The Separation of Microplastics by Froth Flotation

A Major Qualifying Project

Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the degree of Bachelor of Science

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April 25, 2024

Abstract

As there is no current technique to effectively separate microplastics by plastic type, they cannot be properly recycled. Polyvinyl chloride (PVC) releases toxins into the air upon heating and creates a structurally weak product when recycled with other plastics. This project proposes the use of froth flotation as a potential scheme to successfully separate PVC from binary plastic mixtures to allow for safe recycling. A variety of parameters were tested to optimize the process such as surfactant concentration, flotation time, conditioning time, agitation speed, and particle size. It was found that PVC can be separated at high recovery, but more testing must be done to reach the purity needed to recycle plastic. Other factors such as cost and sustainability were also discussed.

Acknowledgements

We would like to express our deepest appreciation to our advisor, Professor Laila Abu-Lail, for supporting us throughout the duration of this project. We thank you for providing us with the opportunity to work on this project under your supervision, and for your continuous support in our research. This project would not have been possible without your guidance, and we are forever grateful.

We would like to extend our gratitude to the lab manager, Ian Anderson, as well as to the facilities department for preparing our flotation device for testing. We appreciate your time and expertise in making our research possible, and for providing us with the equipment necessary for the success of this project.

We would also like to thank Doug White and Professor Christopher Lambert for providing us with the imaging of our samples. We are grateful for your help producing the imaging needed for us to obtain a deeper knowledge of our results, and for your time and willingness to assist our project.

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Chapter 1: Introduction

Microplastics are one of the largest concerns in water quality today. Due to their size and characteristics, they create a number of problems in aquatic environments. They also have high absorbability which makes them ideal for carrying toxins into aquatic and terrestrial environments carrying many risks for the organisms within. The prevalence of microplastics in waterways also creates increased risk for households all over the world as they can be easily ingested through tap water and cause long term health issues still being studied today.

Current methods focus solely on the removal of microplastics from waterways, however, recycling companies often hit a wall when it comes to properly disposing of the collected plastics. Mixed streams of plastic cannot be recycled together due to the different needs of each plastic type. Some plastics such as polyvinyl chloride (PVC) release harmful gases when heated and create a weak product when recycled with other plastic types. For this reason, it is important to selectively separate the undesired plastics from a mixed stream of microplastics.

As knowledge of microplastics increases, so do the studies of microplastic separation. More research is being put into finding ample ways to separate microplastics to create ways to properly recycle them. Froth flotation has been one of the many techniques that has shown promising results to achieve this separation. Froth flotation utilizes water agitation and surface treatment to change the hydrophobicity and characteristics of specific particles, causing some particles to float and others to sink.

The goal of this project was to determine if froth flotation is a potential scheme to successfully separate PVC from binary plastic mixtures to allow for safe recycling. The other plastics used in the binary mixtures were poly(ethylene terephthalate) (PET), poly(acrylonitrile-co-butadiene-co-styrene) (ABS), polystyrene (PS), and poly(methyl methacrylate) (PMMA). While doing so, a variety of different flotation parameters were tested in order to optimize the flotation process to increase the recovery of PVC and the purity of the floated product. The environmental effects and sustainability of froth flotation were considered, and a cost analysis of the process compared to other systems was analyzed.

Chapter 2: Background

2.1 The Use of Plastics

Plastic usage has increased by nearly 20 times in the last 50 years. A majority of plastic falls into the categories of packaging, consumer and institutional products, and building and construction. In 2018, plastic generation totaled nearly 36 million tons, and approximately half of that was created by plastic packaging alone. From that number, approximately three million tons get recycled, six million get incinerated, and the rest wind up either becoming litter or in a landfill [23].

2.2 An Introduction to Microplastics

Microplastics are defined as plastic particles that are between 5 mm and 100 nm in size, however, the scientific definition is still heavily debated [8]. Despite the debate about the exact definition, the fact that microplastics are dangerous is not a focus in the scientific community, and still a contested idea. As pervasive as plastic is currently, microplastics are considered more difficult to manage due to their small size. Their size makes it very easy for microplastics to enter waterways and soil which creates a serious health hazard to humans and ecosystems [22]. Furthermore, microplastics are incredibly difficult to remove once they enter the environment and exist essentially everywhere in the ecosystem [11]. While microplastics have existed as long as typical plastic, they are only recently being studied despite the danger they have caused for years.

2.2.1 The Creation and Identification of Microplastics

There are two main ways that microplastics are created: primary and secondary. Primary microplastics are microplastics created specifically to be microplastics. These are most notably found in cosmetics as exfoliating beads and as plastic fibers in synthetic fabrics. Currently, the only legislation related to microplastics passed in the United States is the Microbead-Free Waters Act of 2015. This act prohibits the manufacturing, packaging, and distribution of rinse-off cosmetics containing plastic microbeads in an attempt to reduce primary microplastic creation and pollution [21].

Secondary microplastics are created when larger plastics break down by various means of degradation including, but not limited to, weathering, exposure, and chemicals [11].

Microplastics are identified by their qualities such as shape and method of creation. The shapes which microplastics are found in are pellets, fragments, fibers, films, ropes, filaments, sponges, foams, rubber, and microbeads. The most common microplastics are secondarily sourced pellets, fragments, and fibers [11]. Figure 1 below shows different forms of microplastics.

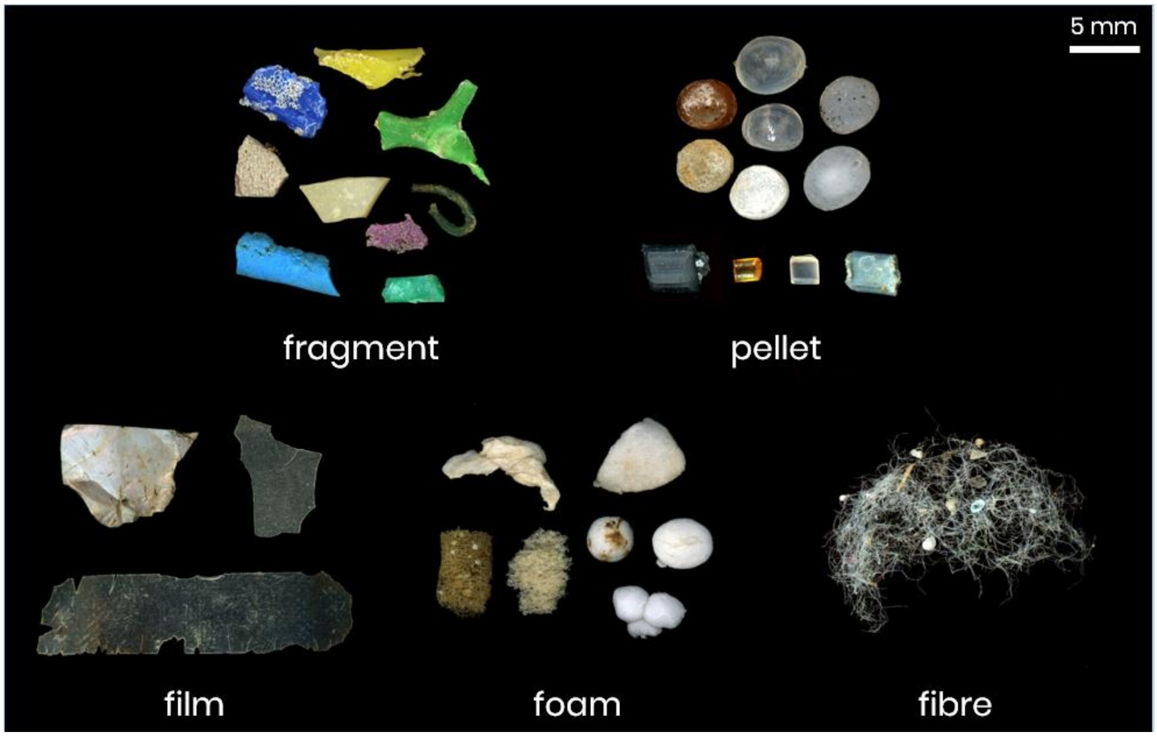


Figure 1: Various shapes of microplastics [17].

2.2.2 Environmental Effects

In recent years, the environmental damage caused by microplastics has become much more apparent. Like any plastics, microplastics take hundreds of years to degrade and can be considered invasive in any environment. While these plastics can invade any space, they are most prevalent in waterways and aquatic spaces. It has been estimated that hundreds of thousands of metric tons of microplastics have been found floating on marine environments [30]. Once in waterways, plastics can cause immense harm due to their resistance to decomposition and their ability to transport toxic pollutants. Due to their absorbility, these plastics easily pick up toxins and bring them to new environments. Their small size allows for aggregates to form with other similar sized molecules. These aggregates often lead to bioaccumulation creating detrimental effects to aquatic and terrestrial ecosystems and the inhabitants within [10]. With how easily they traverse through different environments and how easily they bioaccumulate, microplastics create a severe threat to any environment they are found in.

2.3 The Problem with Recycling Plastic

Many plastic streams are mixed and not properly separated based on their properties which can cause many issues as not all plastics are easily recyclable. Depending on the plastic, it may be seen as less valuable and may be harder to produce a desired amount of reusable plastic. This means that many companies will not go through the effort of properly recycling these plastics as it may cost more than it is worth. Recycling can also create unknown dangers to those physically recycling plastic since some plastic types emit harmful gasses upon heating [19].

2.3.1 Current Recycling Techniques

Recycling can be broken down into four sections, primary, secondary, tertiary and quaternary. Primary and secondary recycling are what is most commonly thought of when thinking of recycling techniques. Primary recycling takes recovered plastic and uses it for its original application, unlike secondary recycling which uses recovered plastic to make a new product which is different from the original. Tertiary recycling uses a chemical process to turn the recovered plastic into another material, and quaternary recycling uses incinerated plastics as an energy source. When looking at the reuse of plastic, primary and secondary recycling are the techniques that utilize the reuse and reproduction of plastics [19]. Primary recycling is the more desirable recycling technique as it keeps similar plastic types for the same use, lessening the chance of mixed recycling. However, many areas have more lax rules on separating plastics, which makes it more difficult to properly recycle the plastic. This means that secondary recycling is often much more common, but this can cause many problems due to the mix of different plastic types [19].

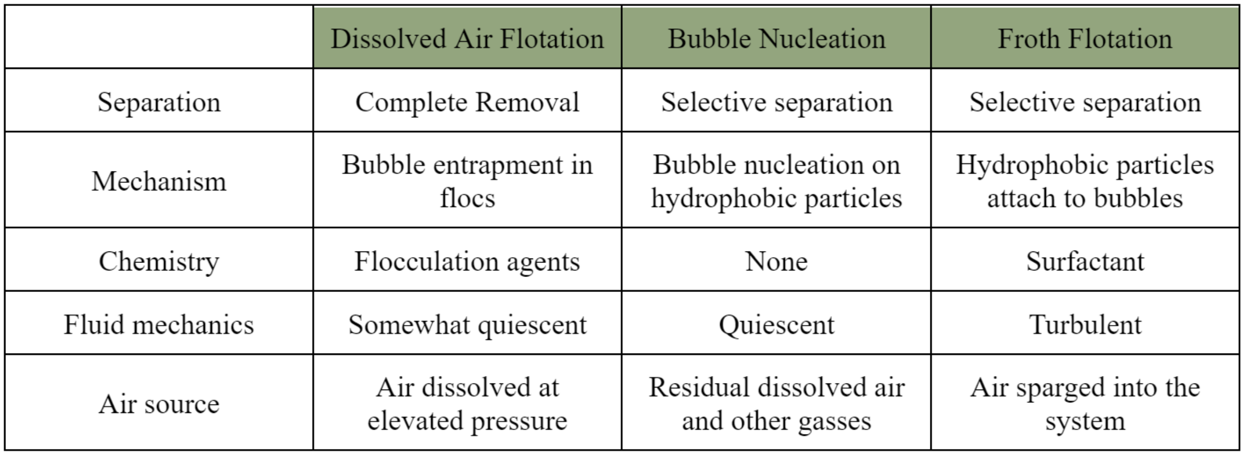
2.3.2 PVC Recycling

Polyvinyl chloride (PVC) plastic is typically a more difficult plastic to recycle and can be considered structurally weak due to the mixing of different plastic types. Its use is pervasive in the world today, however, to allow for its sought-after characteristics, there are many additives in PVC plastic. It is these additives that make the recycling of PVC so difficult. PVC often contains dangerous chemicals such as phthalates. When phthalates heat up, such as they do in the recycling process, they leach into the environment at much higher rates than normal. Exposure to phthalates can cause major reproductive issues. Additionally, heating PVC releases dioxins. Dioxins are incredibly dangerous to humans and the environment alike, targeting many organs in the body [16]. In order to properly recycle PVC, the plastic must be at 98% purity or better, leading to a significant amount of PVC not being recycled due to the effort needed to achieve the necessary purity [12].

2.4 Flotation Processes

The use of flotation methods has been widely explored in recent years due to its performance in removing or separating solids from liquids. Each type of flotation process has different mechanics and uses different chemicals to successfully remove or separate the suspended solids which makes choosing the right method critical to produce the desired outcome. Table 1 below summarizes the most used flotation processes. While there are other flotation processes than discussed below, they are not commercially used and are emerging processes with little known experimental outcomes [26].

Table 1: Comparison of flotation processes [9].



	Dissolved Air Flotation	Bubble Nucleation	Froth Flotation
Separation	Complete Removal	Selective separation	Selective separation
Mechanism	Bubble entrapment in flocs	Bubble nucleation on hydrophobic particles	Hydrophobic particles attach to bubbles
Chemistry	Flocculation agents	None	Surfactant
Fluid mechanics	Somewhat quiescent	Quiescent	Turbulent
Air source	Air dissolved at elevated pressure	Residual dissolved air and other gasses	Air sparged into the system

2.4.1 Dissolved Air Flotation

Dissolved air flotation (DAF) is a removal technique that completely removes any suspended solids from a slurry. In this method, flocculation chemicals are added to cause the solids to stick together and create clumps, also known as flocs, of unwanted material. Air is then dissolved under extremely high pressure and when released, the dissolved air comes out of the liquid where it attaches to the flocs and causes them to float to the top [9]. The flocs are then skimmed off from the top of the liquid and disposed of. This process is done under somewhat quiescent conditions with relatively no liquid aggregation to keep the flocs from breaking apart. Since DAF is a removal technique rather than a separation technique, there is no way to selectively separate one solid from another. While this may be simple enough for some experiments, it is important to have selective separation when discussing a flotation method for the use of microplastics in order to properly recycle each type of plastic [9].

2.4.2 Bubble Nucleation Separation

Bubble Nucleation Separation (BNS) is a separation technique that can selectively separate one material from another. In this method, a vacuum is applied to the slurry to pull dissolved gasses out of the liquid in the form of bubbles [9]. Hydrophobic solids act as nucleation sites, places for bubbles to form and grow, which causes them to float to be skimmed off from the top of the liquid. Hydrophilic particles remain at the bottom of the slurry to be removed. This process is completely quiescent with no water aggregation to keep the bubbles from detaching from the solid surface. No chemicals are added to the slurry in BNS which means that the properties such as surface characteristics of the suspended solids are not altered. This makes BNS successful only when the desired material has a large enough difference of physical properties and hydrophobicity as the other material. This is not optimal when considering the use of BNS for the separation of microplastics since many types of plastics have the same characteristics and hydrophobicity, meaning that the desire for selective separation would not be met with the BNS process [9].

2.4.3 Froth Flotation

Froth flotation is a separation technique that uses the addition of surfactants to aid in the selective separation of suspended solids from liquid. In this method, a controlled turbulence is used to agitate the water and disperse air that is sparged into the system [9]. Surfactants are used to change the hydrophobicity of the suspended solids in order to increase their attachment to bubbles and allow them to float to the top. Based on the surfactant that is used, the surface characteristics of different materials are altered which allows them to be separated from a mixture. This makes this process desirable for the separation of microplastics since there is the ability to selectively separate different plastics from each other, even if they have similar properties. Froth flotation is a promising method to selectively separate microplastics from a mixture to be properly recycled which is something that cannot be done using the DAF or BNS processes [9].

2.5 Prior Uses of Froth Flotation

While froth flotation has a wide range of uses, the main use is separation of solvents using densities, specifically in mining. The mining industry uses flotation in two main categories: separation and cleaning.

When using froth flotation for the cleaning of ores, the bubbles created do the brunt of the work. Without worrying about separation, a mix of ores is placed in a column which has a gas feed constantly creating bubbles. These bubbles will agitate the ores, knocking off any dirt or excess particles that affect their cleanliness [6]. For separation, Flotation is used to separate the valuable ore from what is known as gangue, the extra mined debris. Column flotation is often used for this which uses mechanical agitation, similar to that of froth flotation. Rather than having a mixer, they use gas bubbles typically created by sparging which helps create a deeper froth [6].

2.6 Factors Affecting Froth Flotation

There are many factors and parameters which affect the success of any separation process. In the case of froth floatation, the main factors which affect the process are density, pH, frother dosage, hydrophilicity, surfactant type and concentration, flotation time, size of the particles, and agitation speed [4].

2.6.1 Density

An important principle in froth flotation is the ability for a certain material to float, which is highly dependent on its density. In the case of plastic, the majority of their densities are higher than that of water, meaning that they would naturally sink. The densities of PVC, ABS, PET, PMMA, and PS are roughly 1.50, 1.20, 1.40, 1.20, and 1.05 g/cm^3 respectively [27]. While froth flotation is not solely dependent on particle density, it does favor particles with higher densities as it increases the probability of collision and adhesion to the bubbles [31]. Since PVC is the plastic with the highest density, it is most favorable for froth flotation.

2.6.2 pH

For selective separation to occur, the optimal pH needs to be found since different pH values can encourage or discourage the attachment to froth bubbles. If the pH value is too high, it hits what is called a ‘critical pH’, which reduces the attachment of bubbles in the flotation [24]. If the pH is too low, it may cause the particles to float indiscriminately, as acid conditions increase the surface tension of water [29]. For plastic, the optimal pH value falls between 8 and 11, which has proven optimal for best particle floatability [15]. The pH of the water used for tests in this project was found to be roughly 6.5, significantly lower than the optimal pH range.

2.6.3 Frother Dosage

A frother is added in the flotation process to increase the surface area of air by creating a layer of froth. Adding too little frother will fail to create an idealized state for the particles to successfully float out of the tank which will decrease the amount of product recovered. However, adding too much frother will cause the tank to overflow, causing more particles to be recovered by the froth and creating less accurate results [15]. There are three main types of frothers: aliphatic alcohols, alkoxyparaffins, and polyglycol ethers. For many types of froth flotation, methyl isobutyl carbinol (MIBC) is a commonly used frother, which is an aliphatic alcohol. Aliphatic alcohols have been observed to work better for less coarse particles such as plastic, while frothers with higher molecular weights are used for particles of high density [31].

2.6.4 Hydrophilicity

Hydrophilicity is the surface characteristic of a material to have an affinity to water whereas its opposite counterpart, hydrophobicity, is the characteristic of a material to have a lack of affinity to water. Because plastics are naturally similar in hydrophobicity by nature, in order to have a successful selective separation of plastic, one or more of the plastic types must become more hydrophilic than the others [18]. This hydrophilicity can be altered by preconditioning the plastics with chemicals such as calcium hypochlorite.

2.6.5 Surfactant

Surfactant helps idealize the hydrodynamic conditions in the flotation tank by further conditioning the plastics to alter their hydrophilicity. Surfactants change the surface characteristics of a material, therefore changing its floatability [9]. Depending on the material, surfactants can make the material either more hydrophobic or hydrophilic, which can alter the recovery. Surfactant type, dose and conditioning time can also affect the hydrophobicity as it can alter how the surfactant interacts with the material. Calcium hypochlorite is often used as a surfactant when dealing with plastics as it has a high chemisorption [15].

2.6.6 Flotation Time

The time for which a particle stays in the flotation tank can affect the recovery rate of the particles. If the time of flotation is too short, the flotation process may not have finished and, in turn, the recovery percentage may be lower than expected. If the particles are left for too long, the recovery grade plateaus as there is a finite number of particles that can be removed. While it may seem as though leaving the particle to float for a long time to ensure a higher recovery grade is the best option, that will heavily increase costs and the time needed to complete flotation [5].

2.6.7 Size

While microplastics must remain within a specific size range to be considered microplastics, sizes within that range play a role in the amount recovered. Froth flotation works by using bubbles to float hydrophobic particles into the froth [28]. Particles will begin to float when the aggregate of the bubble and the particle is less dense than the flotation liquid.

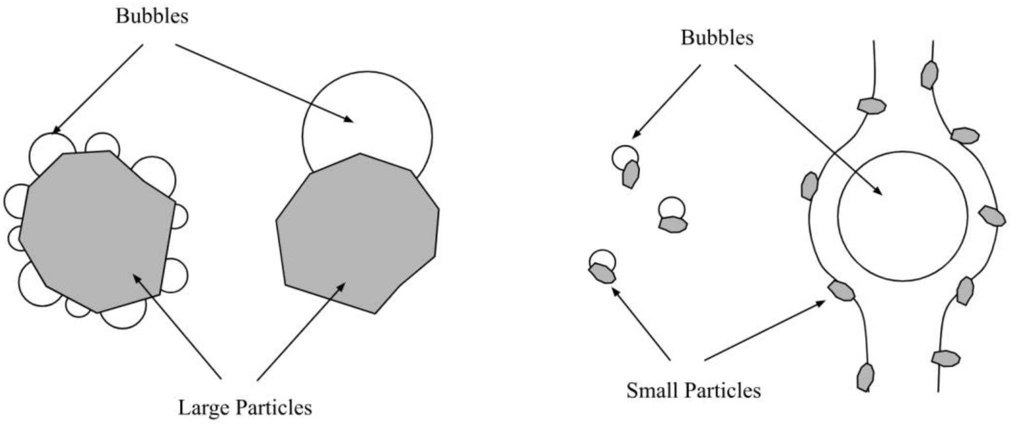


Figure 2: The effect of bubble size on large and small particles [13].

Figure 2 above shows the relationship between particle size and bubble size. Smaller particles will require less bubbles, or smaller bubbles to float, whereas larger particles need more bubbles or larger bubbles to float. Despite floating easier, smaller particles do not always present good separation as they are more prone to floating accidentally due to hydrodynamic forces, whereas larger particles are less likely to accidentally float [15]. Additionally, larger particles have been found to create more stable froth, which leads to a more successful froth flotation [2].

2.6.8 Agitation Speed

The speed at which the flotation device is stirring the mixture plays a role in recovery success rates. Unlike size, however, there is not an easy and direct comparison between speed and success rate from material to material. Stir speed is directly linked to the turbulent energy of the mixture, which affects the attachment and detachment rates of bubbles [14]. When stirring speed falls too slow, the attachment rate falls and in turn, recovery gets worse. When the stirring speed is too rapid, there is more turbulence which causes bubbles to detach from the material, and recovery success rates are lower. The one exception to this is in minimally hydrophobic particles. In the case of these particles, low stirring speed is more beneficial as they require longer contact time for attachment [14]. Faster agitation speeds can also produce fast flotation kinetics as it increases the frequency of particle-bubble collisions, as well as the force of the collisions.

2.7 Other Analysis Techniques

2.7.1 Cost Analysis

The costs associated with froth flotation include initial investment, maintenance, usage, and energy costs. While machine costs differ due to many factors such as size and how often the machine is running, it is generally accepted that larger machines cost less in the long run due to requiring less maintenance and energy [20]. Overall, the largest cost in froth flotation is energy costs, which accounts for approximately 60-80% of the costs over a 25-year cycle and includes costs such as energy source as well as air supply and pumping costs [25]. The easiest way to analyze energy is with an energy meter which gets hooked up between the energy source and machine to track the energy requirements [25]. Energy costs can be reduced by improving the process and lowering rotation speed. The next largest contributor to costs is in the reagents needed to complete the experiments, accounting for about 19% of total costs. Maintenance costs, which account for about 7% of the cost, are the ones which are most often reduced. However, by choosing the cheaper options for maintenance, costs often increase elsewhere due to less optimal conditions, or more regular maintenance being needed. The initial investment costs are another area that can be reduced more easily than the others, however, buying less than ideal machines often causes additional costs in other categories.

2.7.2 Contact Angle

The contact angle of a water droplet with a solid surface is used to determine if a material is hydrophobic or hydrophilic, where contact angle is an angle created between a tangent line on the water droplet and the liquid-solid interface. Typically, a material is deemed hydrophilic if the contact angle is less than 90 degrees whereas a hydrophobic material has a contact angle greater than 90 degrees [18]. A schematic of water droplets and contact angle is shown below in Figure 3.

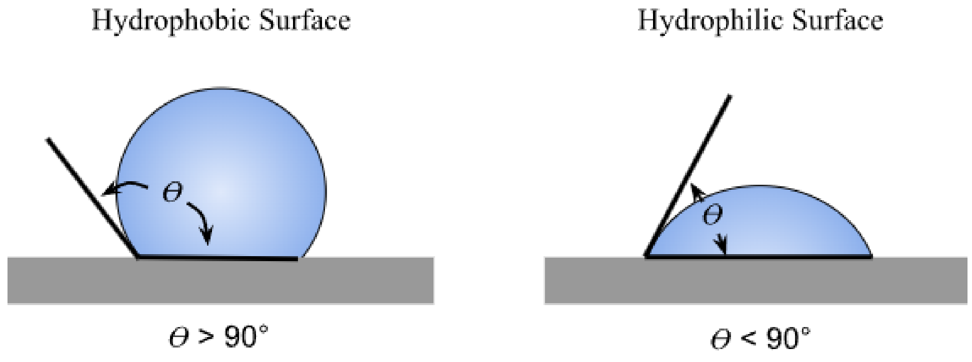


Figure 3: Contact angle measurements used to determine if a surface is hydrophobic or hydrophilic.

There is discussion as to whether a 90-degree cut-off accurately describes phobicity and philicity since a small change in contact angle can switch a material from hydrophobic to hydrophilic, however, this cut-off is accepted in practice [26].

2.7.3 Scanning Electron Microscopy

Scanning electron microscopy (SEM) is a technique used to create magnified images of an object. Unlike other forms of microscopy that uses light to create an image, SEM uses a beam of electrons [1]. The wavelength of visible light limits image resolution whereas electrons have a much shorter wavelength and are able to create high resolution images. Through the use of electromagnetic lenses and magnetic fields, the microscope is able to control the electrons and focus them on the sample. When the electrons interact with the simple, it creates two types of responses: backscattered electrons and secondary electrons. Backscattered electrons are reflected back to the lens from the surface of the sample whereas secondary electrons from atoms within the sample – both of which are used to create an image of the sample by showing up as brighter or darker regions. Obtaining SEM images of a sample allows for a visual examination of its surface characteristics and topography, which can be a useful analysis technique to characterize solid surfaces.

2.7.4 Theoretical Correlations

The concepts of recovery, separation, and purity are often misunderstood and used interchangeably; however, they are not the same. Understanding the difference between these concepts is important to this project in comprehending how the results are discussed.

The overall recovery of a flotation experiment refers to how much of a sample was collected versus the amount uncollected. For example, a trial in this experiment would have high recovery if a large amount of plastic was recovered in the froth rather than being collected as the sunken product. The amount of recovery is determined as a percent using Equation 1 below.

$$\%\,Recovery = \frac{recovered\ weight}{initial\ weight}\ x\ 100 \tag{1}$$

The amount separation of a trial refers to the difference in recovery of two samples. In this experiment, a trial would have high separation if one plastic was recovered in the froth more than another plastic. The amount of separation can be determined visually or as a percent (Equation 2).

$$separation\ =\ \%Recovery_{sample\ 1} - \%Recovery_{sample\ 2} \tag{2}$$

The purity of a sample is directly proportional to the amount of separation, however, the purity of a trial refers to how much of one sample was collected versus the total amount of sample collected. For example, a trial in this experiment would have high purity if the floated product contained a majority of one plastic type. The purity of a trial is determined as a percent using Equation 3 below.

$$Purity\ =\ \frac{weight_{sample\ 1}}{weight_{sample\ 1} + weight_{sample\ 2}}\ x\ 100 \tag{3}$$

Chapter 3: Experimental

3.1 Materials

The plastics used in this study include poly(vinyl chloride) (PVC), poly(ethylene terephthalate) (PET), poly(acrylonitrile-co-butadiene-co-styrene) (ABS), polystyrene (PS), and poly(methyl methacrylate) (PMMA). These plastics were obtained from commercial sources in pellets or sheets based on availability. Each plastic has a different color which allows for manual sorting at the end of each experiment. The PS sample was in pellet form and was obtained from LNS Technologies in the color black. The PET, PC, ABS, PVC, and PMMA samples were in sheets with the PET obtained from HTVRONT in clear, ABS obtained from Zuvas in red, PVC obtained from Global Industrial in yellow, and PMMA obtained from Uxcell in purple.

Calcium hypochlorite (CHC) was used as the surfactant in this study and was obtained from Sigma-Aldrich in powder form. Deionized water was used as the flotation medium with methyl isobutyl carbinol (MIBC) as a frothing agent obtained from Sigma-Aldrich.

3.2 Procedure

Flotation tests were conducted using an XFD-12 Lab Flotation Machine manufactured by GTEK Mineral Technologies. A schematic of the flotation device is shown in Figure 4. Different runs were made of binary mixtures PVC/PET, PVC/PS, PVC/ABS, and PVC/PMMA while testing a variety of flotation parameters.

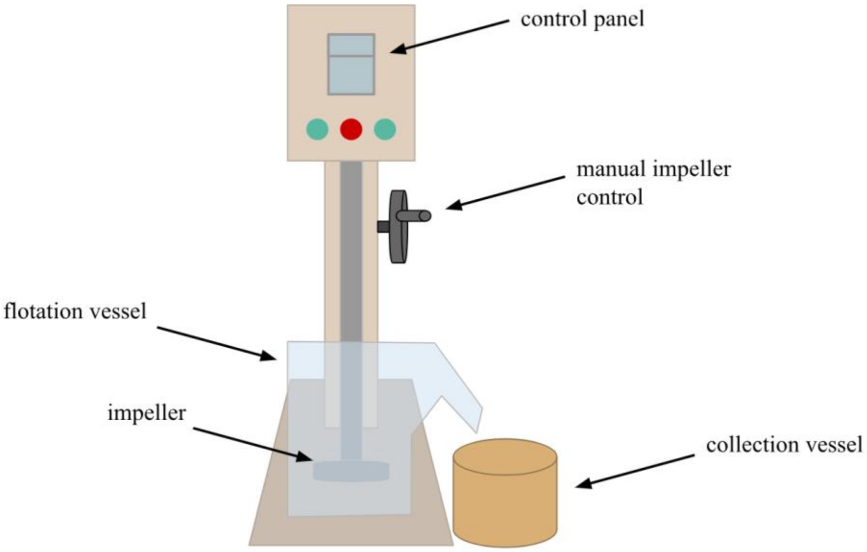


Figure 4: Flotation machine schematic.

3.2.1 Sample Preparation

1. Cut sheets of one plastic type into smaller pieces to fit into the kitchen blender.
2. Blend a few pieces of plastic at a time, stopping occasionally to prevent overheating.
3. Empty the contents of the blender into the sieve trays to sort the plastic particles by size. Plastic particles larger than any of the desired sizes should be re-blended. Figure 5 shows an image of the particle sizes used for this experiment.

Figure 5: One gram of PVC samples of sizes 3.36-4.75mm (left), 2.37-3.36mm (middle), and 1.19-2.37mm (right).

4. Prewash the plastic samples with DI water to remove any debris and allow them to dry at room temperature.
5. Once dry, place samples into separate containers labeled by size and type of plastic.
6. Repeat steps 1-5 with all plastic types. For pellet samples, flatten them with a hammer and cut them into smaller pieces with scissors.

3.2.2 Surfactant Concentration

1. Create 4 baths of treatment solution containing 50mL of water and 0.01g of CHC to create a concentration of 0.2g/L, and one treatment solution containing 200mL of water and 0.04g of CHC.
2. Place 4g samples of PET, PS, PMMA, and ABS of size 2.37-3.36mm into their own 50mL treatment bath and a 16g sample of PVC of size 2.37-3.36mm into the 200mL treatment bath. Allow to soak for 40 minutes.
3. After conditioning, rinse the plastic samples with DI water to remove excess surfactant and allow them to dry at room temperature.
4. Once dry, re-weight samples and record their initial weight. Add 4g of the conditioned PVC to each of the other conditioned samples.
5. Place each binary plastic sample into separate containers labeled by size, plastic type, and surfactant concentration. Figure 6 shows an example of each binary plastic sample placed in separate containers.

Figure 6: Binary plastic samples of PVC and PMMA (first), PVC and ABS (second), PVC and PET (third), and PVC and PS (last) of sizes 2.37-3.36mm.

6. Repeat steps 1-5 for treatment solutions with surfactant concentrations of 0.4, 0.6, 0.8, 1, 1.2, and 1.4 g/L.
7. Add 2800mL of water and one binary plastic sample to the 3-liter flotation vessel. Start the machine with an impeller speed of 800rpm.
8. After agitating for a few seconds, add 1mL of MIBC to the flotation vessel and let stir for a few more seconds.
9. Turn on the airflow rate to 0.8 m^3/h and begin a 5-minute timer when a sufficient layer of froth appears. During the flotation test, use the provided paddles to help push froth into the collection vessel.
10. At the end of the flotation test, turn down the airflow and turn the impeller off.
11. Separate the floated and sunken products from water through filtration. Ensure to collect any plastic caught in the impeller and assume this to be part of the sunken product.
12. Allow the products to dry at room temperature.
13. Once dry, manually separate the floated product by color and weigh each plastic type.
14. Calculate the percent recovery of each plastic in the floated and sunken product. The surfactant concentration that produces the most difference between the percent recovery of each binary mixture should be used in succeeding experiments.
15. Repeat steps 7-14 for each binary mixture at each surfactant concentration.

3.2.3 Flotation Time

1. Follow steps 1-5 of the Surfactant Concentration Procedure using the predetermined optimal surfactant concentration from the previous test.
2. Add 2800mL of water and one binary plastic sample to the 3-liter flotation vessel. Start the machine with an impeller speed of 800rpm.
3. After agitating for a few seconds, add 1mL of MIBC to the flotation vessel and let stir for a few more seconds.
4. Turn on the airflow rate to 0.8 m^3/h and begin a 10-minute timer when a sufficient layer of froth appears.

5. Every minute of the flotation test, start a new collection vessel. During the flotation test, use the provided paddles to help push froth into the collection vessel.
6. At the end of the flotation test, turn down the airflow and turn the impeller off.
7. Separate the floated and sunken products from water through filtration. Ensure to collect any plastic caught in the impeller, and assume this to be part of the sunken product.
8. Allow the products to dry at room temperature.
9. Once dry, manually separate the floated product at each minute interval by color.
10. Weigh each plastic type collected at each minute interval, adding the weight to the previous minute.
11. Calculate the percent recovery of each plastic in the floated and sunken product at each time interval. The optimal flotation time is when the percent recovery and separation no longer increase.

3.2.4 Conditioning Time

1. Follow steps 1-5 of the Surfactant Concentration Procedure using the predetermined optimal surfactant concentration. Repeat this step for conditioning times of 0, 10, 20, 30, 40, 50, and 60 minutes.
2. Add 2800mL of water and one binary plastic sample to the 3-liter flotation vessel. Start the machine with an impeller speed of 800rpm.
3. After agitating for a few seconds, add 1mL of MIBC to the flotation vessel and let stir for a few more seconds.
4. Turn on the airflow rate to 0.8 m^3/h and begin a timer when a sufficient layer of froth appears using the previously determined optimal flotation time. During the flotation test, use the provided paddles to help push froth into the collection vessel.
5. At the end of the flotation test, turn down the airflow and turn the impeller off.
6. Separate the floated and sunken products from water through filtration. Ensure to collect any plastic caught in the impeller and assume this to be part of the sunken product.
7. Allow the products to dry at room temperature.
8. Once dry, manually separate the floated product by color and weigh each plastic type.
9. Calculate the percent recovery of each plastic in the floated and sunken product. The optimal conditioning time is when the percent recovery and separation no longer increase.
10. Repeat steps 2-9 for each binary mixture at each conditioning time.

3.2.5 Agitation Speed

1. Follow steps 1-5 of the Surfactant Concentration Procedure using the predetermined optimal surfactant concentration.
2. Add 2700mL of water and one binary plastic sample to the 3-liter flotation vessel. Start the machine with an impeller speed of 1000rpm.
3. After agitating for a few seconds, add 1mL of MIBC to the flotation vessel and let stir for a few more seconds.
4. Turn on the airflow rate to 0.6 m^3/h and begin a timer of the previously determined optimal flotation time when a sufficient layer of froth appears.
5. During the flotation test, use the provided paddles to help push froth into the collection vessel. At the end of the flotation test, turn down the airflow and turn the impeller off.

6. Separate the floated and sunken products from water through filtration. Ensure to collect any plastic caught in the impeller, and assume this to be part of the sunken product.
7. Allow products to dry at room temperature.
8. Once dry, manually separate the floated product by color and weigh each plastic type.
9. Calculate the percent recovery of each plastic in the floated and sunken product. The agitation speed that produces the most difference between the percent recovery of each binary mixture should be used in succeeding experiments.
10. Repeat steps 2-9 for each binary mixture using an agitation speed of 1200 rpm and 1400 rpm. For the 1200 rpm test, use 2700mL of water with an airflow rate of 0.4 m^3/h to keep the water level below the lip of the collection vessel. For the 1400 rpm test, use 2600mL of water with an airflow rate of 0.4 m^3/h.

3.2.6 Particle Size

1. Follow steps 1-5 of the Surfactant Concentration Procedure using the predetermined optimal surfactant concentration and particle sizes of 1.19-2.37 mm and 3.36-4.75 mm
2. Add water and one binary plastic sample to the 3-liter flotation vessel and start the machine. Use the amount of water and the optimal agitation speed determined in the previous test.
3. After agitating for a few seconds, add 1mL of MIBC to the flotation vessel and let stir for a few more seconds.
4. Turn on the airflow to the optimal rate determined in the previous test and begin a 10-minute timer when a sufficient layer of froth appears.
5. Every minute of the flotation test, start a new collection vessel. During the flotation test, use the provided paddles to help push froth into the collection vessel.
6. At the end of the flotation test, turn down the airflow and turn the impeller off.
7. Separate the floated and sunken products from water through filtration. Ensure to collect any plastic caught in the impeller and assume this to be part of the sunken product.
8. Allow products to dry at room temperature.
9. Once dry, manually separate the floated product by color and weigh each plastic type.
10. Calculate the percent recovery of each plastic in the floated and sunken product at each time interval and of each particle size. The particle size that produces the most difference between the percent recovery of each binary mixture should be used in succeeding experiments.
11. Repeat steps 2-9 for each binary mixture of each size.

Chapter 4: Results and Discussion

4.1 Surface Characteristics

The surface characteristics of each plastic type were analyzed using SEM imaging. Understanding the morphology of each plastic type is important when discussing its flotation probability. Depending on the crevices available for a bubble to attach to, one plastic type may be more prone to be captured by a bubble. The results of the SEM imaging are shown below in Figure 7 and 8.

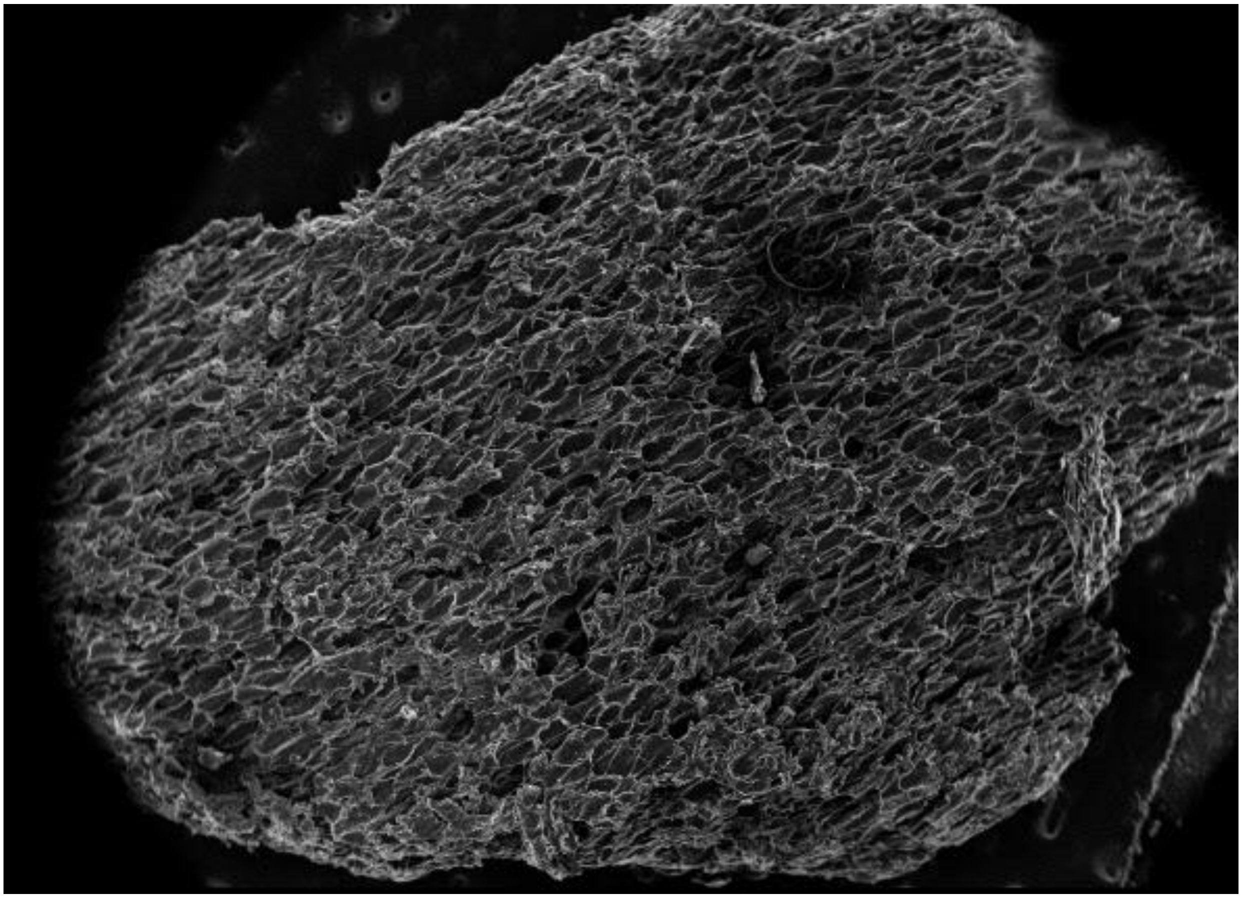


Figure 7: SEM image of PVC at a magnification of 22 using an Amray scanning electron microscope.

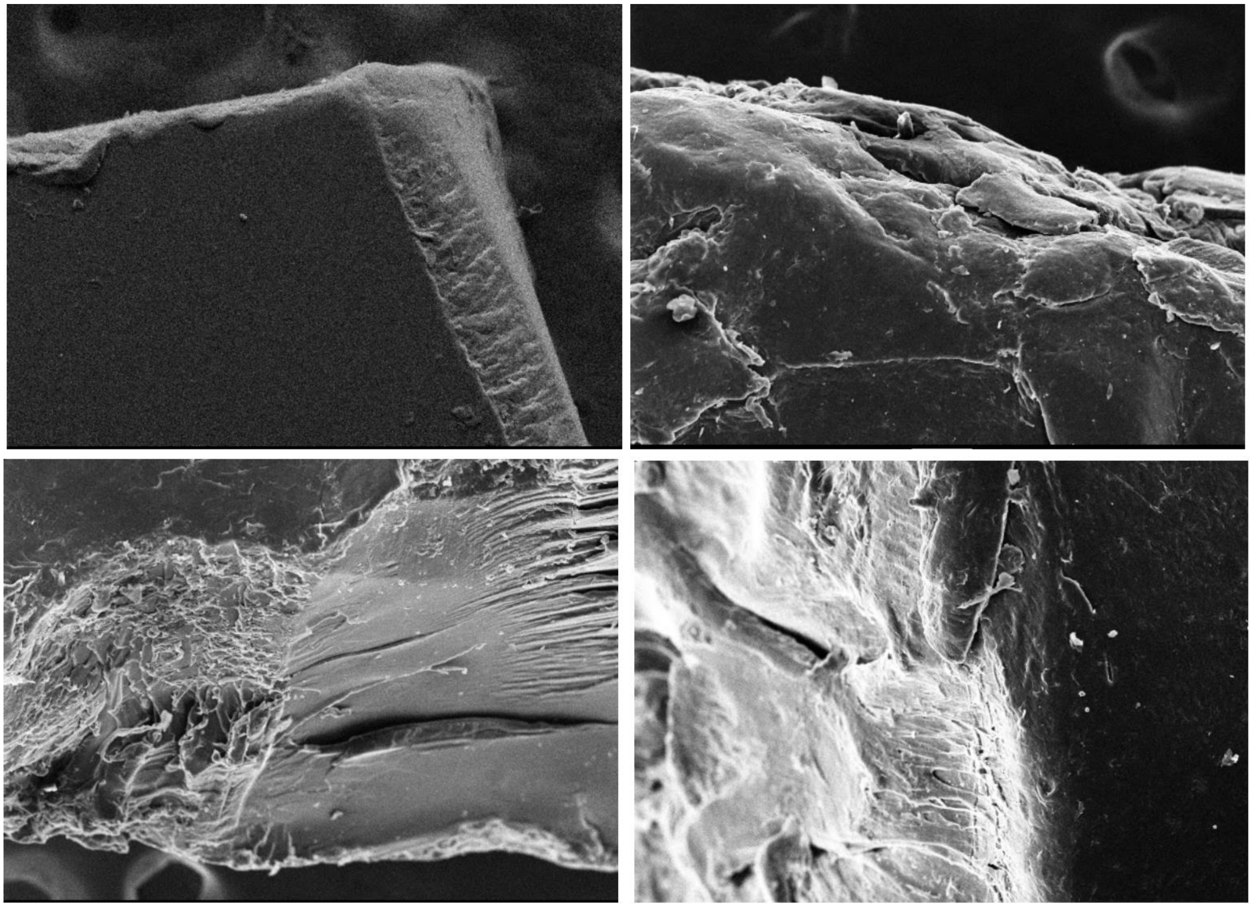


Figure 8: SEM images of PET (top left), ABS (top right), PMMA (bottom left), and PS (bottom right) at a magnification of 120 using an Amray scanning electron microscope.

As seen in Figure 7, PVC is composed of thousands of small craters along its surface. This morphology is ideal for capturing bubbles since each crater holds the possibility to house a bubble with little opportunity to escape. This surface texture is unlike all of the other plastic types used in this experiment, which leads to PVC having the best chance of being recovered in the froth. Since the goal of this project is to successfully separate PVC from the other plastic types, this conclusion is optimal. When looking at the SEM imaging of the other plastic types in Figure 8, most have very similar surface characteristics. The surface of ABS, PMMA, and PS all have cracks and indentations, however, the surface of PET is almost completely smooth with small indentations along the edge of the sample. This means that ABS, PMMA, and PS have a better chance of bubbles getting caught on their surface imperfections than PET.

Each sample of a specific plastic type is different from the rest due to how it broke down and how much contact it had with the blender blades. For this reason, it is impossible to equally compare two samples. Taking SEM images of untreated and treated samples would have shown how much surface change was inflicted by the surfactant if the images were of the same singular piece. Since the images for this project were taken at the conclusion of testing, having an untreated and treated sample was not an option.

4.2 Surfactant Concentration

The surfactant concentration plays a vital role in the recovery and separation of particles in froth flotation. Depending on the concentration of surfactant used, the change in hydrophilicity inflicted on the particle can differ greatly. Based on the results shown in Figure 9, it can be seen that the difference between the flotation recovery of untreated PVC from ABS, PMMA, and PS is minimal. This indicates that separation through froth flotation with no surfactant treatment would be difficult, if not impossible, which makes surface treatment of the plastic particles necessary to achieve successful separation.

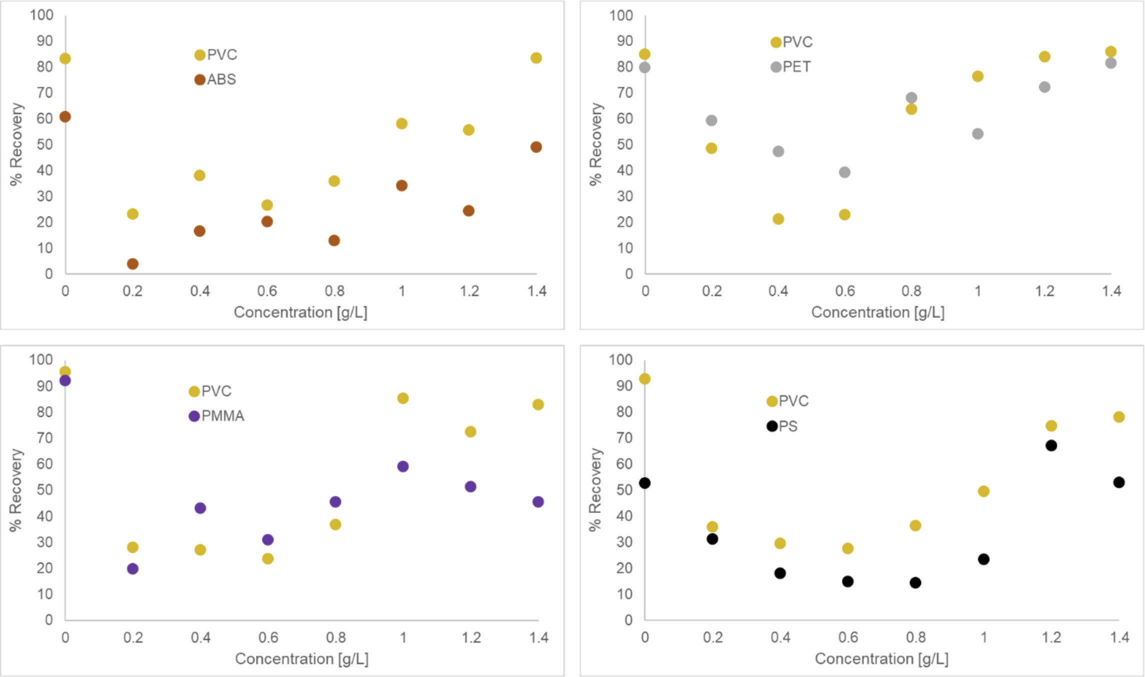


Figure 9: Flotation recovery of single plastics in binary mixtures as a function of surfactant concentration.

The overall trend in recovery for all binary plastic mixtures is decreasing at low surfactant concentrations and then increasing at higher surfactant concentrations, representing a U-shaped curve. This trend can be attributed to the repulsion between the net charge on the surface of the particle and the surfactant. At low concentrations, the surface of the particle attempts to repeal the surfactant adsorption due to the difference in charge. At higher surfactant concentrations, the repulsion between the surface of the particle and the surfactant decreases as the charges associate along the surface [3]. Therefore, the extent of adsorption is dependent on the charge difference between the particle surface and surfactant. This ideology is responsible for the concave trends seen in the data for this experiment.

When choosing the optimal surfactant concentration, the most important factor is the separation between PVC and the other plastics, which is more ideal at higher surfactant concentrations. With the exception of PET, the separation of PVC is similar for surfactant concentrations from 1 g/L to 1.4 g/L. This means that the high-end surfactant concentration was found since the separation no longer increases. The surface characteristics of the plastic can only be altered to a certain degree, meaning that higher concentrations would not induce more change. The separation of PVC from PET, however, decreases at higher surfactant concentrations. Similar to the phenomena noticed around a surfactant concentration of 0.8 g/L where the recovery of PVC surpasses that of PET, a similar phenomena might be reached at a higher concentration where the recovery of PET surpasses that of PVC again. While a surfactant concentration between 1 g/L and 1.4 g/L would work for ABS, PMMA, and PS, the negative effect that higher concentrations had on the separation of PVC from PS could not be ignored. For this reason, the surfactant concentration of 1 g/L was chosen as the optimal surfactant concentration since it worked for all binary plastic mixtures. Other researchers have found that lower surfactant concentrations under 1 g/L is most optimal; however, those experiments also conducted conditioning at high temperatures [28]. Since temperature was not tested in this project, all conditioning took place at room temperature which may have affected the adhesion of the surfactant to the particle, requiring a higher concentration.

4.3 Flotation Time

The amount of time in which the particles were floated was another factor that needed to be optimized. Ensuring that the minimal amount of flotation time is used will not only cut down operating costs, but will also ensure that the most amount of PVC is collected and nothing else. As seen in Figure 10, both recovery and separation continuously increased for all binary plastic mixtures from 0 to 5 minutes. With the exception of PS, the results began to plateau and continued plateauing around the six-minute mark until the test was concluded at ten minutes. This shows that the optimal flotation time was six minutes as the flotation recovery no longer increased and the separation from PVC remained constant.

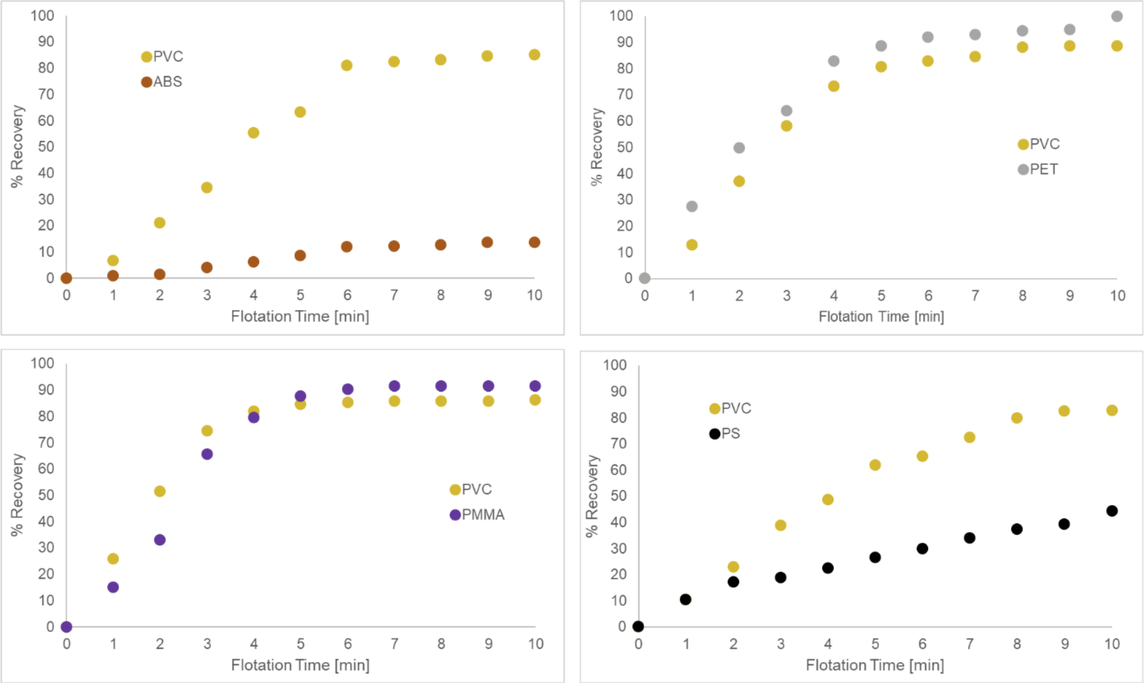


Figure 10: Flotation recovery of single plastics in binary mixtures as a function of flotation time.

The results for the PS test showed a less obvious plateau since only the start of the plateau was captured from 8 to 10 minutes. At this time, PVC recovery began to plateau while PS recovery continued to increase linearly with time, possibly due to its low density. This data suggests that at higher flotation times, the separation of PVC and PS would decrease. Between five and seven minutes, PS separation from PVC stayed nearly constant, suggesting that six minutes is a reasonably optimized flotation time for PS as well.

The rate of recovery of PVC from 0-6 minutes from ABS, PET, PMMA, and PS was found to be 0.56 g/min, 0.61 g/min, 0.59 g/min, and 0.46 g/min respectively. While the rate of recovery was the highest for PVC in the PET and PMMA tests, those tests also had the lowest amount of separation. This may be due to the fact that PMMA and PET have similar densities to PVC, making separation more difficult. On the other hand, the plastics that have the largest difference in density from PVC had the lowest rate of recovery but the highest separation. Despite having similar densities, PVC separated from the ABS better than PS did since it is more hydrophilic than PS.

4.4 Conditioning Time

The conditioning time of each plastic plays an important role in both separation and recovery. This variable has a large influence on the amount of change inflicted on the surface of the particle depending on how much time it has to absorb the surfactant. Too little time does not allow for the bond to truly affect the surface of the plastic whereas too much time changes the surface drastically This makes the two plastics in a binary mixture too alike causing a decrease in separation.

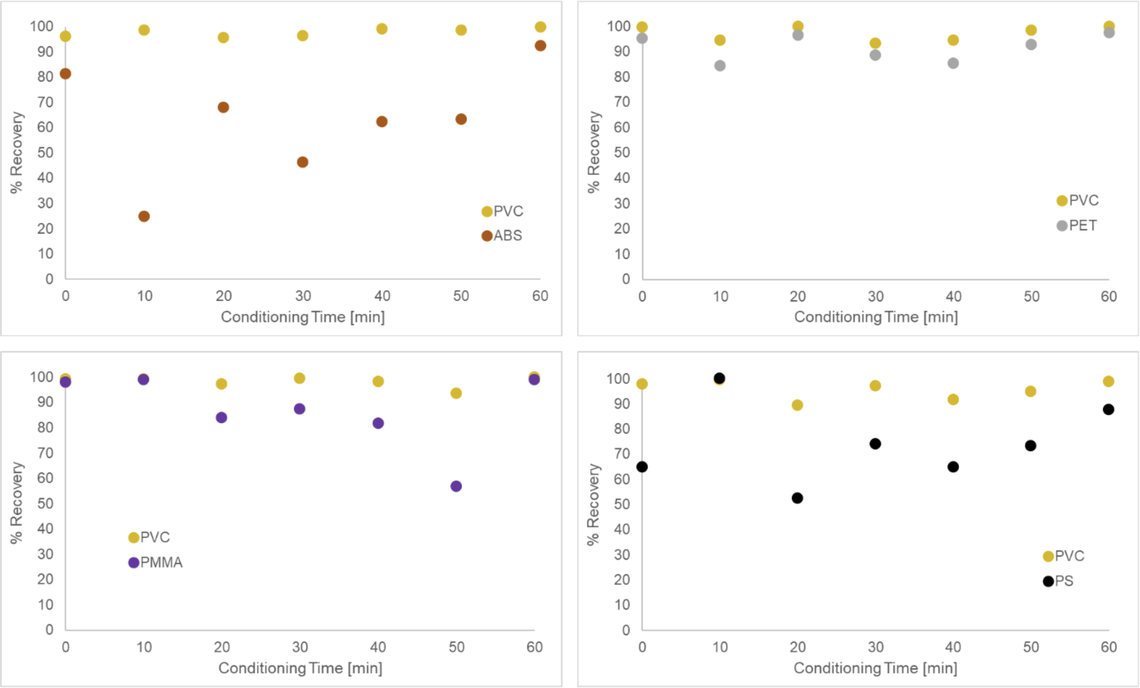


Figure 11: Flotation recovery of single plastics in binary mixtures as a function of conditioning time.

The more complex the cut of the plastic, the more surfaces the surfactant had to bond to. This effect can be seen in the soft plastics, PVC, ABS and PS. As seen in Figure 11, the results for ABS and PS show larger differences in recovery between each time period. The opposite can be seen with the plastics with a crystal structure, PMMA and PET, since their surfaces are significantly less complex. As seen in the results, the separation of PVC from PET and PMMA was minimal. It must also be noted that PVC showed constant recovery at all conditioning times. This can be attributed to the bonding between CHC and PVC. Since PVC has a very complicated surface and in turn has the largest surface area, it gives the surfactant many surfaces to bond to. This combined with the strength of the bond means it very quickly changes the surface of the plastics meaning time is a nonfactor. With all of these results taken under consideration, a conditioning time of 40 minutes was chosen due to the fact that there was promising separation between all binary mixtures at that time. Racherarch by others who have used froth flotation in the attempt to separate PVC from other plastic types also found that a conditioning time of 40-50 minutes with a CHC solution was optimal in creating the most amount of separation [28].

4.4.1 Contact Angle

Contact angle measurements were taken of each plastic before and after treatment to determine the change in hydrophilicity inflicted by the surfactant. These measurements are shown in Figure 12 on the following page. Before treatment, all of the plastics presented as slightly hydrophilic, with contact angles in the 65-90 degree range. After surface treatment, both ABS and PMMA became more hydrophilic while PVC, PET, and PS became more hydrophobic. This means that ABS and PMMA would be more prone to be collected as sunken products due to its affinity to water, which is exactly what was noticed during testing. The most hydrophobic plastic after treatment was PVC with a contact angle of 90.9°, giving further reason as to why it is consistently recovered by the froth over the other plastics. The contact angle of PS after treatment, however, is very close to that of PVC. This means that PS may be expected to float along with PVC, especially due to its low density.

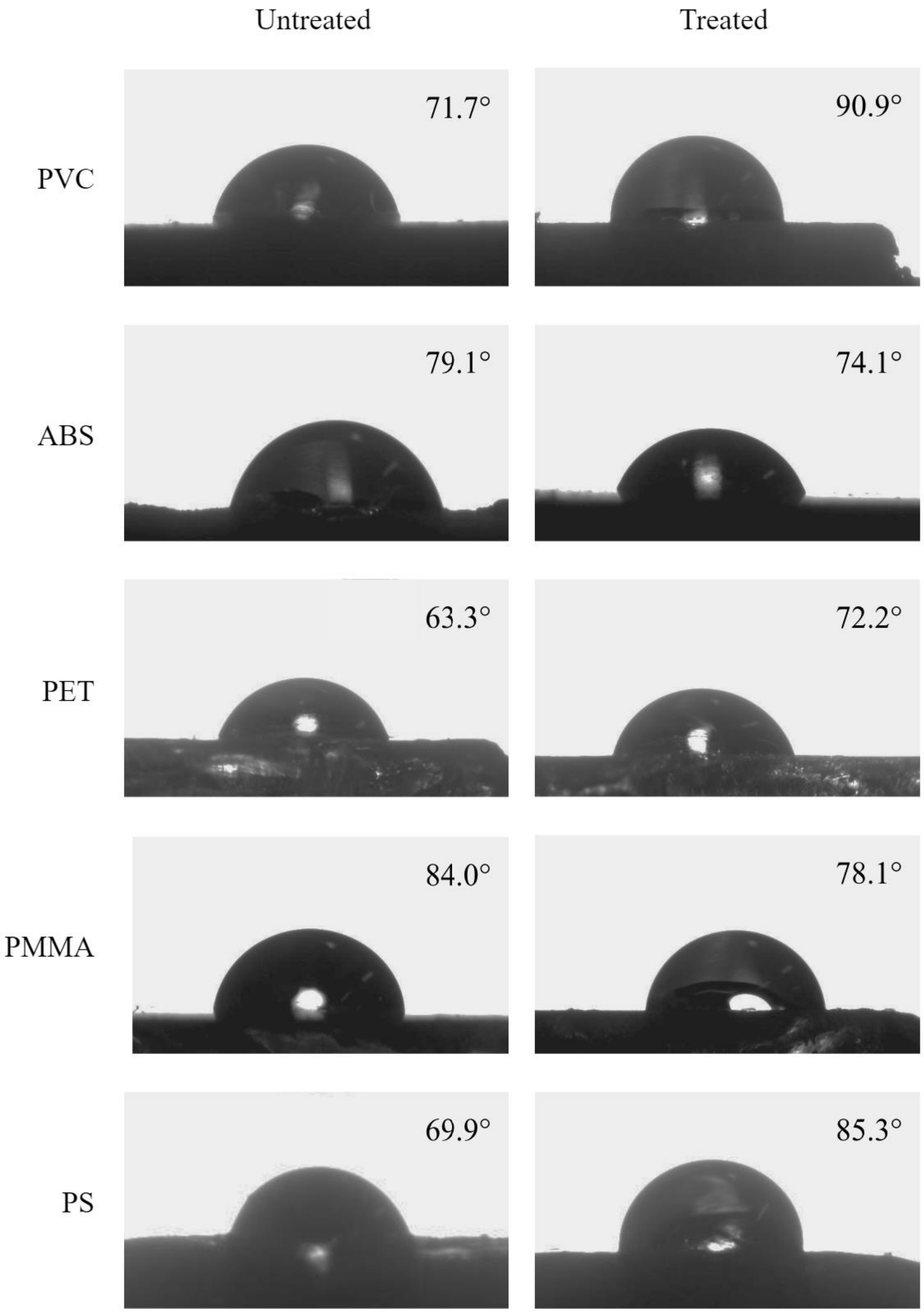


Figure 12: Contact angle of untreated and treated microplastics using a surfactant concentration of 1 g/L and a conditioning time of 40 minutes.

4.5 Agitation Speed

The flotation parameters were further optimized by finding which agitation speed produced the largest separation between each binary mixture. With the prior knowledge that bubble size is directly related to the agitation speed, results can be discussed as a function of both agitation and bubble size. As seen in Figure 13, the results of this experiment further prove the importance that agitation speed and bubble size have on separation and flotation recovery.

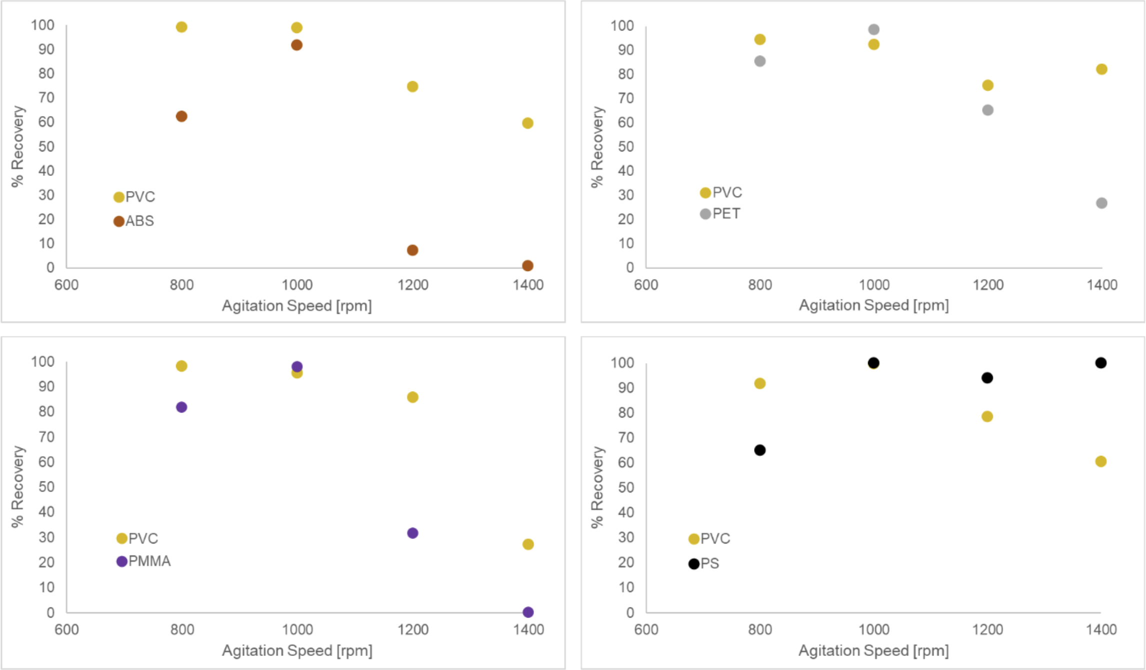


Figure 13: Flotation recovery of single plastics as a function of agitation speed.

At lower speeds, the bubble size produced by the machine is significantly larger than the bubble size created at higher agitation speeds. This is due to the rotation of the impeller breaking up the airflow coming in at different rates, resulting in different-sized bubbles. At slower speeds, the impeller rotates less and therefore causes large amounts of air to escape before the next rotation, creating larger bubbles. At high agitation speeds, the impeller rapidly breaks apart the flow of air, creating a spurge of small bubbles. Having a lot of small bubbles rather than a few large bubbles increases the chances of bubbles attaching to the plastic particles, increasing the capture probability of particles and flotation recovery.

With the baseline tests performed at an agitation speed of 800rpm, a slower agitation rate of 600 rpm was tested first. However, this slow speed did not allow for a sufficient layer of froth to be established with the large bubbles that were being produced. It was decided that 800rpm would mark the low-end agitation speed and to continue tests with agitation speeds higher than the original baseline. At these higher agitation speeds, the liquid level and airflow rate were changed slightly to ensure that water did not spill over into the collection vessel once the impeller was turned on. At lower agitation speeds, it was noticed that a significant amount of plastic particles would get stuck in the corners of the flotation vessel, indicating that there were zones of low water movement. These particles caught in the corners created a significant source of error since they created a void in the froth layer. This means that these plastics were unable to successfully attach to bubbles or sink. However, this was not an issue at higher agitation speeds as the water movement was able to break apart the plastic buildup in the corners of the vessel, allowing all particles to participate in froth flotation.

While an agitation speed of 1200rpm produced significant separation of PVC from ABS and PMMA, this speed had a negligible effect on the separation of PVC from PET and PS. Therefore, it was decided to test the agitation speed of 1400rpm which significantly increased the separation of PVC from PET and PS while also working well for ABS and PMMA. It is possible that higher speeds would produce better separation, but due to 1400rpm being the recommended agitation maximum of the flotation machine, higher speeds were unable to be tested. For this reason, an agitation speed of 1400 rpm was chosen as the optimal agitation speed and used in succeeding experiments. Theoretically, there would be a point where the agitation of the water would hinder the results more than the bubble size itself. This would result when the agitation of the water is too fast and knocks the bubbles off of the particles rather than promoting attachment. This point of detachment was also unable to be determined without hindering the safety of the experiment.

4.6 Particle Size

The ability of a bubble to successfully float a plastic particle above the froth layer is highly dependent on the size and weight of the particle itself. After previously determining that more separation between plastic particles is noticed at a higher agitation speed, and therefore smaller bubble size, the relationship between particle and bubble can now be discussed.

4.6.1 Small Particle Size (1.19-2.37 mm)

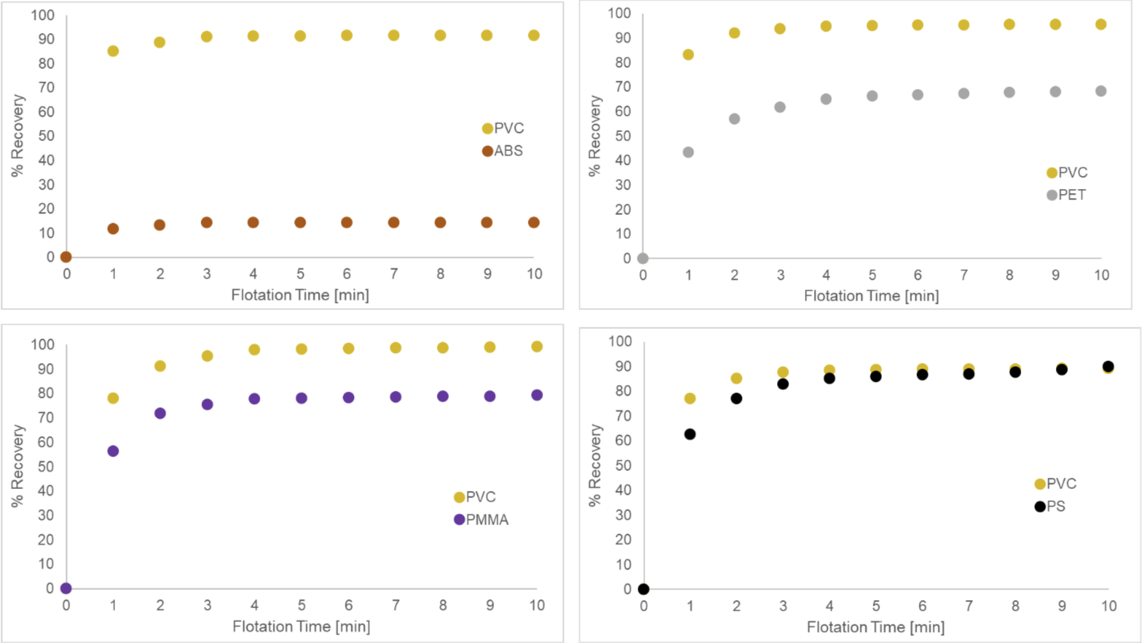


Figure 14: Flotation recovery of plastic particles of size 1.19-2.37mm as a function of flotation time.

As seen in Figure 14, the overall recovery of each plastic is high when the plastic particles are small, however, the separation of PVC for PET, PMMA, and PS was very low. The agitation speed at which these tests were conducted created a large quantity of small bubbles that had the potential to float any particle. When the plastic particles are this small and their weight is minuscule, a singular bubble has the ability to float one or multiple particles. This means that the attachment between the bubble and the particle was significantly easier, no matter the surface characteristics of the particle. Not only this, but smaller particles are more prone to be swept up into the froth by the hydrodynamic forces around the bubbles, causing the particles to travel upward with the movement of the bubbles.

The separation of PVC from ABS at this small size, however, was significant. This may be attributed to the overall shape and weight of the ABS particles. The sieves used for sorting the plastic particles by size assume the shape of the particles, which means that a particle must only be the sieve size in two dimensions. The ABS sheets were slightly thicker than the other plastics, meaning that the small size particles were closer to the sieve size in all three dimensions. This would add extra weight to these particles making them less prone to be carried up to the froth through hydrodynamic forces.

4.6.2 Medium Particle Size (2.37-3.36 mm)

While a flotation time test for the medium-sized particles was previously conducted, that test was not done at the optimized agitation speed of 1400 rpm. In order to accurately compare the results of the small and large-sized particles to the results of the medium-sized particles, a flotation test using all previously determined optimized parameters was needed.

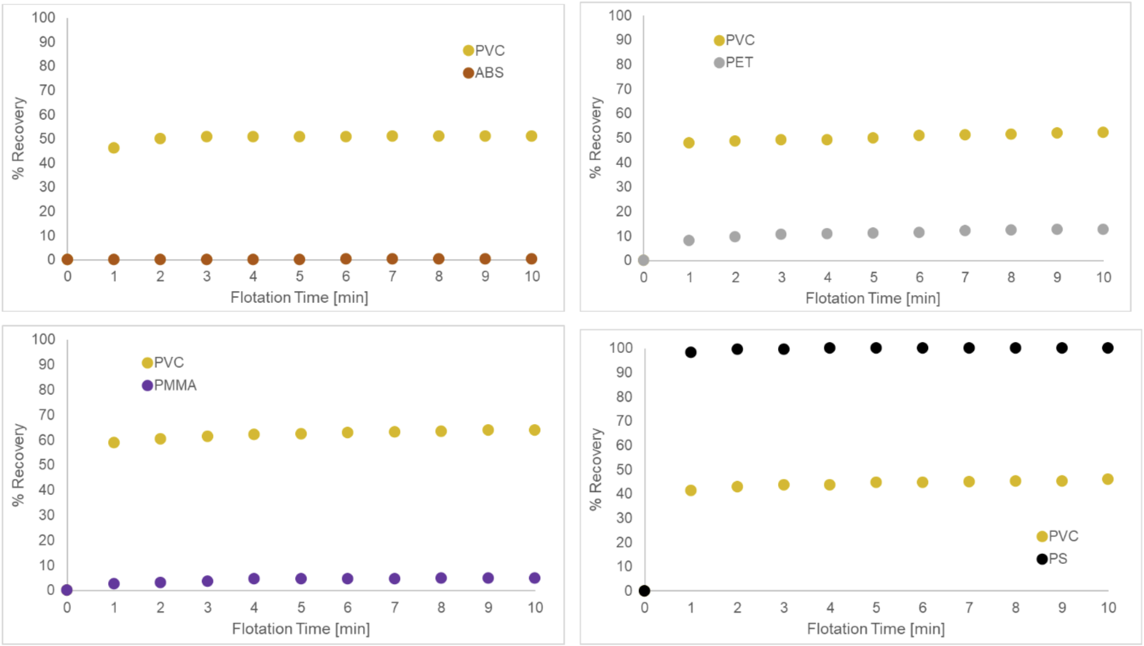


Figure 15: Flotation recovery of plastic particles of size 2.37-3.36mm as a function of flotation time.

The first flotation time test using medium plastic particles was conducted at a speed of 800 rpm where the optimal flotation time was determined to be 6 minutes. The flotation time results using the optimal agitation speed of 1400 rpm are shown in Figure 15 where the separation of each binary plastic mixture stayed constant throughout the duration of the time test. This means that a flotation time of only 1 minute is needed for medium plastic particles at high agitation speeds, significantly cutting the flotation time and machine usage down. This proves that there is a relationship between agitation speed and flotation time where flotation time decreases with an increase in agitation speed, and increases with a decrease in agitation speed.

As seen in Figure 15, the separation of PVC from ABS, PET, and PMMA significantly improved using medium-sized particles rather than the small plastic particles. However, the overall recovery of PVC dropped from roughly 90% using small particles to roughly 50% using medium-sized particles. Similar to the phenomenon noticed using small-sized particles where separation decreased and recovery increased due to their low weight and size compared to the bubble, the opposite is true for medium plastic particles. Due to the increase in particle weight, a bubble cannot easily carry the particles up into the froth unless there is a strong affinity between the bubble and the particle. This also means that the plastic particles are less prone to be carried upward by the hydrodynamic forces around the bubbles due to the increase in weight. This allows for more selectivity based on the hydrophilicity of the particles, therefore causing a decrease in overall recovery while increasing separation.

It was also noticed that under these optimized parameters, PS was recovered in the floated product whereas PVC was recovered in the sunken product. This same trend was noticed in the agitation speed tests at 800 rpm. This may be caused by two factors: its density and its uniformity. While the conditioning of plastics aims to alter the surface characteristics of each plastic to allow for separation, density also plays a vital role in which plastic is recovered from the froth. PS has the smallest density compared to all other tested plastics and has the largest difference in density from PVC. Since PS has a much smaller density than PVC and has a density much closer to that of water, it was much more likely for PS to be recovered from the froth than PVC. Another huge difference between PS and the other plastics was its uniform shape since PS was the only plastic to be obtained in pellet form. It is possible that froth flotation favors particles of uniform shape and size, however, more experimentation would need to be conducted to prove this idea.

4.6.3 Large Particle Size (3.36-4.75 mm)

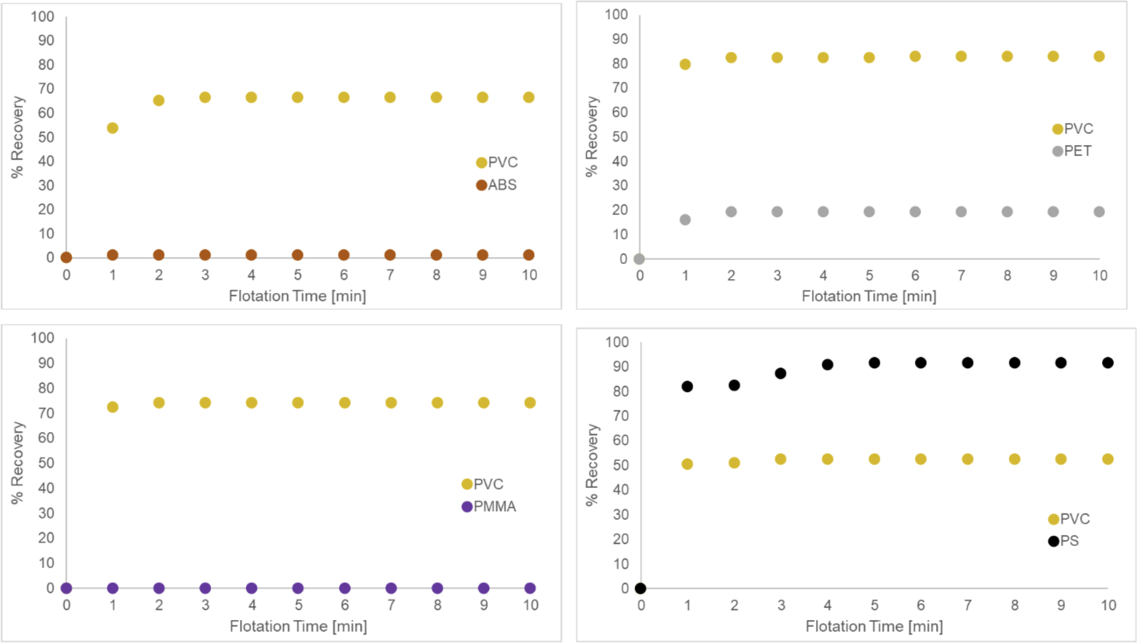


Figure 16: Flotation recovery of plastic particles of size 3.36-4.75mm as a function of flotation time.

As seen in Figure 16, the separation of PVC further improved using larger plastic particles. The same trend seen when using the medium-sized particles can be noted with the large plastic particles where the flotation time needed to reach significant recovery is reached after only a few minutes of flotation. When large particles are used in froth flotation with a relatively small bubble size, more bubbles are needed to float a singular piece of plastic. This means that the plastic must have a strong affinity to the bubbles in order to successfully float above the froth layer. The more hydrophilic plastic particles would therefore have less affinity to the bubbles, unable to collect enough to float to the surface. The added weight of the large-sized particles also makes it harder for the hydrophilic particles to accidentally float to the top through the hydrodynamic forces around the bubbles. This creates more separation between PVC and the other plastic particles, and why there is negligible recovery of the other plastics. Due to the high separation using large plastic particles, the optimal particle size was deemed to be 3.36-4.75mm. It is possible that more separation may be created using particles larger than 3.36-4.75mm, however, this idea would need further testing.

4.7 Purity

Considering all of these results, it is important to keep the goal of recycling in mind. In order to do this, it is necessary to keep the aforementioned recycling purity in mind. As stated in section 2.3.2, a 98% purity is the minimum separation necessary to properly recycle PVC. Having high purity when recycling PVC ensures no dioxins are released. After all parameters had been optimized, the purity of PVC separated from PET, ABS, PMMA, and PS mixtures were calculated to be 81.01%, 98.40%, 100%, and 38.17% respectively. This shows that the separation of PVC from ABS and PMMA were most successful and succeeded in achieving the expected 98% purity. However, the separation of PVC from PET and PS did not meet the necessary purity in order to safely recycle PVC. These results show that more parameters must be optimized before using this technique in practice.

4.8 Environmental Effects

There are many environmental aspects to consider when using this flotation device for separation. Water usage is at the forefront of environmental concerns within this process. Each test used a total of 2800 ml of water. It should also be noted that this water cannot be disposed of in a way that allows for it to go back into waterways. The chemical MIBC must be treated as a chemical waste, meaning the water can no longer be dumped down the sink. This is an immense amount of water usage and an immense amount of waste generation with each test. Testing at a larger scale would mean a lot more water usage.

Another factor that should be discussed is the effect of the impeller speed on the plastics. At high agitation rates, the plastics hit the impeller and break apart. This process creates nanoplastics that do not have the ability to be properly separated and processed at this time. As this project deals with environmentalism in terms of plastics in waterways, it seems counterproductive to introduce more microplastics into the environment. Comparing froth flotation to column flotation in this aspect, column flotation does not create this issue; it does not require an impeller. For froth flotation, the only way to minimize the amount of nanoplastics created would be to use a slower agitation speed.

The energy consumption of this machine was also considered. While the speed that created the most separation was the maximum and would require the most power usage, the flotation time at that speed is significantly reduced meaning that the machine would not need to run as long. For a minute long test, the power consumption is 0.003 kilowatt hours. The average cost of electricity in Massachusetts is 33 cents per kilowatt hour [7]. The cost to sustain the bench scale experiment for a month running 8 hours a day, 5 days a week, would be $10.34. While this seems low in cost, in practice, bench scale equipment would not be practical. Large scale equipment would use a considerable amount of energy which may become costly.

Conclusions

This project proposed the use of froth flotation as a potential scheme to selectively separate microplastics from water to allow for safe recycling. Some plastics such as PVC create poor products when recycled with other plastic types, as well as release harmful gasses when heated. This project laid the blueprint for future testing by evaluating the separation of PVC in binary mixtures including ABS, PET, PMMA, and PS. There are many factors that affect the success of froth flotation which need to be optimized to produce the most separation of PVC from other plastic types. The parameters chosen to be optimized in this project were the surfactant concentration, flotation time, conditioning time, agitation speed and particle size. After rigorous testing, the optimal parameters that created the most amount of separation were found to be a surfactant concentration of 1 g/L, flotation time of 6 minutes, conditioning time of 40 minutes, an agitation speed of 1400 rpm, and a larger particle size of 3.36-4.75 mm.

In order to safely recycle PVC plastic, a purity of 98% must be reached. The purity of PVC recovered from PET, ABS, PMMA, and PS mixtures were 81.01%, 98.40%, 100%, and 38.17% respectively. This means that the purity needed to properly recycle PVC from all plastic types was not reached under the flotation parameters tested in this project. This does not mean that froth flotation is not suitable to separate PVC from other plastics, more so that more parameters must be tested before this technique is used in practice.

Recommendations

It is strongly encouraged for another group to continue this project where it was left off. Other parameters such as pH, temperature, frother dosage, and surfactant type can be tested to increase the separation. Throughout experimentation it was noticed that PS continuously was recovered in the froth due to its low density. As a result, the use of a density separator prior to froth flotation may be necessary to remove PS from a mixed stream of plastic. This will ensure that PVC is recovered from the froth rather than PS.

The environmental effects implicated by the use of a froth flotation device were also discussed. Since the goal of selectively separating microplastics is to have the ability to properly recycle them, making sure the procedure is sustainable was important. Each test used almost a gallon of water that needed to be treated as chemical waste, creating an unnecessary amount of waste that would only increase at a larger scale. The optimal agitation speed that created the most amount of separation was also the max speed of the machine, increasing cost and the amount of nanoplastics created in the process. For this reason, it is recommended to use a slightly slower agitation speed, such as 1200 rpm instead of 1400rpm. The success rates of froth flotation using a smaller vessel size should also be tested in order to cut down on the amount of water and chemical waste created.

The cost of the electricity to run the machine was calculated to be $2.38 for an average work week. It must be considered that this was calculated using bench scale equipment and would not accurately represent what a scale up of this procedure would cost. It can be inferred that any scale up would create a considerable increase in energy usage, which in turn will drastically increase the weekly costs to run the machine.

It was expressed that the use of a bench scale froth flotation device may be used as a laboratory experiment included in the Unit Operations course at WPI. While this may be doable, the amount of tasks and time will need to be cut down to fit in the 4-hour period allotted for the lab. One of the most time consuming aspects of this project was allowing a few days for the plastic samples to dry after pre-washing or testing. It is possible to significantly decrease drying time with the use of a heat source to allow the plastics to dry at high temperatures, however, it would need to be proven that this does not affect the results. It is also recommended to have the plastic samples conditioned and dry before the start of lab to allow time for physical testing. A test that may work under the time conditions of the course while also allowing for successful analysis of the results would be the flotation time test.

To ensure the ease of experimentation, the form in which the plastic is obtained is important. Breaking down sheets of plastic was found to be significantly easier than using pellets due to their shape. It is recommended to source sheets of plastic rather than pellets if the availability of that plastic type allows for it. The color of these sourced plastics was also found to be important. Ensuring that the color of the samples do not match the color of the collection vessel, or are clear, makes sorting significantly easier.

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Appendices

Appendix A: Calculated Data

Appendix A.1: Surfactant Concentration

Table A.1.1: Surfactant Concentration Data for Binary Mixture of PVC and PET

Surfactant Concentration [g/L]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PET		PVC		PET	
	PVC	PET	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
0	4.00	3.97	3.40	85.02	3.16	79.72	0.60	14.98	0.80	20.28
0.2	4.04	3.98	1.96	48.48	2.36	59.24	2.08	51.52	1.62	40.76
0.4	4.00	3.95	0.85	21.28	1.86	47.23	3.15	78.72	2.08	52.77
0.6	3.95	3.95	0.90	22.84	1.55	39.16	3.05	77.16	2.41	60.84
0.8	3.91	3.94	2.49	63.76	2.69	68.20	1.42	36.24	1.25	31.80
1.0	4.08	3.99	3.12	76.30	2.16	54.11	0.97	23.70	1.83	45.89
1.2	3.98	4.00	3.34	83.97	2.89	72.38	0.64	16.03	1.10	27.62
1.4	3.98	3.97	3.42	85.94	3.24	81.65	0.56	14.06	0.73	18.35

A flotation time of 5 minutes, conditioning time of 40 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.1.2: Surfactant Concentration Data for Binary Mixture of PVC and ABS

Surfactant Concentration [g/L]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		ABS		PVC		ABS	
	PVC	ABS	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
0	4.01	3.99	3.33	83.11	2.42	60.76	0.68	16.89	1.57	39.24
0.2	3.99	4.01	0.92	23.08	0.15	3.77	3.07	76.92	3.86	96.23
0.4	4.11	4.07	1.57	38.04	0.67	16.48	2.55	61.96	3.40	83.52
0.6	3.90	3.94	1.04	26.60	0.79	20.10	2.86	73.40	3.15	79.90
0.8	4.17	3.98	1.49	35.77	0.52	12.96	2.68	64.23	3.47	87.04
1.0	3.96	3.92	2.29	57.92	1.34	34.13	1.67	42.08	2.58	65.87
1.2	4.09	3.98	2.27	55.56	0.97	24.41	1.82	44.44	3.01	75.59
1.4	4.00	3.99	3.33	83.30	1.96	49.02	0.67	16.70	2.04	50.98

A flotation time of 5 minutes, conditioning time of 40 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.1.3: Surfactant Concentration Data for Binary Mixture of PVC and PMMA

Surfactant Concentration [g/L]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PMMA		PVC		PMMA	
	PVC	PMMA	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
0	4.00	3.99	3.82	95.47	3.67	92.15	0.18	4.53	0.31	7.85
0.2	3.97	3.99	1.12	28.10	0.79	19.72	2.85	71.90	3.20	80.28
0.4	3.95	4.01	1.07	27.13	1.73	43.09	2.88	72.87	2.28	56.91
0.6	3.99	3.97	0.95	23.71	1.23	30.97	3.04	76.29	2.74	69.03
0.8	3.94	4.00	1.44	36.64	1.82	45.48	2.49	63.36	2.18	54.52
1.0	3.97	3.95	3.38	85.24	2.33	59.11	0.59	14.76	1.61	40.89
1.2	4.01	4.04	2.91	72.39	2.07	51.20	1.11	27.61	1.97	48.80
1.4	4.00	4.00	3.32	82.89	1.82	45.35	0.69	17.11	2.19	54.65

A flotation time of 5 minutes, conditioning time of 40 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.1.4: Surfactant Concentration Data for Binary Mixture of PVC and PS

Surfactant Concentration [g/L]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PS		PVC		PS	
	PVC	PS	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
0	4.00	3.99	3.71	92.75	2.10	52.73	0.29	7.25	1.89	47.27
0.2	3.99	4.03	1.42	35.71	1.25	31.06	2.56	64.29	2.78	68.94
0.4	3.98	3.99	1.18	29.53	0.72	18.01	2.81	70.47	3.27	81.99
0.6	4.08	3.92	1.12	27.38	0.58	14.84	2.96	72.62	3.34	85.16
0.8	3.94	4.02	1.43	36.34	0.58	14.42	2.51	63.66	3.44	85.58
1.0	3.94	3.95	1.94	49.38	0.93	23.40	1.99	50.62	3.03	76.60
1.2	3.99	3.96	2.98	74.61	2.65	67.08	1.01	25.39	1.30	32.92
1.4	4.09	4.00	3.20	78.07	2.12	52.93	0.90	21.93	1.88	47.08

A flotation time of 5 minutes, conditioning time of 40 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Appendix A.2: Flotation Time

Table A.2.1: Flotation Time Data for Binary Mixture of PVC and PET

Flotation Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PET		PVC		PET	
	PVC	PET	Weight [g]	%Recovery	Weight [g]	%Recovery	Weight [g]	%Recovery	Weight [g]	%Recovery
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	4.05	3.94	0.52	12.79	1.08	27.49	3.53	87.21	2.86	72.51
2	4.05	3.94	1.49	36.88	1.96	49.70	2.56	63.12	1.98	50.30
3	4.05	3.94	2.35	57.99	2.51	63.78	1.70	42.01	1.43	36.22
4	4.05	3.94	2.97	73.22	3.26	82.69	1.09	26.78	0.68	17.31
5	4.05	3.94	3.27	80.70	3.49	88.48	0.78	19.30	0.45	11.52
6	4.05	3.94	3.35	82.79	3.62	91.83	0.70	17.21	0.32	8.17
7	4.05	3.94	3.43	84.55	3.66	92.82	0.63	15.45	0.28	7.18
8	4.05	3.94	3.57	88.00	3.72	94.31	0.49	12.00	0.22	5.69
9	4.05	3.94	3.59	88.50	3.73	94.70	0.47	11.50	0.21	5.30
10	4.05	3.94	3.59	88.50	3.93	99.77	0.47	11.50	0.01	0.23

A surfactant concentration of 1g/L, conditioning time of 40 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.2.2: Flotation Time Data for Binary Mixture of PVC and ABS

Flotation Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		ABS		PVC		ABS	
	PVC	ABS	Weight [g]	%Recovery	Weight [g]	%Recovery	Weight [g]	%Recovery	Weight [g]	%Recovery
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	4.00	4.01	0.27	6.63	0.04	1.02	3.73	93.37	3.97	98.98
2	4.00	4.01	0.84	21.06	0.05	1.35	3.16	78.94	3.96	98.65
3	4.00	4.01	1.38	34.47	0.16	3.99	2.62	65.53	3.85	96.01
4	4.00	4.01	2.21	55.35	0.24	6.08	1.79	44.65	3.77	93.92
5	4.00	4.01	2.53	63.16	0.35	8.70	1.47	36.84	3.66	91.30
6	4.00	4.01	3.24	80.99	0.48	11.89	0.76	19.01	3.54	88.11
7	4.00	4.01	3.30	82.52	0.49	12.19	0.70	17.48	3.52	87.81
8	4.00	4.01	3.32	83.04	0.51	12.76	0.68	16.96	3.50	87.24
9	4.00	4.01	3.38	84.57	0.54	13.53	0.62	15.43	3.47	86.47
10	4.00	4.01	3.40	84.99	0.54	13.53	0.60	15.01	3.47	86.47

A surfactant concentration of 1g/L, conditioning time of 40 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.2.3: Flotation Time Data for Binary Mixture of PVC and PMMA

Flotation Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PMMA		PVC		PMMA	
	PVC	PMMA	Weight [g]	%Recovery	Weight [g]	%Recovery	Weight [g]	%Recovery	Weight [g]	%Recovery
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	4.09	4.01	1.05	25.67	0.60	14.96	3.04	74.33	3.41	85.04
2	4.09	4.01	2.10	51.34	1.32	32.88	1.99	48.66	2.69	67.12
3	4.09	4.01	3.05	74.47	2.63	65.55	1.04	25.53	1.38	34.45
4	4.09	4.01	3.35	81.96	3.19	79.49	0.74	18.04	0.82	20.51
5	4.09	4.01	3.46	84.47	3.52	87.71	0.63	15.53	0.49	12.29
6	4.09	4.01	3.48	85.18	3.63	90.35	0.61	14.82	0.39	9.65
7	4.09	4.01	3.50	85.67	3.66	91.33	0.59	14.33	0.35	8.67
8	4.09	4.01	3.50	85.67	3.66	91.33	0.59	14.33	0.35	8.67
9	4.09	4.01	3.50	85.67	3.66	91.33	0.59	14.33	0.35	8.67
10	4.09	4.01	3.52	86.06	3.66	91.33	0.57	13.94	0.35	8.67

A surfactant concentration of 1g/L, conditioning time of 40 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.2.4: Flotation Time Data for Binary Mixture of PVC and PS

Flotation Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PS		PVC		PS	
	PVC	PS	Weight [g]	%Recovery	Weight [g]	%Recovery	Weight [g]	%Recovery	Weight [g]	%Recovery
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	3.95	3.98	0.41	10.42	0.41	10.41	3.54	89.58	3.56	89.59
2	3.95	3.98	0.91	22.92	0.69	17.22	3.05	77.08	3.29	82.78
3	3.95	3.98	1.53	38.76	0.75	18.80	2.42	61.24	3.23	81.20
4	3.95	3.98	1.93	48.72	0.90	22.55	2.03	51.28	3.08	77.45
5	3.95	3.98	2.44	61.75	1.05	26.42	1.51	38.25	2.93	73.58
6	3.95	3.98	2.57	65.12	1.19	29.96	1.38	34.88	2.79	70.04
7	3.95	3.98	2.87	72.50	1.35	33.96	1.09	27.50	2.63	66.04
8	3.95	3.98	3.16	79.94	1.49	37.33	0.79	20.06	2.49	62.67
9	3.95	3.98	3.26	82.52	1.56	39.32	0.69	17.48	2.41	60.68
10	3.95	3.98	3.27	82.80	1.76	44.34	0.68	17.20	2.21	55.66

A surfactant concentration of 1g/L, conditioning time of 40 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Appendix A.3: Conditioning Time

Table A.3.1: Conditioning Time Data for Binary Mixture of PVC and PET

Conditioning Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PET		PVC		PET	
	PVC	PET	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
0	4.00	3.97	3.98	99.57	3.77	95.13	0.02	0.43	0.19	4.87
10	4.00	4.08	3.78	94.46	3.44	84.31	0.22	5.54	0.64	15.69
20	3.99	3.93	3.99	99.92	3.79	96.48	0.00	0.08	0.14	3.52
30	4.02	4.01	3.74	93.23	3.55	88.59	0.27	6.77	0.46	11.41
40	3.99	4.01	3.76	94.38	3.42	85.38	0.22	5.62	0.59	14.62
50	4.06	4.00	4.00	98.42	3.70	92.69	0.06	1.58	0.29	7.31
60	4.00	4.01	4.00	100.00	3.91	97.36	0.00	0.00	0.11	2.64

A surfactant concentration of 1g/L, flotation time of 6 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.3.2: Conditioning Time Data for Binary Mixture of PVC and ABS

Conditioning Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		ABS		PVC		ABS	
	PVC	ABS	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
0	4.01	3.99	3.85	96.06	3.24	81.24	0.16	3.94	0.75	18.76
10	3.99	3.94	3.93	98.52	0.98	24.78	0.06	1.48	2.97	75.22
20	4.00	3.96	3.83	95.65	2.69	67.96	0.17	4.35	1.27	32.04
30	4.00	4.02	3.86	96.40	1.85	46.18	0.14	3.60	2.16	53.82
40	4.00	4.10	3.96	99.10	2.55	62.35	0.04	0.90	1.54	37.65
50	3.98	3.96	3.93	98.57	2.50	63.30	0.06	1.43	1.45	36.70
60	4.00	3.98	3.98	99.72	3.67	92.35	0.01	0.28	0.30	7.65

A surfactant concentration of 1g/L, flotation time of 6 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.3.3: Conditioning Time Data for Binary Mixture of PVC and PMMA

Conditioning Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PMMA		PVC		PMMA	
	PVC	PMMA	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
0	4.00	3.99	3.97	99.25	3.90	97.97	0.03	0.75	0.08	2.03
10	3.99	3.99	3.96	99.27	3.94	98.85	0.03	0.73	0.05	1.15
20	4.01	4.02	3.89	97.18	3.38	83.98	0.11	2.82	0.64	16.02
30	4.02	3.99	4.00	99.48	3.49	87.26	0.02	0.52	0.51	12.74
40	3.97	4.01	3.90	98.28	3.28	81.77	0.07	1.72	0.73	18.23
50	4.00	3.97	3.74	93.50	2.25	56.83	0.26	6.50	1.71	43.17
60	4.00	3.99	3.99	99.92	3.95	99.05	0.00	0.08	0.04	0.95

A surfactant concentration of 1g/L, flotation time of 6 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.3.4: Conditioning Time Data for Binary Mixture of PVC and PS

Conditioning Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PS		PVC		PS	
	PVC	PS	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
0	4.00	3.99	3.91	97.90	2.59	64.94	0.08	2.10	1.40	35.06
10	3.99	3.95	3.98	99.62	3.95	100.00	0.02	0.38	0.00	0.00
20	4.00	3.91	3.58	89.36	2.05	52.43	0.43	10.64	1.86	47.57
30	4.01	3.98	3.89	97.08	2.95	74.09	0.12	2.92	1.03	25.91
40	4.00	4.00	3.67	91.71	2.60	64.98	0.33	8.29	1.40	35.02
50	3.99	3.97	3.78	94.83	2.91	73.28	0.21	5.17	1.06	26.72
60	4.04	4.01	4.00	98.94	3.52	87.71	0.04	1.06	0.49	12.29

A surfactant concentration of 1g/L, flotation time of 6 minutes, agitation speed of 800 rpm, and particle size of 2.37-3.36mm was used for this test until later optimized.

Appendix A.4: Agitation Speed

Table A.4.1: Agitation Speed Data for Binary Mixture of PVC and PET

Agitation Speed [rpm]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PET		PVC		PET	
	PVC	PET	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
800	3.99	4.01	3.76	94.38	3.42	85.38	0.22	5.62	0.59	14.62
1000	3.98	3.97	3.68	92.49	3.92	98.59	0.30	7.51	0.06	1.41
1200	3.95	4.00	2.98	75.52	2.61	65.23	0.97	24.48	1.39	34.77
1400	3.88	3.97	3.19	82.16	1.06	26.80	0.69	17.84	2.91	73.20

A surfactant concentration of 1g/L, flotation time of 6 minutes, conditioning time of 40 minutes and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.4.2: Agitation Speed Data for Binary Mixture of PVC and ABS

Agitation Speed [rpm]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		ABS		PVC		ABS	
	PVC	ABS	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
800	4.00	4.10	3.96	99.10	2.55	62.35	0.04	0.90	1.54	37.65
1000	4.01	3.99	3.96	98.75	3.66	91.78	0.05	1.25	0.33	8.22
1200	4.00	4.09	2.98	74.58	0.30	7.34	1.02	25.42	3.79	92.66
1400	3.99	3.99	2.38	59.57	0.04	0.93	1.61	40.43	3.95	99.07

A surfactant concentration of 1g/L, flotation time of 6 minutes, conditioning time of 40 minutes and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.4.3: Agitation Speed Data for Binary Mixture of PVC and PMMA

Agitation Speed [rpm]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PMMA		PVC		PMMA	
	PVC	PMMA	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
800	3.97	4.01	3.90	98.28	3.28	81.77	0.07	1.72	0.73	18.23
1000	3.97	4.02	3.79	95.47	3.94	97.89	0.18	4.53	0.09	2.11
1200	3.99	4.00	3.43	85.82	1.26	31.55	0.57	14.18	2.74	68.45
1400	3.98	4.00	1.09	27.31	0.00	0.00	2.89	72.69	4.00	100.00

A surfactant concentration of 1g/L, flotation time of 6 minutes, conditioning time of 40 minutes and particle size of 2.37-3.36mm was used for this test until later optimized.

Table A.4.4: Agitation Speed Data for Binary Mixture of PVC and PS

Agitation Speed [rpm]	Initial Weight [g]		Floated Product				Sunken Product			
			PVC		PS		PVC		PS	
	PVC	PS	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
800	4.00	4.00	3.67	91.71	2.60	64.98	0.33	8.29	1.40	35.02
1000	4.06	3.98	4.05	99.75	3.98	100.00	0.01	0.25	0.00	0.00
1200	3.96	3.99	3.12	78.67	3.76	94.06	0.85	21.33	0.24	5.94
1400	4.08	3.98	2.47	60.47	3.98	100.00	1.61	39.53	0.00	0.00

A surfactant concentration of 1g/L, flotation time of 6 minutes, conditioning time of 40 minutes and particle size of 2.37-3.36mm was used for this test until later optimized.

Appendix A.5: Particle Size

Table A.5.1: Particle Size Data for Binary Mixture of PVC and PET

Particle Size	Flotation Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
				PVC		PET		PVC		PET	
		PVC	PET	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
Small	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.92	3.94	3.26	83.07	1.71	43.35	0.66	16.93	2.23	56.65
	2	3.92	3.94	3.61	91.97	2.25	56.98	0.32	8.03	1.70	43.02
	3	3.92	3.94	3.67	93.65	2.44	61.82	0.25	6.35	1.51	38.18
	4	3.92	3.94	3.71	94.65	2.56	65.04	0.21	5.35	1.38	34.96
	5	3.92	3.94	3.72	94.95	2.61	66.16	0.20	5.05	1.33	33.84
	6	3.92	3.94	3.74	95.28	2.64	66.84	0.19	4.72	1.31	33.16
	7	3.92	3.94	3.74	95.33	2.65	67.33	0.18	4.67	1.29	32.67
	8	3.92	3.94	3.74	95.39	2.67	67.78	0.18	4.61	1.27	32.22
	9	3.92	3.94	3.74	95.39	2.68	68.04	0.18	4.61	1.26	31.96
	10	3.92	3.94	3.74	95.41	2.69	68.26	0.18	4.59	1.25	31.74
Medium	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.89	3.99	1.87	48.06	0.33	8.25	2.02	51.94	3.66	91.75
	2	3.89	3.99	1.90	48.78	0.38	9.63	1.99	51.22	3.60	90.37
	3	3.89	3.99	1.92	49.24	0.42	10.56	1.98	50.76	3.57	89.44
	4	3.89	3.99	1.92	49.34	0.43	10.84	1.97	50.66	3.55	89.16
	5	3.89	3.99	1.94	49.94	0.45	11.24	1.95	50.06	3.54	88.76
	6	3.89	3.99	1.99	51.01	0.46	11.47	1.91	48.99	3.53	88.53
	7	3.89	3.99	2.00	51.27	0.49	12.19	1.90	48.73	3.50	87.81
	8	3.89	3.99	2.01	51.61	0.49	12.37	1.88	48.39	3.49	87.63
	9	3.89	3.99	2.03	52.04	0.51	12.69	1.87	47.96	3.48	87.31
	10	3.89	3.99	2.03	52.22	0.51	12.69	1.86	47.78	3.48	87.31
Large	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.98	3.99	3.17	79.65	0.64	16.03	0.81	20.35	3.35	83.97
	2	3.98	3.99	3.28	82.34	0.77	19.26	0.70	17.66	3.22	80.74
	3	3.98	3.99	3.28	82.34	0.77	19.26	0.70	17.66	3.22	80.74
	4	3.98	3.99	3.28	82.34	0.77	19.26	0.70	17.66	3.22	80.74
	5	3.98	3.99	3.28	82.34	0.77	19.26	0.70	17.66	3.22	80.74
	6	3.98	3.99	3.30	82.81	0.77	19.26	0.68	17.19	3.22	80.74
	7	3.98	3.99	3.30	82.81	0.77	19.26	0.68	17.19	3.22	80.74
	8	3.98	3.99	3.30	82.81	0.77	19.26	0.68	17.19	3.22	80.74
	9	3.98	3.99	3.30	82.81	0.77	19.26	0.68	17.19	3.22	80.74
	10	3.98	3.99	3.30	82.81	0.77	19.26	0.68	17.19	3.22	80.74

A surfactant concentration of 1g/L, flotation time of 6 minutes, conditioning time of 40 minutes and particle size of 1.19-2.37mm (small), 2.37-3.36mm (medium), and 3.36-4.75mm (large).

Table A.5.2: Particle Size Data for Binary Mixture of PVC and ABS

Particle Size	Flotation Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
				PVC		ABS		PVC		ABS	
		PVC	ABS	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
Small	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	4.01	3.98	3.41	85.15	0.47	11.80	0.60	14.85	3.51	88.20
	2	4.01	3.98	3.56	88.75	0.53	13.31	0.45	11.25	3.45	86.69
	3	4.01	3.98	3.65	91.09	0.57	14.24	0.36	8.91	3.41	85.76
	4	4.01	3.98	3.66	91.34	0.57	14.24	0.35	8.66	3.41	85.76
	5	4.01	3.98	3.67	91.49	0.57	14.24	0.34	8.51	3.41	85.76
	6	4.01	3.98	3.67	91.54	0.57	14.24	0.34	8.46	3.41	85.76
	7	4.01	3.98	3.67	91.57	0.57	14.36	0.34	8.43	3.40	85.64
	8	4.01	3.98	3.67	91.59	0.57	14.42	0.34	8.41	3.40	85.58
	9	4.01	3.98	3.67	91.62	0.57	14.42	0.34	8.38	3.40	85.58
	10	4.01	3.98	3.67	91.67	0.57	14.42	0.33	8.33	3.40	85.58
Medium	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	4.02	4.00	1.86	46.27	0.00	0.00	2.16	53.73	4.00	100.00
	2	4.02	4.00	2.01	50.02	0.00	0.00	2.01	49.98	4.00	100.00
	3	4.02	4.00	2.04	50.70	0.00	0.00	1.98	49.30	4.00	100.00
	4	4.02	4.00	2.04	50.70	0.00	0.00	1.98	49.30	4.00	100.00
	5	4.02	4.00	2.04	50.70	0.00	0.00	1.98	49.30	4.00	100.00
	6	4.02	4.00	2.05	50.92	0.01	0.20	1.97	49.08	3.99	99.80
	7	4.02	4.00	2.05	51.07	0.01	0.20	1.97	48.93	3.99	99.80
	8	4.02	4.00	2.05	51.07	0.01	0.20	1.97	48.93	3.99	99.80
	9	4.02	4.00	2.05	51.07	0.01	0.20	1.97	48.93	3.99	99.80
	10	4.02	4.00	2.06	51.12	0.01	0.20	1.97	48.88	3.99	99.80
Large	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.98	3.98	2.14	53.78	0.04	1.06	1.84	46.22	3.94	98.94
	2	3.98	3.98	2.59	65.03	0.04	1.06	1.39	34.97	3.94	98.94
	3	3.98	3.98	2.64	66.33	0.04	1.06	1.34	33.67	3.94	98.94
	4	3.98	3.98	2.64	66.33	0.04	1.06	1.34	33.67	3.94	98.94
	5	3.98	3.98	2.64	66.33	0.04	1.06	1.34	33.67	3.94	98.94
	6	3.98	3.98	2.64	66.33	0.04	1.06	1.34	33.67	3.94	98.94
	7	3.98	3.98	2.64	66.33	0.04	1.06	1.34	33.67	3.94	98.94
	8	3.98	3.98	2.64	66.33	0.04	1.06	1.34	33.67	3.94	98.94
	9	3.98	3.98	2.64	66.33	0.04	1.06	1.34	33.67	3.94	98.94
	10	3.98	3.98	2.64	66.33	0.04	1.06	1.34	33.67	3.94	98.94

A surfactant concentration of 1g/L, flotation time of 6 minutes, conditioning time of 40 minutes and particle size of 1.19-2.37mm (small), 2.37-3.36mm (medium), and 3.36-4.75mm (large).

Table A.5.3: Particle Size Data for Binary Mixture of PVC and PMMA

Particle Size	Flotation Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
				PVC		PMMA		PVC		PMMA	
		PVC	PMMA	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
Small	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.98	3.97	3.11	78.09	2.24	56.43	0.87	21.91	1.73	43.57
	2	3.98	3.97	3.63	91.31	2.86	71.94	0.35	8.69	1.12	28.06
	3	3.98	3.97	3.79	95.28	3.00	75.38	0.19	4.72	0.98	24.62
	4	3.98	3.97	3.90	97.89	3.10	77.90	0.08	2.11	0.88	22.10
	5	3.98	3.97	3.91	98.14	3.10	78.05	0.07	1.86	0.87	21.95
	6	3.98	3.97	3.92	98.44	3.11	78.30	0.06	1.56	0.86	21.70
	7	3.98	3.97	3.93	98.64	3.12	78.50	0.05	1.36	0.85	21.50
	8	3.98	3.97	3.93	98.82	3.13	78.76	0.05	1.18	0.84	21.24
	9	3.98	3.97	3.94	99.02	3.13	78.83	0.04	0.98	0.84	21.17
	10	3.98	3.97	3.95	99.35	3.15	79.21	0.03	0.65	0.83	20.79
Medium	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	4.00	4.00	2.35	58.83	0.11	2.65	1.65	41.18	3.89	97.35
	2	4.00	4.00	2.42	60.43	0.12	3.08	1.58	39.58	3.87	96.92
	3	4.00	4.00	2.45	61.28	0.14	3.50	1.55	38.73	3.86	96.50
	4	4.00	4.00	2.49	62.18	0.19	4.65	1.51	37.83	3.81	95.35
	5	4.00	4.00	2.50	62.50	0.19	4.65	1.50	37.50	3.81	95.35
	6	4.00	4.00	2.52	62.93	0.19	4.65	1.48	37.08	3.81	95.35
	7	4.00	4.00	2.52	63.10	0.19	4.65	1.48	36.90	3.81	95.35
	8	4.00	4.00	2.54	63.45	0.20	4.95	1.46	36.55	3.80	95.05
	9	4.00	4.00	2.56	64.03	0.20	4.95	1.44	35.98	3.80	95.05
	10	4.00	4.00	2.56	64.03	0.20	4.95	1.44	35.98	3.80	95.05
Large	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.99	3.95	2.89	72.45	0.00	0.00	1.10	27.55	3.95	100.00
	2	3.99	3.95	2.97	74.25	0.00	0.00	1.03	25.75	3.95	100.00
	3	3.99	3.95	2.97	74.25	0.00	0.00	1.03	25.75	3.95	100.00
	4	3.99	3.95	2.97	74.25	0.00	0.00	1.03	25.75	3.95	100.00
	5	3.99	3.95	2.97	74.25	0.00	0.00	1.03	25.75	3.95	100.00
	6	3.99	3.95	2.97	74.25	0.00	0.00	1.03	25.75	3.95	100.00
	7	3.99	3.95	2.97	74.25	0.00	0.00	1.03	25.75	3.95	100.00
	8	3.99	3.95	2.97	74.25	0.00	0.00	1.03	25.75	3.95	100.00
	9	3.99	3.95	2.97	74.25	0.00	0.00	1.03	25.75	3.95	100.00
	10	3.99	3.95	2.97	74.25	0.00	0.00	1.03	25.75	3.95	100.00

A surfactant concentration of 1g/L, flotation time of 6 minutes, conditioning time of 40 minutes and particle size of 1.19-2.37mm (small), 2.37-3.36mm (medium), and 3.36-4.75mm (large).

Table A.5.4: Particle Size Data for Binary Mixture of PVC and PS

Particle Size	Flotation Time [min]	Initial Weight [g]		Floated Product				Sunken Product			
				PVC		PS		PVC		PS	
		PVC	PS	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery	Weight [g]	% Recovery
Small	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.99	3.97	3.08	77.05	2.48	62.53	0.92	22.95	1.49	37.47
	2	3.99	3.97	3.40	85.12	3.06	77.08	0.59	14.88	0.91	22.92
	3	3.99	3.97	3.50	87.58	3.29	82.93	0.50	12.42	0.68	17.07
	4	3.99	3.97	3.53	88.33	3.37	84.97	0.47	11.67	0.60	15.03
	5	3.99	3.97	3.54	88.58	3.40	85.72	0.46	11.42	0.57	14.28
	6	3.99	3.97	3.55	88.83	3.44	86.50	0.45	11.17	0.54	13.50
	7	3.99	3.97	3.55	89.00	3.45	86.91	0.44	11.00	0.52	13.09
	8	3.99	3.97	3.55	89.00	3.48	87.58	0.44	11.00	0.49	12.42
	9	3.99	3.97	3.56	89.05	3.52	88.74	0.44	10.95	0.45	11.26
	10	3.99	3.97	3.56	89.13	3.57	89.80	0.43	10.87	0.41	10.20
Medium	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	4.02	3.98	1.66	41.30	3.91	98.32	2.36	58.70	0.07	1.68
	2	4.02	3.98	1.73	43.04	3.96	99.55	2.29	56.96	0.02	0.45
	3	4.02	3.98	1.76	43.79	3.96	99.55	2.26	56.21	0.02	0.45
	4	4.02	3.98	1.76	43.79	3.98	100.00	2.26	56.21	0.00	0.00
	5	4.02	3.98	1.80	44.76	3.98	100.00	2.22	55.24	0.00	0.00
	6	4.02	3.98	1.80	44.76	3.98	100.00	2.22	55.24	0.00	0.00
	7	4.02	3.98	1.81	44.98	3.98	100.00	2.21	55.02	0.00	0.00
	8	4.02	3.98	1.81	45.16	3.98	100.00	2.20	54.84	0.00	0.00
	9	4.02	3.98	1.82	45.35	3.98	100.00	2.19	54.65	0.00	0.00
	10	4.02	3.98	1.85	45.98	3.98	100.00	2.17	54.02	0.00	0.00
Large	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.98	3.99	2.00	50.35	3.27	81.88	1.97	49.65	0.72	18.12
	2	3.98	3.99	2.03	51.02	3.29	82.34	1.95	48.98	0.71	17.66
	3	3.98	3.99	2.09	52.53	3.49	87.32	1.89	47.47	0.51	12.68
	4	3.98	3.99	2.09	52.53	3.63	90.85	1.89	47.47	0.37	9.15
	5	3.98	3.99	2.09	52.53	3.65	91.43	1.89	47.47	0.34	8.57
	6	3.98	3.99	2.09	52.53	3.65	91.43	1.89	47.47	0.34	8.57
	7	3.98	3.99	2.09	52.53	3.65	91.43	1.89	47.47	0.34	8.57
	8	3.98	3.99	2.09	52.53	3.65	91.43	1.89	47.47	0.34	8.57
	9	3.98	3.99	2.09	52.53	3.65	91.43	1.89	47.47	0.34	8.57
	10	3.98	3.99	2.09	52.53	3.65	91.43	1.89	47.47	0.34	8.57

A surfactant concentration of 1g/L, flotation time of 6 minutes, conditioning time of 40 minutes and particle size of 1.19-2.37mm (small), 2.37-3.36mm (medium), and 3.36-4.75mm (large).

Appendix B: Sample Calculations

The following sample calculations are based on the surfactant concentration test of PVC and PET at a surfactant concentration of 1 g/L. Please see Table A.1.1.

The floated product weight of each plastic in the binary mixture was determined experimentally by manually separating the product and weighing each plastic type.

<u>Percent Recovery: Floated Product</u>

$$\% \, Recovery_{PVC} = \frac{recovered\ PVC}{initial\ PVC} \ x\ 100 = \frac{3.12g}{4.08g} \ x\ 100 = 0.7630 = 76.30\%$$

$$\% \, Recovery_{PET} = \frac{recovered\ PET}{initial\ PET} \ x\ 100 = \frac{2.16g}{3.99g} \ x\ 100 = 0.5411 = 54.11\%$$

The sunken product weight was determined by assuming no loss in mass. Therefore…

$$weight_{sunk} = weight_{initial} - weight_{float}$$

<u>Percent Recovery: Sunken Product</u>

$$\% \, Recovery_{PVC} = \frac{recovered\ PVC}{initial\ PVC} \ x\ 100 = \frac{0.97g}{4.08g} \ x\ 100 = 0.2370 = 23.70\%$$

$$\% \, Recovery_{PET} = \frac{recovered\ PET}{initial\ PET} \ x\ 100 = \frac{1.83g}{3.99g} \ x\ 100 = 0.4589 = 45.89\%$$

<u>Purity: Floated Product</u>

$$Purity_{PVC} = \frac{recovered_{PVC}}{recovered_{PVC} + recovered_{PET}} \ x\ 100 \ = \ \frac{3.12g}{3.12g + 2.16g} \ x\ 100 \ = 0.5909 = 59.09\%$$

**Note: the purity of the floated product stream was only calculated after all flotation factors were optimized to determine the ability for recycling.

<u>Cost Calculations</u>

The following calculations were based on a one minute test run at 1400 rpm. An assumption of 33 cents per kilowatt hour was used to complete these calculations.

<u>Energy consumption in a work week</u>

$Energy = 2400\, minutes\ x\ 0.003kWh/minute = 7.2kWh/work\ week$

<u>Cost in a work week</u>

$Cost = 7.2kWh\ x\ 0.33cents/kWh = \$2.38$