CHAPTER 15
Physical Properties in Evidence:
Mineralogical, Soil, Glass, and Paint Analysis
## IV. Physical Properties in Evidence

### Chapter 15: Physical Properties: Mineralogical, Soil, Glass, and Paint Analysis

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Chapter 15.1: Physical Properties in Evidence

Learning Goals and Objectives

Physical properties can be used to define key features of evidence. In this chapter, you will need to understand the following concepts:

- What is meant by chemical and physical properties and change;
- What is meant by the intrinsic and extrinsic properties of substances;
- What are density and viscosity and how can they be measured;
- What are refraction, refractive index, and birefringence and how are they determined;
- How are colors formed and perceived in additive and subtractive methods.

Introduction

Thus far, we have focused upon properties of evidence that relate specifically to their biological and chemical characteristics, especially upon their unique behaviors and classifications. The characterization of the physical properties of evidence, such as glass and plastic fragments, can often be critical to a successful forensic investigation. In this chapter, however, we will explore some of the key physical properties of evidence and examine how these types of properties provide important information about the composition and classification of evidence.

Chemical and Physical Properties: In describing matter, we define two general types of properties: chemical and physical properties. Each substance has its own unique set of these properties that dictates its behavior and allows us to distinguish it from all other substances. Chemical properties are those that can be measured only by attempting to change the chemical identity of the material itself through some sort of chemical transformation: a chemical reaction. Physical properties, in contrast, are those that can be measured without changing a material’s chemical identity. Some selected examples of these two types of properties are given in Table 15.1.1.

Chemical properties are described by changes that are observed only by looking at potential chemical reactions of a substance and are, therefore, always defined with respect to a particular chemical process. For example, the combustion, reactivity, or stability properties of a compound are measured by examining their potential reactions with oxygen (combustion) or other chemical reagents (reactivity or stability). In fact, chemical properties are always defined relative to a specific chemical process.

Table 15.1.1. Selected Chemical and Physical Properties.

<table>
<thead>
<tr>
<th>Chemical Property</th>
<th>Physical Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat of combustion</td>
<td>Color</td>
</tr>
<tr>
<td>Toxicity</td>
<td>Density</td>
</tr>
<tr>
<td>Flammability</td>
<td>Melting Point</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Boiling Point</td>
</tr>
<tr>
<td>Reactivity</td>
<td>Solubility</td>
</tr>
<tr>
<td>Stability</td>
<td>State (solid, liquid, gas)</td>
</tr>
<tr>
<td></td>
<td>Hardness</td>
</tr>
</tbody>
</table>

Table 15.1.2. Intrinsic and Extrinsic Properties.

<table>
<thead>
<tr>
<th>Intrinsic Property</th>
<th>Extrinsic Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Mass (weight)</td>
</tr>
<tr>
<td>Density</td>
<td>Volume</td>
</tr>
<tr>
<td>Melting/Boiling Point</td>
<td>Dimensions (length)</td>
</tr>
<tr>
<td>Conductivity</td>
<td>Number (quantity)</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
</tr>
</tbody>
</table>
reaction that includes the reactants and reaction conditions. For example, zinc metal is stable to water (no reaction occurs) while unstable toward hydrochloric acid (forming ZnCl₂ and H₂ when the two come into contact at room temperature). In contrast, lithium metal is unstable towards water, transforming the lithium metal into LiOH and H₂. Specifying reaction conditions is necessary to defining chemical properties – a reaction may occur extremely slowly or not at all at 0° while it may proceed very quickly at 100°C. Chemical reaction conditions that may need to be defined when describing chemical properties often include temperature, concentration, pressure, light irradiation, and the presence or absence of a catalyst.

The measurement of physical properties is not defined relative to any chemical process but is defined as a property related to the state of the matter itself. For example, measurement of the density, melting point and state (solid, liquid or gas) of a substance does not result in changing the substance into some other chemical substance. These properties are dependent upon the unique chemical structures and features of the substance, such as how the atoms are arranged in space to form the solid and how much energy is needed to separate the individual molecules or atoms. When a substance undergoes a physical change, it alters its appearance but not its chemical composition. For example, when ice melts - a physical change - it visibly changes from a hard solid to a mobile liquid but it always remains H₂O. Among the physical properties are density, melting/boiling points, and color.

**Intrinsic and Extrinsic Properties:**

Some physical properties of a substance depend upon how much of the material is present while others do not (Table 15.1.2). Intrinsic properties are those that are the same no matter how much of the material is present in the sample. These properties are particularly useful in the forensic analysis of substances since a small sample can be used to determine the properties of the entire item and help lead to its identification. Intrinsic properties include melting point, boiling point, density, color, temperature, and luster (shininess) – the measured properties are the same regardless of the sample size used. Extrinsic properties, however, are those that change if the amount of material in the sample changes. Extrinsic properties include mass, volume and length. Both intrinsic and extrinsic properties are important in forensic evidence analysis – the

**Table 15.1.3. Density of Selected Compounds (g/cm³).**

<table>
<thead>
<tr>
<th>Substance</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.0013</td>
</tr>
<tr>
<td>Mica</td>
<td>0.54</td>
</tr>
<tr>
<td>Wood</td>
<td>0.85</td>
</tr>
<tr>
<td>Water</td>
<td>1.00</td>
</tr>
<tr>
<td>Ice</td>
<td>0.93</td>
</tr>
<tr>
<td>Flint Glass</td>
<td>1.39*</td>
</tr>
<tr>
<td>Window Glass</td>
<td>1.94*</td>
</tr>
<tr>
<td>Windshield Glass</td>
<td>2.57*</td>
</tr>
<tr>
<td>Quartz</td>
<td>2.64</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.70</td>
</tr>
<tr>
<td>Lead</td>
<td>11.3</td>
</tr>
<tr>
<td>Gold</td>
<td>19.3</td>
</tr>
</tbody>
</table>

* Values vary considerably by type and composition of the glass.
intrinsic properties of an item can help identify its chemical composition while the extrinsic measurements can tell if the item fits a particular scenario. For example, the intrinsic properties of a bullet cartridge can tell what alloy was used in its manufacture while the extrinsic properties can identify its caliber, type, and manufacturer.

Some physical properties of matter are particularly useful in identifying an unknown material and have found routine uses in forensic settings. These include density, refractive index, birefringence, and color.

**Density**: Density is very useful in the identification of certain types of forensic materials, especially soil, geological, and glass samples. It is simply defined as the amount of mass of a material contained in a particular unit of volume, or \( d = \frac{m}{V} \). Density is most commonly expressed in terms of grams per cubic centimeter, or g/cm\(^3\) (note: 1 cm\(^3\) = 1 mL or milliliter). The densities of several common substances are given in Table 15.1.3 and vary greatly. The density of water is 1.00 g/cm\(^3\) at 4°C since the gram was originally defined as the weight of 1 cm\(^3\) of water.

Several ways have been devised to experimentally measure the density of a substance, even for very small samples such as glass shards and minute soil samples. For liquid samples, the direct determination of density simply requires determining the mass of a known volume of the liquid. For example, the mass of one cm\(^3\) (mL) of a liquid can be measured directly to give the density. Density measurements for solids are more difficult, however, since determining the volume of a solid accurately can present significant challenges.

For regularly shaped solids, the volume can be measured by determining the dimensions of the object and calculating the volume. In most circumstances, however, this is not possible because of the irregular shapes found for solids, especially for small forensic samples. Three common methods have been employed to determine solid volumes in density determination - displacement, floatation, and buoyancy (or up-thrust) measurements:

- **Volume by Displacement**: This method involves the direct measurement of the displacement of a liquid, such as water, by a sample (the Archimedes discovery described in Chapter 4). In this process, the amount of water displaced by the liquid gives the volume of the solid.
A completely submerged solid is measured and is equal to the volume of the unknown solid (Figure 15.1.1). The major drawbacks of this method are the potential inaccuracies in measuring the volume change upon adding the solid to the water and occasional problems with the solubility of the solid in the liquid. Often forensic samples are very small, making it exceptionally difficult to determine accurately the very small volume changes when the liquid is displaced. The advantage of this method for larger samples, however, is that it is experimentally very simple.

- **Flotation**: Floatation can be used to approximate the density of a sample. A solid sample will sink through a liquid of lower density than its own, float on top of liquids with higher densities, and be suspended in a liquid that has the same density. In this method, a gradient column is employed that contains several different liquids of varying density. The column, such as shown in Figure 15.1.2, is prepared by carefully layering the different liquids on top of one another with the most dense on the bottom to the least dense on the top. The solid to be determined then is dropped onto the top of the column and it will sink until it reaches a liquid layer that has a higher density than it own (Figure 15.1.3) where it will float on the top of this denser liquid. The density of the solid can then be approximated as less than the density of the liquid it floats on and greater than the density of the next higher layer that it sank through. For example, if ebony wood is found to float on a chloroform layer and sink in water (d = 1.00 g/cm³), the relationship of the densities of the three components must then be water<ebony<chloroform or the density of ebony is 1.00 g/cm³<1.48 g/cm³. The closer together the density of the gradient layers, the more accurately the density of the solid sample can be approximated.

Density gradient techniques are the most common methods employed in forensic determinations and they often employ an instrument such as that shown in Figure 15.1.4. An alternative method to a standard density gradient column is to change the density of a single dense liquid in a column by heating it and noting the temperature where the sample just sinks. Using a known curve that relates the density of the liquid to temperature, the density of the solid sample can be determined.
of the liquid when the sample sank can be determined and, therefore, the density of the sample closely approximated.

- **Buoyancy:** When a solid object is placed in a liquid, such as water, two opposite forces act on the solid - the first is gravitational force pulling the sample down through the liquid, as illustrated in Figure 15.1.5. The second is the density of the liquid that acts in an opposite direction to buoy up the sample. Archimedes’ principle says that the buoyant force (up-thrust force) experienced by a submerged object is equal to the weight of the liquid displaced by the object. In this method, a solid sample suspended by a thin line is submerged in a known weight of water. The weight of the water (and flask) is measured both with and without the submerged solid. Since the weight increase of the water when the object is submerged is equal to the weight of the water displaced, we can calculate the volume of the water displaced as equal to the volume of the submerged object (remember, we know two of the three variable in the density equation \( d = \frac{m}{V} \) – we know the mass of the displaced water and the density of the water (1.00 g/cm³) so we can calculate the volume of water displaced). In essence, the water is holding up some of the weight of the object – exactly the weight of the water the object displaces. Therefore, the difference in weight between the two measurements is equal to the volume of the water displaced by the glass sample (since the density of water is 1.00 g/cm³).

For example, if a solid with a 2 mL volume that weights 5 grams is suspended in the water, the flask and water with the sample will weigh 2 g more than just the flask and water (the weight of the water displaced by the 2 mL volume of sample). Thus, the weight difference is equal to the volume of the sample since the density of water is about 1 g/cm³. Another way to view this is that the 5 g mass of the sample is partially supported and held up by the water (2 grams worth) and the remaining mass (3 g) of the sample is the load on the line that suspends the solid.

- **Viscosity:** Viscosity, often referred to as the “thickness” of a liquid, is the resistance of a liquid to flow. For example, water is “thin” and flows readily at room temperature while syrup is “thick” and flows slowly, as illustrated by several different fluids in Figure 15.1.6. The less viscous the fluid, the easier it flows. A viscosity measurement can be a useful characterization in certain types of forensic evidence, especially in paint, motor oil, lubricants, industrial fluids, and related substances (Figure 15.1.7).
The viscosity of a liquid sample can be measured in a variety of ways but usually is determined using an instrument called a viscometer. Most viscometers measure the time it takes for a fixed amount of liquid sample to pass either through a hole or through a tube. Of course, the viscosity of the liquid sample is greatly affected by its temperature – things generally become less viscous when they are heated (compare cold versus hot syrup).

**Refractive Index:** Light travels at about 3.0 x 10^8 m/sec. in a vacuum and slows and bends when it enters a transparent substance. The amount of slowing and, therefore, the observed bending of the light beam depends upon the properties of the substance through which the light beam moves. You’ve seen this effect if you’ve ever noticed a straw standing in a glass of water that appears to the observer viewing from an angle to be bent at the point where it enters the water (Figure 15.1.8). This effect is caused by the change in the speed of the light as it passes from one transparent substance (the air) into another transparent substance (the water). This effect is referred to as the **refraction** of light by a substance. Every transparent substance, such as glass or plastic, for example, exhibits a characteristic amount of refraction of light called its **index of refraction** (or refractive index, RI) that is largely dictated by the substance’s density and chemical structure. The refractive index of a substance is defined as the velocity of light in a vacuum divided by the velocity of light in the substance. For example, the index of refraction for a diamond is calculated as follows;

\[
\text{Refractive Index (diamond)} = \frac{\text{Velocity of light in vacuum}}{\text{Velocity of light in diamond}}
\]

\[
\text{Refractive Index (diamond)} = \frac{3 \times 10^8 \text{ m/sec}}{1.2 \times 10^8 \text{ m/sec}}
\]

\[
\text{Refractive Index (diamond)} = 2.42
\]

Every transparent substance has its own characteristic refractive index and knowing the refractive index of a substance can help characterize it. For example, the RI can help to tell the difference between a small shard of broken glass as coming from a window, a headlight or a pair of eyeglasses. The refractive indices and densities for some commonly encountered transparent materials are shown in Table 15.1.4.

The amount of bending of the light beam that occurs upon entering the substance depends upon the refractive index of the two transparent substances the light is moving between (air to water; glass to water) and the angle between the light beam and the line perpendicular to the surface separating the two substances. This is illustrated in Figure 15.1.9. The refractive index can be easily calculated for a substance by...

*Figure 15.1.7.* (www.best.synthetic.com/techprops.shtml).

*Figure 15.1.8.* The effect of differing refractive indices of water in air on the optical “illusion” of a bent straw (from: *Nature* 455, 299 (2008).)
measuring the angles associated with the observed bending that occurs when a light beam moves from the air into a transparent substance, such as glass (assuming that light has about the same speed in a vacuum as in air). The angle between the incoming light beam and a line perpendicular to the surface as it crosses from one medium to another is called the angle of incidence (usually denoted as $\theta_{\text{air}}$ since the light is measured traveling from air into the transparent material). The angle between the light beam and the perpendicular as it enters a medium is called the angle of refraction ($\theta_{\text{substance}}$).

One method for directly determining the refractive index of a transparent substance involves the physical measurement of the bending of a light beam. A Dutch physicist named Willebrord Snell (1591-1626) long ago derived a relationship between the different angles of light ($\theta_{\text{air}}$ and $\theta_{\text{substance}}$) as it passes from one transparent medium to another. This is referred to as Snell's law which states (see Figure 15.1.9);

$$\text{RI}_{\text{(material leaving)}} \sin(\text{incident angle}) = \text{RI}_{\text{(material entering)}} \sin(\text{refractive angle})$$

$$\text{RI}_{\text{(air)}} \sin(\theta_{\text{air}}) = \text{RI}_{\text{(substance)}} \sin(\theta_{\text{substance}})$$

By directly measuring the amount of bending that a light beam undergoes upon travelling from the air into a sample, the RI of the sample can be directly determined. Since the refractive index of air is approximately 1.00, then Snell’s Law simplifies to:

$$\text{RI}_{\text{(substance)}} \approx \frac{\sin(\theta_{\text{air}})}{\sin(\theta_{\text{substance}})}$$

### Table 15.1.4. Some selected densities and Refractive Indices (RI) of transparent materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/mL)</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glasses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead Glass (Soft) [Corning]</td>
<td>3.05</td>
<td>1.560</td>
</tr>
<tr>
<td>Borosilicate Pyrex Glass [Corning]</td>
<td>2.23</td>
<td>1.474</td>
</tr>
<tr>
<td>Window Glass</td>
<td>2.47 – 2.56</td>
<td>1.51</td>
</tr>
<tr>
<td>Headlight Glass</td>
<td>2.47 – 2.63</td>
<td>1.47 – 1.49</td>
</tr>
<tr>
<td>Quartz</td>
<td>2.65</td>
<td>1.644</td>
</tr>
<tr>
<td>Plastics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Density Polyethylene (HDPE, #2)</td>
<td>0.952 – 0.965</td>
<td>1.54</td>
</tr>
<tr>
<td>Low Density Polyethylene (LDPE, #4)</td>
<td>0.917 – 0.940</td>
<td>1.50 – 1.54</td>
</tr>
<tr>
<td>Polypropylene (PP, #5)</td>
<td>0.900 – 0.910</td>
<td>1.49</td>
</tr>
<tr>
<td>Polystyrene (PS, in solid form, #6)</td>
<td>1.04 – 1.05</td>
<td>1.59 – 1.60</td>
</tr>
<tr>
<td>Polyvinyl Chloride (PVC, rigid, #3)</td>
<td>1.30 – 1.58</td>
<td>1.54</td>
</tr>
</tbody>
</table>

**Figure 15.1.10.** Garnet grains in oil (RI = 1.55) showing a Becke line round the perimeter of the crystals

(http://faculty.plattsburgh.edu/maya/rodentice/courses/mineral%20descriptions/bec ke%20lines%20and%20relief.pdf)

**Figure 15.1.9.** Angles involved in determining the refractive index (RI) or a solid (JTS).
The refractive index (RI) of a sample can be determined by placing it in various liquids with different refractive indices. When a transparent sample is placed in a liquid with a higher RI than it has, a halo is observed around the edges of the sample, referred to as the **Becke line** (Figure 15.1.10). As the RI of the liquid is changed, for example by heating the liquid, and its RI approaches the RI of the sample, the Becke line gradually fades until the glass sample can no longer be seen. At this point, the RI of the liquid matches the RI of the sample and the RI of the sample can be determined if the RI of the liquid is known. If, however, the sample subjected to this type of analysis was obtained from the crime scene, a sample found on the suspect can be placed in the same RI solution to determine if the two have identical RI’s. This type of comparison can most efficiently show that two pieces are dissimilar since the RI of the samples can be very quickly measured and compared. A plot of the refractive indices for samples of sheet glass in an FBI study shows the range of RI values (Figure 15.1.11).

**Birefringence**: Birefringence is essentially a double refraction phenomenon in certain crystalline materials where the refractive index is different depending upon which direction the light goes through the crystal. This phenomenon is common with some type of crystals and plastics. In other words, light travels at different speeds through a birefringent material depending upon the actual pathway it takes relative to the orientation of the atoms or molecules in the material. Two examples are shown in Figure 15.1.12. Birefringence can be used to help identify minerals, fibers, and different types of plastics and polymers as well as to detect stress in glass and other transparent materials.

**Color**: Color is the way that our eyes and brain perceive different wavelengths of light in the visible range. In our eyes, there are three different types of color receptors, called cone cells (S, M, and L type cone cells) - each responding to its own region of the visible spectrum. Our perception of color results from the differing stimulation of these

\[
\text{RI}_{\text{substance}} = \frac{\sin \theta_{\text{air}}}{\sin \theta_{\text{substance}}}
\]

Thus, by measuring the values for \( \theta_{\text{air}} \) and \( \theta_{\text{substance}} \), we can calculate the index of refraction for the sample directly.
different cone cells. Each color causes a different “mixture” of signals from the stimulation of the three types of cone cells to be sent to the brain. The brain combines the information from the three receptors to give us our perception of color.

Color can be used to help define an object and understand what wavelengths of light the object absorbs, reflects, or transmits. In forensic settings, a color determination can help identify a paint chip, a fiber, a specific ink, or any other colored object. There are, however, a number of ways that the visible color we perceive for an object can be first produced and then measured. Two of the most important of these processes are referred to as subtractive and additive color methods.

One very common color production process that most people are familiar with has to do with a process called subtractive color mixing. Subtractive mixing results from mixing pigments together, such as with paints and dyes. In the subtractive process, blending all pigments together yields black and the absence of any pigment yield white. The mixing of both pigments and light to produce other colors follows the same basic principles of light reflection and absorption. With pigments, each pigment or dye selectively absorbs some wavelengths of light and transmit others to our eyes to perceive. In this system, the three primary colors are usually defined as red, blue and yellow (RYB system) or, more recently, as cyan (blue-green), magenta, and Yellow (CMYK system), as shown in Figure 15.1.13 for the subtractive CMYK color wheel. For example, if we shine white light, as shown in Figure 15.1.14 (simplified in the drawing as a beam of red, green and blue light), onto a painted surface that absorbs the blue and green components of the light, then the red wavelengths are not absorbed and are transmitted to our eyes. We then see the surface as colored red. Similarly, if the red and blue wavelengths are absorbed by the pigment molecules and green is transmitted, we perceive the surface as green. Finally, if none of the colors are absorbed, the color of the surface appears white. This situation is probably the most

![Figure 15.1.13. Additive and subtractive color wheels](www.dycalculator.com/sp-cvision.shtml).

![Figure 15.1.14. Subtractive color scheme from shining white light from the left onto different colors of paint. The pigments in each color remove (or subtract) some wavelengths of light from the white light through absorption. The remaining wavelengths of light are then detected by our eyes to be interpreted as color](www.dycalculator.com/sp-cvision.shtml).
common way that we encounter color from solid objects.

**Additive color mixing** is essentially the opposite case to subtractive color mixing. White light consists of a mixture of all possible wavelengths, or colors, of light. There are three **primary colors** used to determine the additive nature of light - red, green and blue. In the additive mixing process, if we start with white light, containing all three of the primary colors. When we remove one of these primary colors, the remaining two colors add together to give us the perception of another different color, as illustrated in Figure 15.1.15. Similarly, adding two beams of two colored light gives the different additive color. For example, if we filter out the blue light from a white light beam, the remaining colors of red and green remain. Red and green then add together to give yellow light. This relationship is commonly displayed in an additive color wheel, shown in Figure 15.1.13. Similarly, if we start by adding together a beam of green light and a beam of red light, such as on a computer screen, TV set, or in theater lighting, we perceive yellow light resulting. Adding three beams of red, green and blue produces white light and filtering all three yields black, as shown in Figure 15.1.15.

Complimentary colors are two colors that when added together yield either white light (additive) or black pigment (subtractive). For example, mixing yellow and blue light gives white light (additive) while mixing yellow and magenta pigments gives black (subtractive). Complimentary colors are displayed in the color wheel on directly opposite sides of the wheel (Figure 15.1.13). Secondary colors are defined as those that arise from mixing together primary colors. In the additive system, the secondary colors are yellow, cyan and magenta. In the subtractive system the secondary colors are green, orange and purple.

**Electrical Properties and Ductility:** Electrical properties can sometimes be helpful in identifying the components of metallic systems, such as telling the difference between aluminum, steel, or zinc or characterizing an alloy (12 K vs. 24 K gold). Resistivity can also tell if a circuit is functional or an electrical object is functional. For example, measuring the resistivity of a fuse of light-bulb filament can easily show if it is intact or damaged from use. Resistivity is a measure of how strongly a material resists the flow of electric current while conductivity indicates how well a substance conducts an electric current. Ductility refers to the ability of a substance to be stretched into a wire of hammered into thin sheets without shattering. Metals are typically quite ductile while ceramics shatter when stressed.

**Other measurements:** Other physical properties that can be measured and are

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**Figure 15.1.15.** Additive color mixing of red, blue, and green from three theatrical lights to produce white, yellow, cyan, and magenta colors (http://vr.theatre.niu.edu.tw/hlee/course/dth6 300/th6 300e.htm).

**Figure 15.1.16.** The measurement of hardness can be used to very quickly and effectively identify different minerals, such as those found in forensic solid and geological samples (http://invsee.asu.edu/nmodules/carbonmod/hardness.html).
used in forensic laboratories to help characterize substances include melting point, boiling point, sublimation point, hardness, and others. Most of these properties and their measurement have already been discussed in previous chapters but will be employed in considering glass, mineral and paint evidence later in this chapter.