ARL-TR-8967 • MAY 2020

Science, Technology, Engineering, and Mathematics (STEM) Activities on a Budget: Part II. Sand

by RA Pesce-Rodriguez and A Rodriguez

ARL-TR-8967 ● MAY 2020

Science, Technology, Engineering, and Mathematics (STEM) Activities on a Budget: Part II. Sand

RA Pesce-Rodriguez
Weapons and Materials Research Directorate, CCDC Army Research Laboratory

A Rodriguez
Long Reach High School

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
May 2020	Technical Report	4 November 2019–4 February 2020

4. TITLE AND SUBTITLE
Science, Technology, Engineering, and Mathematics (STEM) Activities on a Budget: Part II. Sand

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
RA Pesce-Rodriguez and A Rodriguez

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
CCDC Army Research Laboratory
ATTN: FCDD-RLW-LB
Aberdeen Proving Ground, MD 21005

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-8967

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In Part II of a series of hands-on science, technology, engineering, and mathematics programs for students of all ages, we provide background information and specific guidance on materials and procedures for 10 activities related to sand. All activities are designed to be executable with minimum expense and hazard. Our program was developed as part of our ongoing "Chemistry in the Library" program, but is also appropriate for traditional and home school programs and museum classes. Background discussion includes key information about the composition, chemistry, and origin of sand as well as a brief discussion regarding sustainability issues.

15. SUBJECT TERMS
science, technology, engineering, and mathematics, STEM, hands-on, "on a budget", sand, silt, gravel, silicon dioxide, SiO_2, silica, hydrogen bonding, pH, microscopy, sieve, particle size, calcium carbonate, pH, magnetite, hematite

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			RA Pesce-Rodriguez
Unclassified	Unclassified	Unclassified	UU	35	19b. TELEPHONE NUMBER (Include area code) (410) 306-1877

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

1. Introduction and Background Information

Over the course of preparing this program for Part II of our science, technology, engineering, and mathematics (STEM) series, we have become arenophiles, or “sand lovers”. Discussing this word with students is a good way to talk about word origins. “Areno” comes from Latin for “sand” and “phile” from Greek for “loving”. The word “psammophile” is of all-Greek origin and also means “sand lover”. Spanish-speaking students will recognize “arena” as the word for sand. Students may be interested to know that the word “arena” come from the ancient Romans (Latin) and means a “sand-strewn places of combat”, like the Roman Colosseum. As we discuss in activity #9, sand is very good at absorbing water and water-based materials (including blood)!

Our primary motivation for preparing this program on sand is to share fun and interesting information about the chemistry of sand, but we also aim to promote awareness about sustainability issues related to sand. We get to the chemistry in a bit, but first we talk about sustainability, which is avoiding the depletion of a natural resource. Most people would find it hard to believe that we could ever deplete our natural sand resources. Sand is all around us. Desserts and beaches are full of it. How could we ever run out of sand? First of all, we have to understand that we use a lot of sand and that there is an ever-increasing need for sand. (We talk shortly about the many, many ways that we use sand.) Second, not all sand is equally useful. As we discuss, desert, beach, and river sands are all very different. Of the three, river sand is the most useful and is absolutely becoming an endangered resource. Mineral rights to locations with high-purity quartz sand are guarded like diamond mines, as they are critical resources for the semi-conductor materials that we need for silicon (Si) chips for electronic devices. Many sources of this high-quality sand are already depleted, making the remaining sites extremely valuable. Dredging of river sand, which is valuable for making concrete, is already heavily taxed or banned altogether in many parts of the world. Because of its great value, it is a source of criminal activity around the world. For a very good discussion of these issues, instructors are referred to Welland (2009) and Beiser (2018, 2019).

Another consideration is that good-quality sand is not always located where it is needed. Given that sand is so heavy, transporting it can be very expensive. For this reason, sand is often “manufactured” (often onsite) (i.e., rock of the appropriate type is mechanically ground up to the right particle size). More information on manufactured sand can be found at The Screed Scientist (2014) and Mining And Construction (n.d.). We are doing several activities with manufactured sand to help understand the differences between it and natural sand.

Now that we know where manufactured sand comes from, how about natural sand? We find that students of all ages rarely think about where the materials we use come from. For a classroom activity, we propose that students be asked to tell where sand comes from. Through encouragement and additional questions, students should arrive at the answer that sand comes from erosion of rocks and minerals, which in turn come from larger rocks and minerals, and ultimately from the crust of the Earth in the form of mountains and other structures (NPS 2015). To get at the idea of sustainability, it is important to push the discussion a bit further and ask students how long they think it takes for sand to form. Depending on the type of sand, it could take hundreds to thousands of years to form. That means that if we use up "good" sand now, it will not be replenished in our lifetimes, or in the lifetimes of their children, or their grandchildren, and so on. Yes, the Earth does have a lot of sand, but the "good stuff" is a very precious resource.

So what do we use sand for? Here's a list that we put together. Students and teachers can surely add to the list:

- Concrete
- Asphalt
- Bricks
- Sand casting (foundry sand)
- Sand blasting
- Fracking
- Sand art
- Sandbags
- Water filtration
- To prevent slipping on ice
- Sand paper
- Fire extinguishment
- Paint
- Glass
- Ceramics
- Si chips/semiconductors
- Fiber optics
- Fiber glass
- Colloidal silica (food additive)
- Flow agent for hygroscopic products
- Toothpaste
- Hair products
- Silicone water proofing

Here's a fun fact: sand is the second most-consumed natural resource on the planet (falling just behind water). Each year, on the order of 50 billion tons are used, most going toward making concrete (Beiser 2018). And not just any sand can be used to make concrete. It has to be "good" sand, usually river sand. Desert sand cannot be used because after so many years of being blown around by wind, the particles of desert sand are too small, too round, and too smooth. Desert sand also tends to have a very high pH because of the presence of carbonates (we provide a demonstration of this in our "pH Test" activity). Ocean sand contains too much salt and calcium carbonates (from shells) and cannot be used without first being processed to remove the salt and shells. Calcium carbonate and calcium magnesium carbonate (dolomite; also found in some sands) are very soft materials and would make concrete weak. (We provide a demonstration of carbonate content in our "Vinegar

Test" activity.) River sand is usually ideal for use in concrete, it is free of salt and shells, has a more neutral pH than desert sand, and has undergone less vigorous erosion than desert sand. The result is silicon dioxide (SiO_2)-rich, irregularly shaped (often jagged) grains can easily get caught on each other, thereby preventing slip and imparting strength to concrete. (We provide a demonstration of this characteristic in the "Stick Test" activity.)

Many natural sands contain iron (Fe) in different forms. Sands that are orange or light brown in color often have Fe on their surface in the form of hematite (Fe_2O_3). Sands with small black particles might be found to contain magnetite (Fe_3O_4). (We test for this in our "Magnet Test" activity.)

After so much discussion about sand, we still have not defined exactly what sand is. While most students will think that all sand is more or less the same, we see from our previous discussion that there are certainly differences with respect to particle size, smoothness, salt content, and shell content, but there is also a more general aspect that we need to discuss. Sand is, for the most part, defined by its size. Regardless of its composition, any material (including salt and shells) that is larger (or coarser) than "silt" (i.e., <0.05 mm) and smaller (or finer) than gravel (i.e., <2 mm) is considered to be "sand". (We provide a demonstration about silt in our "Silt Test" activity.)

While any material with the right particle size can be considered to be sand, most of what we call sand is composed of silicon dioxide, also known as silica and SiO_2. "Good" sand is mostly SiO_2. Considering that most of our Earth's crust (more than three-quarters) is made up of silicon (Si) and oxygen (O) (Sandatlas n.d.; Wikipedia 2020a), and given that sand comes from erosion of materials in the Earth's crust, it makes a lot of sense that most sand is also made up of Si and O. One form of SiO_2 is called "quartz" and is a highly desirable form of sand for semiconductor applications.

2. Safety

To instill good laboratory safety behavior, students should be provided with safety glasses or goggles, and must be advised against tasting any provided materials or eating while conducting the activities described herein.

3. Recording Data

While data recording for activities in this program is not required and can be omitted for younger students, older students should be encouraged to record data and observations as they work through the program, if time permits. At a minimum, a datasheet like the one shown in Fig. 1 should be used. If possible, students should keep a lab notebook to record their results. If this is to be done, having a small dedicated composition book is advised. Composition books are inexpensive and usually thread-bound, reducing the risk of lost pages. Students using lab notebooks should be instructed to number pages in the book and use the first page for a table of contents. A nice summary for student notebook setup and usage is given by Causey (n.d.).

	Desert Sand	Zircon Sand	Pompano Beach Sand	Daytona Beach Sand	Play sand	Construction Sand
Observations (microscope)						
Sieve (small)	g	g	g	g	g	g
Sieve (medium)	g	g	g	g	g	g
Sieve (large)	g	g	g	g	g	g
pH test						
Vinegar test						
Magnet test						
Stick test						
Silt test						

Fig. 1 Sample datasheet

4. Sand Samples

For this program, it is ideal to examine several different kinds of sand. Sand can be found in local neighborhoods (parks, backyards, beaches). Students or instructors might also ask family and friends who live in other places to provide sands local to their area. Sand can also be purchased from pet stores (for use in aquariums and reptile habitats). Hardware stores often sell sand for sandboxes (referred to as “play sand” in this report) and manufactured sand (referred to as “construction sand” in this report). Play sand is usually river sand and contrasts very well against construction sand in most activities described in this report. Both play sand and construction sand are very inexpensive (approximately $5 for 40 lb). If no other types of sand are available, working with just those two types will suffice.

The samples we used in our program are shown in labeled glass vials in Fig. 2. In place of vials, plastic “shot glasses” labeled with felt-tipped pens on masking tape work very well. For dispensing sand specimens, we have found that plastic tasting spoons (gelato spoons) work very well. They can be used either as one would normally use a spoon or "upside down and backwards" as shown in Fig. 3 for a narrow-mouthed vial.

Fig. 2 Sand samples in labeled glass vials. To save on expenses, reusable plastic shot glasses also work well.

Fig. 3 Use of a tasting spoon as a spatula for dispensing a sand specimen

5. Hands-on Program

We now present 10 hands-on activities related to sand. The program can be used in its entirety as part of a single program (time required 1.5–2 h), as part of an ongoing program (e.g., one session per week for 10 weeks), or as an a la carte mix of activities that best suits the need of a given curriculum. We have tried to offer a broad range of activities that highlight the important chemistry and properties of sand, while at the same time offering engaging activities that give students the opportunity to work with materials and methods similar to those used by professional chemists, and make observations and conclusions about the materials being investigated.

5.1 Activity #1: Silt Test

For this activity, we recommend using one or two types of sand. For the example in Fig. 4, we chose play sand and construction sand purchased from a local hardware store. We added an equivalent volume of sand to two 15-mL centrifuge tubes (we filled to the 4-mL mark). The tubes (Fig. 5) can be purchased online for a reasonable cost (~$20 for 100 tubes), and can be rinsed and used repeatedly for other activities. Water is then added to the tube (we filled to the 12-mL mark) and then both tubes were vigorously shaken. Silt from the sand makes the water above the sand cloudy. The tubes were then allowed to sit undisturbed until the silt settled (30–45 min). We prepared our samples at the beginning of our session and then checked on the silt level at the end of the program. After the water is clear, silt can be observed to have accumulated on top of the sand. Using the gradation marks on the tube, the amount of silt relative to the sand can be estimated. The volume percent of silt can be calculated by taking the ratio of silt to sand and multiplying by 100%: (volume silt/volume sand) × 100%. For use in concrete, the silt content should not exceed 8% (Dashore 2020). For our sample, we found that the construction sand exceeded the limit, while the play sand fell below the limit.

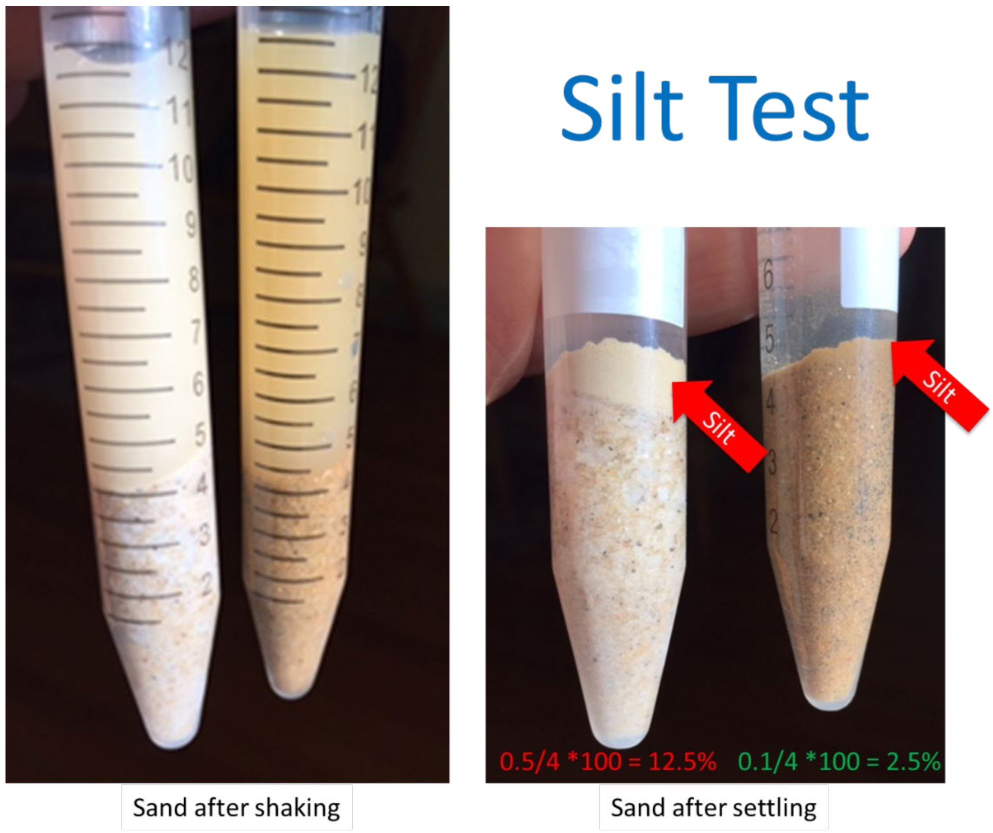

Fig. 4 Construction sand (left in each photo) and play sand (right in each photo) after shaking (left photo) and after the silt has settled (right photo)

Fig. 5 15-mL centrifuge tubes

5.2 Activity #2: Magnet Test

For this test, we put a small amount of each of our sand specimens in plastic petri dishes (Fig. 6) and taped the dishes so that we could use them for many programs. For a single classroom session, sand could instead be placed in the bottom of a small paper or plastic cup. To test for magnetic particles, we swiped mini neodymium magnets across the bottom of the petri dish and looked at the particles that followed the motion of the magnet (Fig. 7). The mini magnet "push pins" that we used were purchased online in a package of 25 (cost ~$8). Any strong magnet will work.

Fig. 6 Small amount of sand samples in individual plastic petri dishes. To save on expenses, reusable plastic shot glasses (see Fig. 2) or paper "Dixie cups" also work well.

Fig. 7 Mini neodymium magnet used to separate the magnetite from the desert sand

Of our six samples, we observed magnetite in only the desert sand.

5.3 Activity #3: Microscopic Analysis

For this module, it is essential that students have access to microscopes. While the need for microscopes for lab work may have been prohibitive in the past, several newer inexpensive microscopes have made them much more accessible. A model that we have been using for the past few years (Carson MicroBrite Plus; Fig. 8) is very popular with students and parents alike, and is available for about $10 each. The microscopes are fairly robust, operate with a single AA battery, and are illuminated with an LED bulb. Magnification goes to 120× and is acceptable for sand analysis by students.

Fig. 8 Mini microscope used for observation of sand specimens

Sand specimens were prepared for microscopic analysis by encasing them in transparent, heavy-duty packing tape. Labels were also encased in the tape, as shown in Fig. 9. Samples prepared in this manner are very robust and can be used by many students without needing to be replaced. The method reduces mess in the lab and facilitates analysis by having all specimens mounted on a single strip.

Fig. 9 Sand specimens for microscopic analysis prepared by encasing in transparent, heavy-duty packing tape

Images of sand specimens taken with a cellphone camera (and a steady hand) through the mini microscope in Fig. 8 are shown in Fig. 10. A piece of blue paper was used in the background to enhance contrast. When examining sand specimens, students should be advised to make observations of particle size and uniformity. Specific features to look for are the very fine particles observed for the manufactured sand ("construction sand") and the absence of such particles in what we believe to be river sand ("play sand"). Given the fine particles and the sharpness of the construction sand relative to the play sand, it is easy to imagine why the former should never be used in a sandbox. The construction sand would be very abrasive to a child's skin and could inflict damage to eyes and soft tissue in the nose, if exposed. Students may also observe shell fragments in beach sand. In the case of our Daytona Beach sand, a shell from the mollusk *donax variabilis* (common name: coquina) is observed (beaches on the northeast coast of the US from Virginia beach to the Florida Keys are known for their coquina content; Wikipedia 2020b). Students will also observe the orange color on the surface of the desert and rivers sands from iron oxide (hematite, Fe_2O_3). This coating is not observed for the zircon sand nor for what appears to be quartz in the Pompano Beach sand. For more images of sand from around the world, see Greenberg et al. (2015) or websites such as MicroBus (2020).

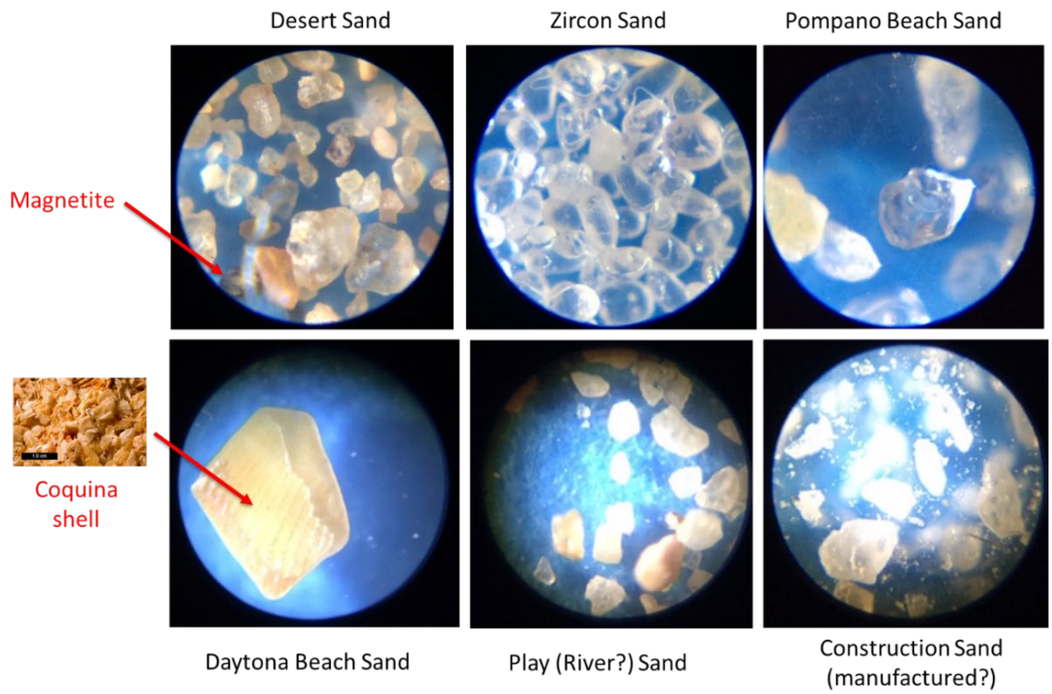

Fig. 10 Images of sand specimens taken with a cellphone camera through the mini microscope in Fig. 8.

5.4 Activity #4: "Stick Test"

In this activity, students observe how the irregular shape of sand particles allows them to hang onto each other. This characteristic is critical to the success of concrete used to build buildings, dams, and roads (among many other things). To prepare our sample, we placed play sand in a 25-mL centrifuge tube, as shown in Fig. 11. In place of the centrifuge tube, an old water bottle could be used instead. The stick we used was a chopstick that we had marked at 1/2-inch intervals using a felt-tipped pen.

Fig. 11 Play sand (assumed to be river sand) loosely packed (left) and compacted (right). Distance into the sand to which a stick may be inserted is limited by inter-particulate interactions.

For our first test, we placed the cap on the tube and then shook the sand before gently turning it upright and inserting the stick into the sand as far as we could without forcing it. We measured the distance at the 6-unit mark. We then removed the stick and gently tapped the tube against a tabletop to allow the particles to tightly pack against each other. We then tried again to insert the stick. This time, we were only able to insert to stick to the 3-unit mark. The explanation for this observation is that after tapping the tube, grains were allowed to push up against each other in such a way that it became difficult for them to move any further. The same thing happens with sand that is part of concrete, giving it strength. If the sand particles were too smooth and too small, they would be easy to push apart by the stick test and be a poor choice for use in making cement.

A variation of the stick test can be described as the "Sand Glue" test (Champak World n.d.). In this test, a stick is inserted into sand in a tube or plastic bottle before tapping to compact the sand. After doing so, the stick becomes so difficult to remove from the sand such that the whole tube or bottle of sand can be lifted by holding just the stick.

A third variation is described by Spangler (2019). In this activity, one end of a cardboard tube (e.g., from a roll of toilet paper) is covered on one end by a piece of tissue paper and held in place by a rubber band. Using a stick (e.g., a chopstick). It is easy to poke a hole in the tissue paper. If the tissue is replaced with a new piece and the cardboard tube filled with sand, it now becomes impossible to poke a hole in the tissue paper because the stick cannot penetrate the compacted sand.

5.5 Activity #5: Sieving Sand

In this activity, students use inexpensive sieves (strainers) purchased from the "dollar store" (usually $1–$2 each) to separate sand into different particle sizes. For younger students, visual inspection of the separate fractions is sufficient. For older students, measurement of the mass of each fraction can be made using an inexpensive battery-operated mini digital balance so that mass percent for each fraction may be calculated. Several mini balances are available online for $10–$15 each. We have several types of these balances and have found them to be very robust and suitable for classroom use.

Here are steps to follow for this activity:

1) Students are to be given two small plastic containers (they can be old food containers or new containers from the dollar store). One container is empty and the other contains about 50 g of sand.
    a) For students who will determine the mass of each fraction, they should first tare (i.e., zero-out the mass of) the empty container, as in Fig. 12.
    b) Next, the entire sample should be poured into the tared container. The mass of the entire sample should then be recorded.
2) Students are also given two sieves, one with relatively large openings and one with relatively small openings. The sieve with the larger openings should be placed directly on top of the sieve with the smaller openings (as in Fig. 13).
3) The entire sand sample is then poured into to top sieve, and the empty (un-tared) container is put underneath the two sieves (to catch small particles).
4) The upper sieve is then gently tapped or stirred so that smaller particles flow into the lower sieve. (Some very small particles may also fall through the lower sieve into the container.)
5) After all of the smaller particles have passed from the upper, large-hole sieve, that sieve can be put aside.
6) The process is now repeated for the contents of the lower, small-hole sieve. The contents should be gently tapped or stirred until all of the small particles have passed from it into the container below it.

7) After all of the smaller particles have passed from the lower, small-hole sieve into the container, that sieve can be put aside.

8) At this point, all students can make visual observations of the three fractions of sand.

   a) Older students can measure and record the mass of each fraction and calculate the mass fraction of each: (mass of fraction/total sample mass) × 100%. The total of all three fractions should be 100%.

Fig. 12 Supplies used when sieving sand (left). Taring the empty plastic container (right).

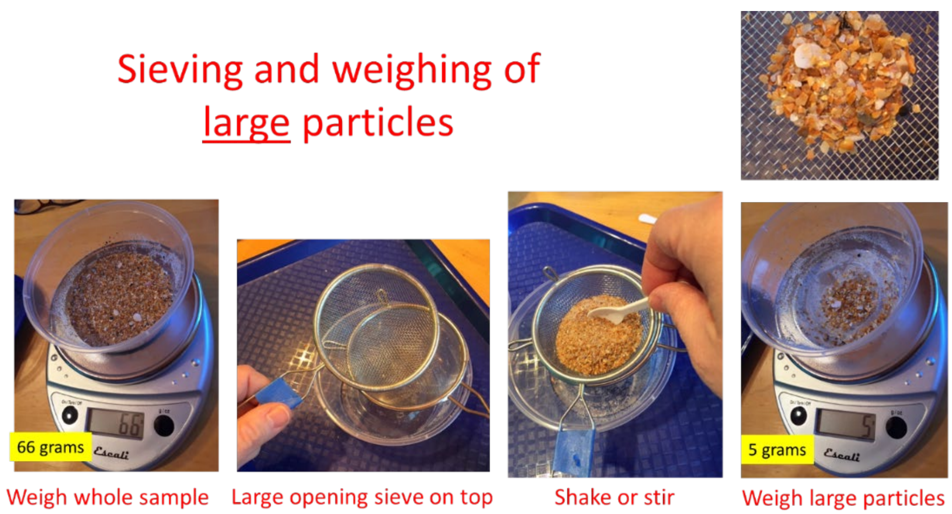

Fig. 13 Photos of first steps in the sieving activity. For this analysis, Daytona Beach sand was used.

General observations for all sand samples include that large particles of minerals and organic debris (leaves, sticks, plastics) will be observed in the large-hole sieve, medium-sized particles will be in the small-hole sieve, and the smallest particles will be in the container. In our analysis, we found that large, medium, and small particles made up 8, 25, and 67 wt% of the overall sample, respectively (Fig. 14).

If available, students can use magnifying glasses (available at most dollar stores) to examine the fractions.

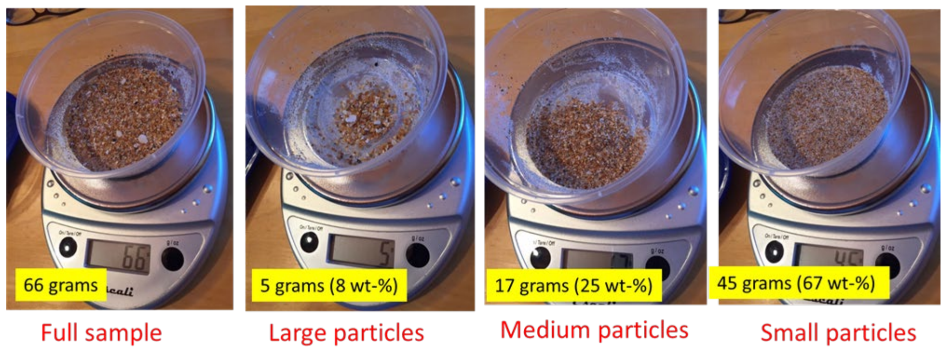

Fig. 14 Mass fractions for large, medium, and small particles

5.6 Activity #6: Vinegar Test

For this test, we used spot plates because we had them on hand. To avoid having to label the spot plate directly, we made a template to place underneath it (Fig. 15).

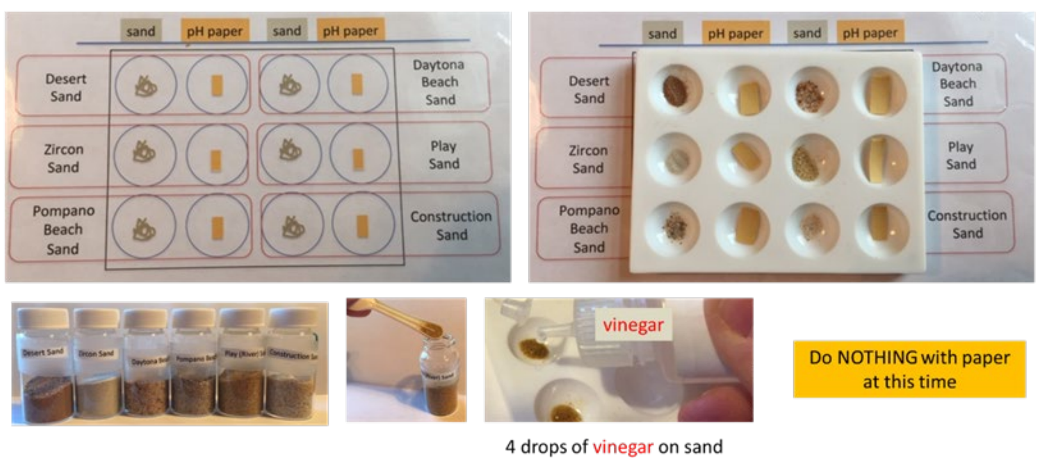

Fig. 15 Setup of the spot plates for the vinegar and pH tests

A small sample of each sand was added to a well in the spot plate, four drops of vinegar were then added. When carbonates are present in the sand (this often happens with ocean sand), bubbling will observed as the carbonates react with the acetic acid in the vinegar to produce carbon dioxide (CO_2) gas (Fig. 16). While most students will not understand the chemistry involved, the reaction that takes place is provide for instructors who are interested in this information:

$$\mathbf{NaHCO_3 + CH_3COOH \rightarrow Na^{+}(aq) + CH_3COO^{-}(aq) + H_2O + CO_2(g)}$$

sodium bicarbonate + acetic acid **sodium acetate dissolved in water + carbon dioxide**

(baking soda) + (vinegar) = (fizz)

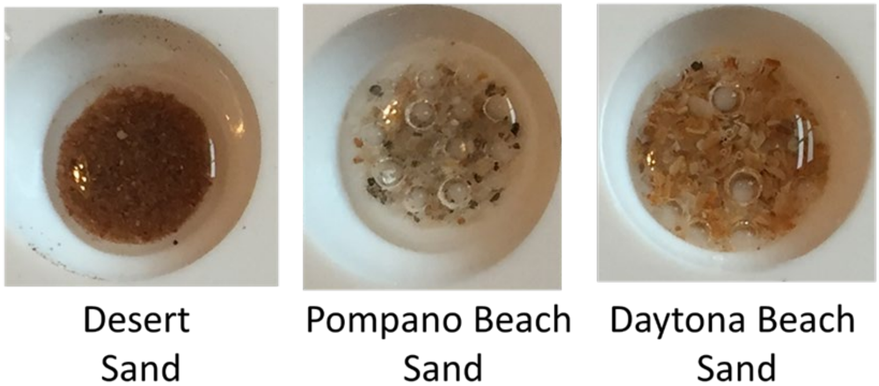

Fig. 16 Evidence of bubbling from CO_2 generation observed for the desert and beach samples

For a lower-budget approach to this activity, foam dinner plates work very well in place of spot plates. The foam plates can be labeled with a ballpoint pen to indicate sample names and they are easily rinsed for reuse (sand is removed, but the ink remains). Figure 17 shows how we successfully used foam plates for our forensics program (Pesce-Rodriguez and Rodriguez 2019). Dropper bottles can be purchased online at a reasonable cost (fifty 10-mL bottles for about $10). An even cheaper alternative to dropper bottles is a plastic straw, as shown in Fig. 18, but we find that controlling the release of liquids with plastic straws can be difficult for younger students.

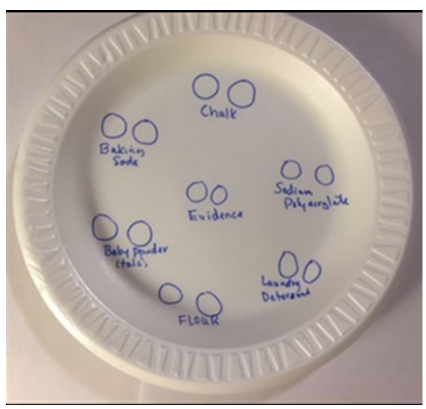

Fig. 17 Use of a foam plate labeled with a ballpoint pen from our forensics program (Pesce-Rodriguez and Rodriguez 2019)

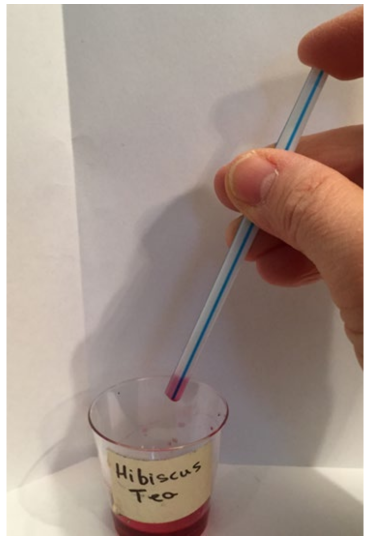

Fig. 18 Use of a plastic straw in place of a dropper bottle to dispense liquids dropwise (Pesce-Rodriguez and Rodriguez 2019)

5.7 Activity #7: pH Test

Testing the pH of sand samples can be performed with universal indicator paper, as shown in Figs. 15, 19, and 20, but can also be done using a cabbage juice or hibiscus tea indicator. We discuss that option shortly. Universal pH indicator paper strips can be purchased inexpensively online. A pack of 80 strips costs about $3. For a team of four students, two strips (each cut into three pieces) is sufficient. So, for a class of 24 students, only 12 strips would be needed. The advantage of paper strips over a liquid indicator is twofold: the strips are logistically easier to manage (no fluid to prepare or dispense) and the color change for the sand samples was found to be much faster for the paper indicator than for the liquid indicator. To perform the test, first moisten the paper with *distilled water,* as shown in Fig. 19. Distilled water can be purchased from most supermarkets at a very low cost (<$1 for a gallon) and is well worth the price. We advise against using tap water or well water because they can often be alkaline enough to make it difficult to observe the change in pH by sand samples or other materials. As was the case for vinegar, low-cost dropper bottles or plastic straws can be used to dispense the water. Next, students sprinkle a small amount of sand onto the paper. As described previously, tasting spoons can be used for this purpose. The end of a dry plastic or paper straw can also be used.

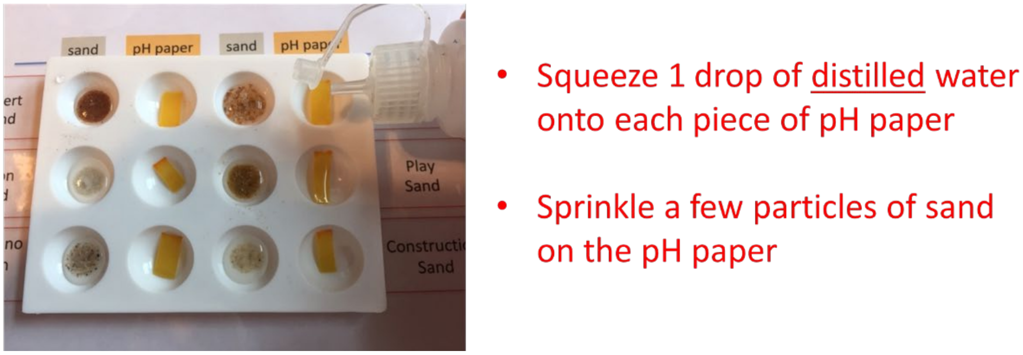

Fig. 19 Preparation of samples for pH testing

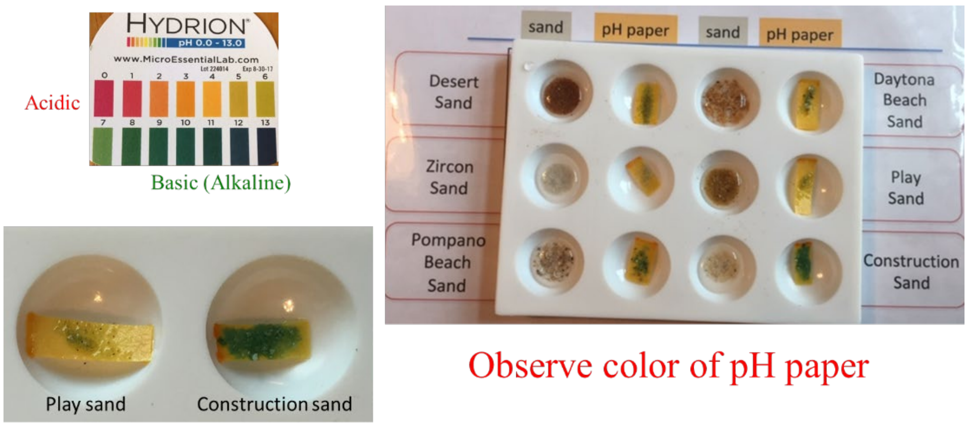

Fig. 20 Photos of sand specimens on universal pH indicator paper. The pH color scale is also shown. Acids turn the indicator paper pink/red; bases or alkaline materials turn the paper green/blue. Sand specimens were observed to be either nearly neutral or alkaline.

Students will start to observe a color change soon after placing the sand particles on the paper. We have never observed acidic sand (pH below 7; indicator paper turns pink or red), but have often observed alkaline sand (pH above 7; indicator paper turns green). Sand tends to be alkaline because of the presence of very small particles of calcium carbonate (from shells) and feldspars. Feldspars are common aluminum silicate minerals containing alkaline and alkaline earth elements (sodium, potassium, and calcium). Fine particles of feldspar are the main ingredient in Bon Ami, a household cleaning product. If students can test the pH of Bon Ami, they will find it to be alkaline, like most of the sands we tested (see Fig. 20).

We found the difference in pH between the play sand and construction sand to be striking. The pH of the play sand (assumed to be river sand) was nearly neutral, while that of the construction sand was fairly alkaline, presumably because of the presence of fine feldspar particles in the latter.

If an instructor prefers to use a liquid indicator in place of indicator paper, cabbage juice works well, but more slowly than the paper indicator. Compared with the paper pH indicator, cabbage juice has the advantage of being readily available (most supermarkets sell red cabbage), making it easy for both instructors and students to purchase. When possible, we like to use readily available materials so students or families can try activities at home. Also, while commercial liquid laboratory-grade universal pH indicators are available, they are relatively expensive and may expose students to potential toxins.

For preparation of cabbage juice from fresh red cabbage, first boil a small amount of water (about 1/2 cup or 100 mL) in a small pot (water can also be microwaved), then turn off the heat and add 1 cabbage leaf (chopped). Allow the mixture to sit for 15–20 min, then collect the liquid only. Store the liquid in the refrigerator if not being used right away.

Another alternative indicator for pH observation is hibiscus tea; one common commercially available product is “Red Zinger” tea by Celestial Seasonings. The tea can be extracted into water or isopropanol (70% rubbing alcohol) to make a concentrated solution. We have found that the extraction is faster in isopropanol than in water.

The range of color changes observed for a number of typical household materials with both cabbage juice and hibiscus tea are given in Fig. 21. While both extracts change color in response to pH, we find the colors of the cabbage juice to be more vibrant and more appealing to students than those of the hibiscus tea.

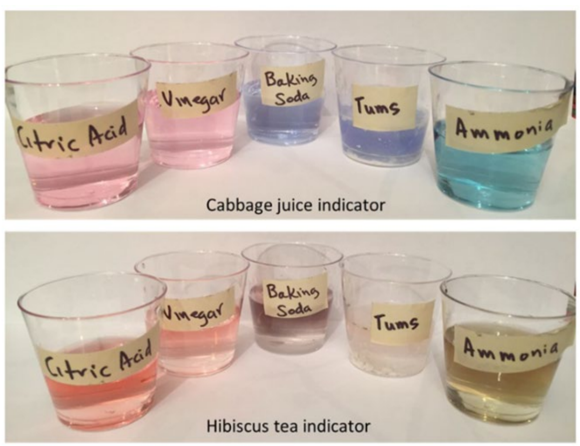

Fig. 21 Photos of various materials with added cabbage juice extract (top) and hibiscus tea (bottom)

Dried cabbage juice powder (Fig. 22) is commercially available. We purchased the product from Educational Innovations (https://www.teachersource.com/product/red-cabbage-extract/chemistry). The powder is handy to use, since it can be prepared immediately before using. Remember to use distilled water when preparing. Figure 23 shows the difference between cabbage juice prepared in distilled and tap water. According to the color chart in Fig. 22, cabbage juice is acidic (pink) in distilled water, but neutral (purple/blue) in tap water indicating that the tap water must be slightly alkaline (i.e., the tap water raises the pH of the cabbage juice solution).

Fig. 22 Commercially available dried cabbage juice extract, reconstituted with water (right). Color/pH chart shown at bottom.

Fig. 23 Powder cabbage juice indicator made in distilled water (left) and tap water (right)

The science behind the use of hibiscus tea or red cabbage juice as pH indicators is based on the chemistry of anthocyanins, which are natural compounds that are responsible for the color in many flowers, fruits, vegetables, and autumn foliage. More information can be found on Wikipedia (2019b).

If using a cabbage juice indicator for testing pH of sand specimens, we recommend that the samples be prepared and then allowed to sit for 20–30 min. After such time, the color change will be very obvious (Fig. 24).

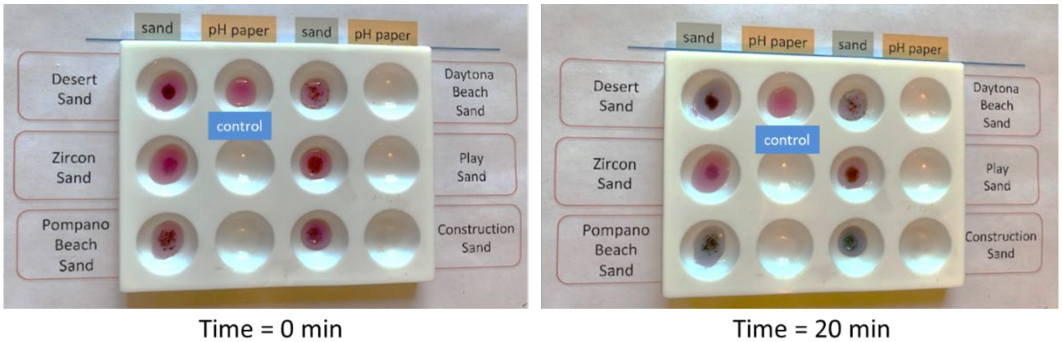

Fig. 24 Testing the pH of sand specimens with the cabbage juice indicator. At time = 0 min, the indicator for all samples and the control solution is pink. At time = 20 min, the indicator color for several specimens turned blue, indicating that they are alkaline.

Testing the pH of "mystery powders" during a forensic analysis is described in Pesce-Rodriguez and Rodriguez (2019) and for the pH of paper in Pesce-Rodriguez and Rodriguez (2020).

5.8 Activity #8: Hydrogen Bonding (Models)

This activity aims to help students understand a very interesting characteristic of sand, that is, when it is dry, it behaves like a liquid (it flows easily), but when it is wet, it behaves more like a solid (we can make sand castles from it). This characteristic is related to the chemical structure of the materials that make up sand. As we have already discussed, sand can be made of many different materials, but most sand contains SO_2 so we focus on that.

A very crude model of how Si and O in is arranged in a sand particle is shown in Fig. 25. Inside the particle, each Si atom is bound to four O atoms, but on the surface of the particle where the extended structure ends, bonds are terminated with hydrogen (H) atoms. We call the ending "-OH", a "hydroxyl group".

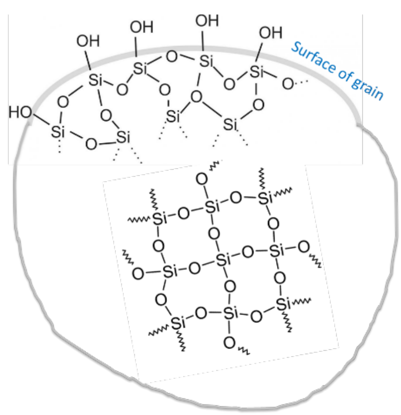

Fig. 25 Crude representation of how Si and O are arranged in a sand particle. To understand how sand interacts with water, we are most interested in the surface -OH groups.

If we now think about the structure of water (H_2O; Fig. 26, left), we see that it too has hydroxyl groups. Considering the nature of O and H in a very simplistic way, we can think of O as a "greedy" element that wants to draw an electron away from the H atoms, which are very "willing to share". The result of this "greediness" and "sharing" is an O atom has a slightly negative charge (δ^-) and the two H atoms have a slightly positive charge (δ^+). If we imagine these "-" and "+" parts of the water molecule as poles of a magnet, we can see how "+" will attract "-" and vice versa. This phenomenon is called "hydrogen bonding" and is what is responsible for the many facinating properties of water. This same kind of interaction can take place between water and -OH groups on the surface of sand particles, resulting in the tendency of water to stick to sand and for water to act as "glue" to help sand stick to itself.

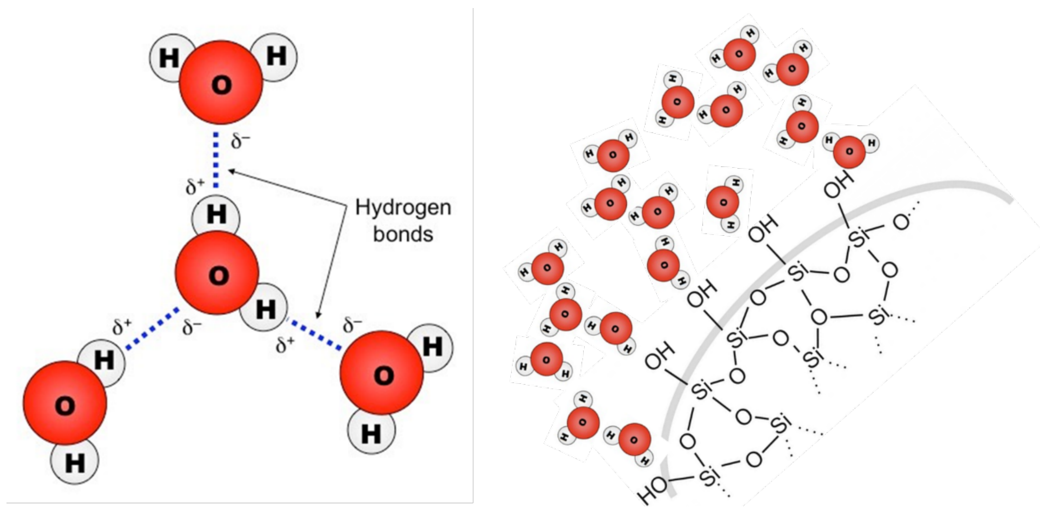

Fig. 26 Hydrogen bonding among water molecules (left) and among water and the surface of a SiO_2 sand particle

To make an inexpensive model of water, students could use toothpicks and marshmallows or gumdrops. A more expensive but very useful and interesting set of a water model can be purchased from 3-D Molecular Designs (https://www.3dmoleculardesigns.com/Education-Products/Water-Kit.htm) (Fig. 27). While we hesitate to mention this product in a report focused on "STEM on a budget", we have found them to be particularly useful in many of our different programs and have found them to be well worth the investment.

Fig. 27 Photo of magnetic water molecules showing hydrogen bonding that attracts water molecules to each other

5.9 Activity #9: "Magic Sand"

While technically not related to the chemistry of natural sand, so-called "magic sand" is useful for demonstrating the difference between natural sand, which is hydrophilic ("water loving") because of hydrogen bonding, and "magic sand", which is hydrophobic ("water hating") because of the absence of hydrogen bonding. As described in Activity #8, hydrogen bonding allows water to readily interact with the surface of a silica sand particle. The same is not true for "magic sand", which is coated with a polymer that contains no -OH groups, so hydrogen bonding is not possble. The result is a sand that cannot be wet. Shown in Fig. 28 are photos of magic and natural sand in water. We used plastic centrifuge tubes, but waterbottles would work equally well. For a classroom activity, we recommend one tube (or bottle) containing water and natural sand and one with magic sand for a team of four students. The amount of magic sand needed per class is actually very little. The product can be purchased online for about $12 for 12 oz.

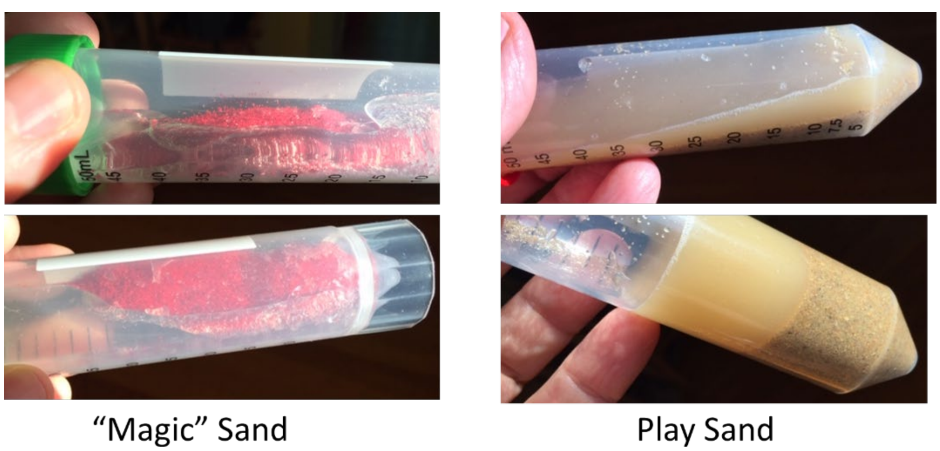

Fig. 28 Photos of magic sand (left) and natural sand (right) in water

Students might also be interesting in “kinetic sand”, which is natural sand coated in a silicone polymer. The polymer helps the sand stick together so that the sand can be formed into shapes. Silicone polymers (structure given in Fig. 29) are among the many materials that are derived from sand. Silicones have many uses, including haircare products, non-stick bakeware and utensils (Fig. 30), silicone grease, and waterproofing for fabrics.

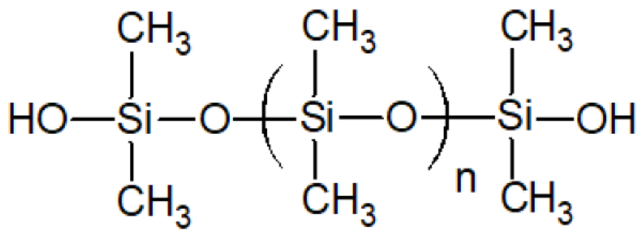

Fig. 29 Chemical structure of a silicone polymer

Fig. 30 Photo of a silicon steamer/strainer and spatula. The products are good for cooking because they are non-stick and thermally stable.

5.10 Activity #10: Quicksand

Our last activity is related to quicksand, which is basically a thick “soup” of sand and water that forms when solid, sandy ground is saturated with water. The sand becomes “quick” when the water surrounding it reduces the friction between the particles to the point where it liquefies. While movies and novels often show quicksand in “exotic” places, it actually occurs in many very common places like riverbanks, shorelines, and marshes. If a person gets stuck in quicksand, the best thing to do is lie on one’s back and float, then try to roll to solid land or wait for help. Struggling in the quicksand results in getting more stuck in it. As a person becomes stuck, the sand exerts pressure around the body making it difficult for blood to flow to extremities (usually the feet) or to breathe (if the chest is submerged).

Quicksand behaves as it does because it is a non-Newtonian fluid, meaning that its viscosity changes with applied stress. This phenomenon can be observed by preparing “cornstarch quicksand”. There are many online recipes for the preparation of this material (e.g., https://www.kidzone.ws/science/cornstarch.htm). It is basically a very thick mixture of cornstarch and water. When at rest or when stirred slowly, the mixture flows like thick glue, but when stirred quickly or if smacked, it becomes a solid.

6. Conclusion

The 10 activities discussed herein are all related by the common sand theme, but also can be used to demonstrate principles including acid-base chemistry (vinegar test), pH, magnetism, molecular interactions (hydrogen bonding), and particle size analysis. Instructors can choose to perform all the activities or only those for which materials are readily available. Sand samples can come from students' neighborhoods or may be purchased from hardware or pet stores. Sand is a very accessible subject for investigation and we hope that by taking a closer look at this common yet fascinating material that students will not only learn the meaning of the word “arenophile”, but come to be one themselves!

7. References

Beiser V. The world in a grain: the story of sand and how it transformed civilization. New York (NY): Riverhead Books; 2018 Aug 7.

Beiser V. Why the world is running out of sand. BBC Future. London (UK): BBC; 2019 Nov 17 [accessed 2020 Apr 4]. https://www.bbc.com/future/article/20191108-why-the-world-is-running-out-of-sand.

Champak World. Easy to make: Sand glue!! Kids Science Experiments. Champak World; n.d. [accessed 2020 Apr 4]. https://www.youtube.com/watch?v=dCWbE3hjNx0.

Causey D. How to set up a lab notebook. n.d. [accessed 2020 Apr 4]. https://www.youtube.com/watch?v=Gp4ue2-5264.

Dashore A. Test for silt content in sand. The Constructor; 2020 [accessed 2020 Apr 4]. https://theconstructor.org/building/building-material/test-silt-content-sand/34520/.

Greenberg G, Kiely C, Clover K. The secrets of sand: a journey into the amazing microscopic world of sand. London (UK): Voyageur Press; 2015 Sep 21.

MicroBus. Sand analysis. MicroBus; 2020 [accessed 2020 Apr 4]. https://microscope-microscope.org/microscope-applications/microscopic-sand/.

Mining And Construction. How about artificial sand compared with natural sand. Mining And Construction; n.d. [accessed 2020 Apr 4]. https://www.beidoou.com/materials/how-about-artificial-sand-compared-with-natural-sand.html.

[NPS]. Erosion and cliff formation. Washington (DC): National Parks Service; 2015 Feb 24 [accessed 2020 Apr 4]. https://www.nps.gov/chcu/learn/nature/erosion-and-cliff-formation.htm.

Pesce-Rodriguez RA and Rodriguez A. Science, technology, engineering, and mathematics (STEM) activities on a budget: part I—forensics. Aberdeen Proving Ground (MD): CCDC Army Research Laboratory; 2019 Apr. Report No.: ARL-TR-8685.

Pesce-Rodriguez RA, Rodriguez A. Science, technology, engineering, and mathematics (STEM) activities on a budget: Part III—paper. Aberdeen Proving Ground (MD): CCDC Army Research Laboratory (US); 2020 May. Report No.: ARL-TR-8968.

The Screed Scientist. The pros and cons of manufactured sand. Slough (UK): The Screed Scientist; 2014 May 12 [accessed 2020 Apr 4]. https://www.screedscientist.com/the-pros-and-cons-of-manufactured-sand/.

Sandatlas. Chemical elements in the crust. Sandatlas; n.d. [accessed 2020 Apr 4]. https://www.sandatlas.org/composition-of-the-earths-crust/.

Spangler S. Strong sand. Denver (CO): Steve Spangler Science; 2019 [accessed 2020 Apr 4]. https://www.stevespanglerscience.com/lab/experiments/strong-sand/.

Welland M. Sand: the never-ending story. Berkeley (CA): University of California Press; 2009.

Wikipedia. Abundance of the chemical elements. San Francisco (CA): Wikimedia Foundation; 2020a Apr [accessed 2020 Apr 4]. https://en.wikipedia.org/wiki/Abundance_of_the_chemical_elements.

Wikipedia. Anthocyanin. 2019b [accessed 2919 Feb 16]. https://en.wikipedia.org/wiki/Anthocyanin.

Wikipedia. *Donax variabilis*. San Francisco (CA): Wikimedia Foundation; 2020b Apr [accessed 2020 Apr 4]. https://en.wikipedia.org/wiki/Donax_variabilis.

List of Symbols, Abbreviations, and Acronyms

CO_2	carbon dioxide
Fe	iron
Fe_2O_3	hematite
Fe_3O_4	magnetite
H	hydrogen
H_2O	water
LED	light-emitting diode
O	oxygen
-OH	hydroxyl group
Si	silicon
SiO_2	silicon dioxide, silica
STEM	science, technology, engineering, and mathematics

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
1 (PDF)	CCDC ARL FCDD RLD CL TECH LIB
1 (PDF)	CCDC ARL FCDD RLW LB R PESCE-RODRIGUEZ