturated Roubidoux sandstone at two speeds showing median, highest, lowest, and the 1st and 3rd quartile values.
Figure 4.20 Boxplots of SP values for dry Roubidoux sandstone at two speeds showing median, highest, lowest, and the 1st and 3rd quartile values.

From the box plots and the hypothesis testing it can be seen that the chosen speeds did not affect the specific penetration or the specific energy in either saturation level. It can therefore be concluded that regardless of the saturation level, the chosen speed difference was not significant enough to affect the rock behavior.

4.8. EFFECTS OF PERMEABILITY

It is generally accepted that specific energy and penetration depend on the effective pressure, that is, on the difference between the pore water pressure and the loading pressure. This common assertion is based on the fact that the apparent strength of rock depends on the difference between the mean total stress and the pore pressure (Detournay and Atkinson, 2000). The pore pressure generated is a function
of the permeability of the indented medium. This means that the pore water pressure, strength of the rock and hence the specific energy are all functions of the near-field permeability of the rock and of the speed of indentation or cutting.

All other factors constant, if the indentation rate is high enough, there will be a quick closure of pores and bedding planes (which are characteristic of the tested rock), which reduces the permeability under the indenter. If the indentation is too fast for the decreased permeability to dissipate excess porewater pressure, the effective pressure is reduced and the rock appears stronger. However, if the indentation rate is low enough, the rock has enough time to dissipate excess porewater pressure. In this case, the mechanical properties of the rock are less affected by the pore pressure and hence the energy required to fragment it would be lower than the previous case.

The two loading rates used in this study were selected with the intent that the two speeds would bracket the rate at which the permeability cannot accommodate the increased porewater pressure, and hence bracket the change that would induce in the specific energy and specific penetration.

The porewater pressure buildup rate at the fast indentation speed (N=11) averaged 134.60 Pa/sec (SD=65.30). By comparison, the porewater pressure buildup rate at the slow loading speed (N=10) averaged only M=11.78 Pa/sec (SD=3.45). This is a 91.3% difference. To test the hypothesis that the slow indentation speed was associated with a statistically significant different porewater pressure buildup rate than the fast indentation speed, a one-tailed independent sample t-test was performed. The means were assumed to be normally distributed. Additionally, the assumption of equal variance was tested and satisfied through Levene’s F test, F(21)=13.057. The t-
test revealed a statistically significant difference between the porewater pressure increases at the two indentation speeds at 95% confidence.

However, as discussed previously, careful examination of the specific energies and specific penetrations indicated no significant difference between the two loading rates in either dry or saturated rocks. The explanation is that both the loading rates were below the minimum threshold for the Roubidoux sandstone to exhibit the expected effect. The maximum porewater pressure recorded in all the tests was 158 Pa (0.0229 psi) as compared to 26.1kPa (3.78 psi) measured by Abu Bakar (2012) at an indentation speed of 100 mm/sec for the same rock. In other words, indentation that was five times faster caused a maximum pore pressure 165 times higher. The porewater pressure observed in the present study was too small to affect the behavior of the sandstone as can be seen in Figure 4.12. Therefore, more data will be required for saturated rock at higher loading rates to verify this model of the behavior of this rock under an indenter.
5. CONCLUSIONS AND FUTURE WORK

5.1. CONCLUSIONS

The purpose of this research was to better understand the behavior of saturated porous rock during excavation, by evaluating the coupled hydro-mechanical response of samples to indentation at two speeds and two saturation levels. The load indentation equipment was equipped with pressure measurement facilities to monitor the porewater pressure generated under the indenter during the tests.

The response of the Roubidoux sandstone to indentation was affected by saturation, at the 80% significance level. Saturation did not affect the specific energy when the indentation rate was slow (0.3 mm/sec), but did decrease it by 32% when the indentation rate was faster (20 mm/sec). The specific penetration, on the other hand, did not appear to be affected by saturation at either indentation rate.

The porewater pressure during indentation at all speeds and all saturation levels never reach levels high enough to affect the behavior of the tested sandstone. Recall that Abu Bakar (2012) recorded a maximum porewater pressure of 26.1KPa at an indenter loading rate of 100 mm/sec in the same rock, which was three orders of magnitude greater than the highest porewater pressure observed in this study (0.158 KPa).

Statistical analysis of the effects of loading rate, with the level of saturation “held constant”, showed results too variable to provide statistically significant conclusions.

The speeds of indentation chosen for these experiments were expected to bracket the hypothesized threshold speed that separates apparent strengthening effects (via
decreased effective indenter pressure) from actual weakening effects of saturation. However, the statistical insignificance of the differences shown by two important indentation-related parameters indicates one of two possibilities:

- The threshold indentation speed between the two states for Roubidoux sandstone exists but is not between the speeds tested, or
- The model is fundamentally flawed.

5.2. RECOMMENDED FUTURE WORK

The contradictory nature of these findings emphasizes the need for improvements to the model of sandstone behavior that formed the basis for this research. The following research directions are recommended for this purpose:

- Perform experiments with high indenter loading rates to more carefully evaluate the belief that the porewater pressure buildup in porous rocks is increased more by higher-speed indentation.
- Create a coupled deformation-hydraulic numerical model to evaluate the ability of the Roubidoux sandstone to drain porewater pressure during indentation at various speeds.
- Improve measurement of the volume of cuttings and especially of the air-entrained dust that forms a major part of the disturbed zone. One possibility is near-field LiDAR scans with the appropriate software to produce a 3-D image of the crater that will allow measurement of the volume.
- Improve the porewater pressure measurement methodology.
- Develop an indentation model which considers the effects of interaction of the adjacent indentations.

- Use different indenters to provide better understanding of the basic rock behavior under different cutter designs.

- Permit higher-resolution visual records of the action during chip formation with high resolution cameras at appropriate locations, angles, and data rates. The Digital Image Correlation (DIC) procedure used by Zhang et al (2013) could be a possibility.

- Perform full scale indentation tests on different rock types of greater and lesser permeability to the Roubidoux sandstone tested here, particularly detrital sedimentary rock types.
APPENDIX

FULL LOAD-INDENTATION CURVES FOR ALL TESTED SAMPLES

The table below shows additional details.

<table>
<thead>
<tr>
<th>Type of Rock</th>
<th>Roubidoux Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample code</td>
<td>Indentation Speed</td>
</tr>
<tr>
<td>10s_aak1_sat</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak2_sat</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak3_sat</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak4_sat</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak5_sat</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak6_sat</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak7_sat</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak8_sat</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak9_sat</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak10_sat</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>600s_aak1_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak2_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak3_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak4_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak5_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak6_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak7_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak8_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak9_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak10_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak11_sat</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>10s_aak1_dry</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak2_dry</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak3_dry</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak4_dry</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak5_dry</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak6_dry</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak7_dry</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak8_dry</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak9_dry</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>10s_aak10_dry</td>
<td>20 mm/sec</td>
</tr>
<tr>
<td>600s_aak1_dry</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak2_dry</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak3_dry</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak4_dry</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak5_dry</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak6_dry</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak7_dry</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak8_dry</td>
<td>0.3 mm/sec</td>
</tr>
<tr>
<td>600s_aak9_dry</td>
<td>0.3 mm/sec</td>
</tr>
</tbody>
</table>
Fast indentation speed-saturated samples.

**10s_aak1_sat**

![Graph 1: Load vs Penetration for 10s_aak1_sat](image1)

**10s_aak2_sat**

![Graph 2: Load vs Penetration for 10s_aak2_sat](image2)
Slow indentation speed-saturated samples.

**600s_aak1_sat**

- Load (N)
- P1 (Pa)
- P2 (Pa)
- P3 (Pa)

**600s_aak2_sat**

- Load (Kg)
- P1 (Pa)
- P2 (Pa)
- P3 (Pa)
600s_aak9_sat

- Load (N)
- P1 (Pa)
- P2 (Pa)
- P3 (Pa)

Penetration (mm)

Load (N)

Penetration (mm)

600s_aak10_sat

- Load (N)
- P1 (Pa)
- P2 (Pa)
- P3 (Pa)

Penetration (mm)

Load (N)
Slow indentation speed-Dry samples.
Fast indentation speed-Dry samples.
BIBLIOGRAPHY


Celik M. Y. and Akbulut H. and Ayse Ergul “Water absorption effect on the strength of Ayazini tuff, such as the uniaxial compressive strength (UCS), flexural strength and freeze and thaw effect” Eviron Earth Sci., 2013.


US Army Corps of Engineers, 


VITA

Azupuri Ayerikujei Kaba hails from Paga-Zenga, Upper East Region, Ghana. He received his B.Sc. in Geological Engineering from Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. He subsequently gained admission to study Geological Engineering (M.S) at Missouri University of Science and Technology in Rolla, Missouri. During his time in Missouri University of Science and Technology, he worked as Teaching and Research Assistant. He received his MS in Geological Engineering in August 2014.