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1 **Development of the reverse hybrid jig: Separation of polyethylene and cross-linked**
2 **polyethylene from eco-cable wire**

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4 Mayumi Ito ^{1,*}, Ayumu Saito ², Megumi Takeuchi ², Nana Murase ²,

5 Theerayut Phengsaart ^{2,3}, Carlito Baltazar Tabelin ^{1,4} and Naoki Hiroyoshi ¹

6

7 ¹ Division of Sustainable Resources Engineering, Faculty of Engineering, Hokkaido
8 University, Kita 13, Nishi 8, Kita-ku, Sapporo 060-8628, Japan

9 ² Division of Sustainable Resources Engineering, Graduate School of Engineering,
10 Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo 060-8628, Japan

11 ³ Department of Mining and Petroleum Engineering, Faculty of Engineering,
12 Chulalongkorn University, Bangkok 10330, Thailand

13 ⁴ School of Minerals and Energy Resources Engineering, The University of New South
14 Wales, Sydney, NSW 2052, Australia

15 * Corresponding author e-mail: itomayu@eng.hokudai.ac.jp

16

17 **Abstract**

18 We have developed various types of jigs for resources recycling focusing
19 primarily on plastic-plastic separation. The RETAC jig could be used to separate plastics
20 heavier than water (specific gravity (SG) > 1.0) with different SGs while the hybrid jig—
21 a process combining jig and flotation—was developed to separate plastics with similar
22 SGs but different surface wettabilities. Meanwhile the reverse jig—a RETAC jig with a
23 top screen—is used to separate plastics lighter than water with different SGs.

24 In this study, a novel method that combines the principle of reverse and hybrid
25 jig, called “reverse hybrid jig separation” was developed to separate plastics lighter than
26 water having similar SGs but different surface wettabilities. The tests were carried out
27 with wastes from an eco-cable wire recycling facility in Japan, which is composed of
28 polyethylene (PE) and cross-linked polyethylene (XLPE). The reverse hybrid jig
29 separation results showed that bubble attachment to and detachment from plastic particles
30 could affect separation efficiency. In addition, the effects of particle size on separation
31 efficiency were also evaluated.

32

33 **Keywords:** Recycling, jig, reverse hybrid jig, plastic separation, polyolefin

34

35 **1. Introduction**

36 Plastics have become ubiquitous in our daily life with applications ranging from
37 simple packaging materials to more complicated applications in electronic devices and
38 automobiles (Jeon et al., 2018a; Tabelin et al., 2021a; Thiounn and Smith, 2020). The
39 total production and consumption of plastics, including waste generation, have increased
40 over the last couple of decades (Plastic waste partnership working group, 2020).

41 Fossil fuel-based plastics are further classified into either thermoplastic or
42 thermosets. Thermoplastics are polymers that soften when heated and solidify upon
43 cooling, a property that allows them to be remolded and recycled (i.e., material recycling).
44 In contrast, thermosets are polymers that set into a mold once and cannot be re-softened
45 or remolded again (Plastic waste partnership working group, 2020).

46 There are two common types of plastic recycling: (1) material recycling wherein
47 plastics are recovered and reused, and (2) thermal recycling whereby plastics are used as
48 fuel for power generation. Thermal recycling is more widely used to manage plastic
49 wastes than material recycling. However, some plastics like polyvinyl chloride (PVC),
50 are unsuitable for thermal treatment because they could generate harmful compounds like
51 chlorine gas (Cl_2) and dioxins that have adverse effects to industrial processes, the
52 environment and human health, so they usually end up in landfills (Ito et al., 2019a;

53 Tabelin et al., 2021b; Phengsaart et al, 2018).

54 Aside from challenges in recycling PVCs, this plastic also contains tribase—a
55 lead compound added into PVC as a thermal stabilizer (Tsunekawa et al., 2011). Lead is
56 a toxic heavy metal notorious for causing irreversible damage to the still-developing
57 nervous systems of fetus, babies and children (Silwamba et al., 2020a, b; Tabelin et al.,
58 2018, 2020). Because of this, the use of PVC as sheath and insulation of electric wires
59 has been gradually replaced by more eco-friendly plastics and are marketed as “eco-
60 cables”. An eco-cable is an environmentally benign electric wire/cable that uses
61 environmentally friendly materials and materials with a reduced environmental footprint
62 like polyethylene (PE) and cross-linked polyethylene (XLPE) (Mo et al., 2013).

63 Among the many types of plastics, polyolefin—plastics that have a specific
64 gravity (SG) lower than water (< 1)—are the most popular class of plastics (Plastic waste
65 partnership working group, 2020). These include polypropylene (PP) and polyethylene
66 (including low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE),
67 Medium-density polyethylene (MDPE), and high-density polyethylene (HDPE)), and in
68 2018, PlasticsEurope (2019) reported that PP, LDPE/LLDPE, and HDPE/MDPE
69 constituted 19.3%, 17.5%, and 12.2%, respectively of overall global plastic consumption.

70 XLPE is a variant of PE (usually HDPE) that was modified by using organic

71 peroxides, ionizing radiation or silane compounds to create cross-linking polymeric
72 chains and change PE from being thermoplastic to become thermoset (Bang et al., 2004).
73 XLPE does not melt at 120°C and has better thermal stability, mechanical strength and
74 corrosion resistance compared with PE. Because of its thermosetting property, XLPE
75 cannot be recycled together with PE via conventional melting. XLPE can, however, be
76 recycled via other methods like powdered filler recycling—an approach using
77 pulverization and co-melting with other thermoplastics—to produce filler materials
78 (Bang et al., 2004), supercritical fluid processing method using thermo-plasticizing
79 technology for de-crosslinking (Goto et al., 2011; Tokuda et al., 2003) and pyrolysis (Mo
80 et al., 2013).

81 Because XLPE cannot be recycled together with PE, the separation of these
82 plastics for more efficient recycling is required. Majority of plastic-plastic separation
83 methods used today are based on separation techniques developed in mineral processing
84 (Hori et al., 2009a, 2009b; Ito et al., 2010, 2019a, 2019b, 2020; Phengsaart et al., 2020;
85 Tsunekawa et al., 2005, 2012) while metal separation-extraction strategies for mixed
86 metal-plastic wastes like E-wastes are modified from hydrometallurgy (Calderon et al.,
87 2020; Choi et al., 2020, 2021; Jeon et al., 2018b, 2020a, 2020b) or pyrometallurgy (Inano
88 et al., 2019). Among all separation methods, jig separation—a type of gravity separation

89 that separate the particles based on their motion in fluid—is one of the oldest and most
90 widely used in mineral processing especially for coal cleaning because of its simple
91 operation, low cost and high efficiency (Tsunekawa et al., 2005).

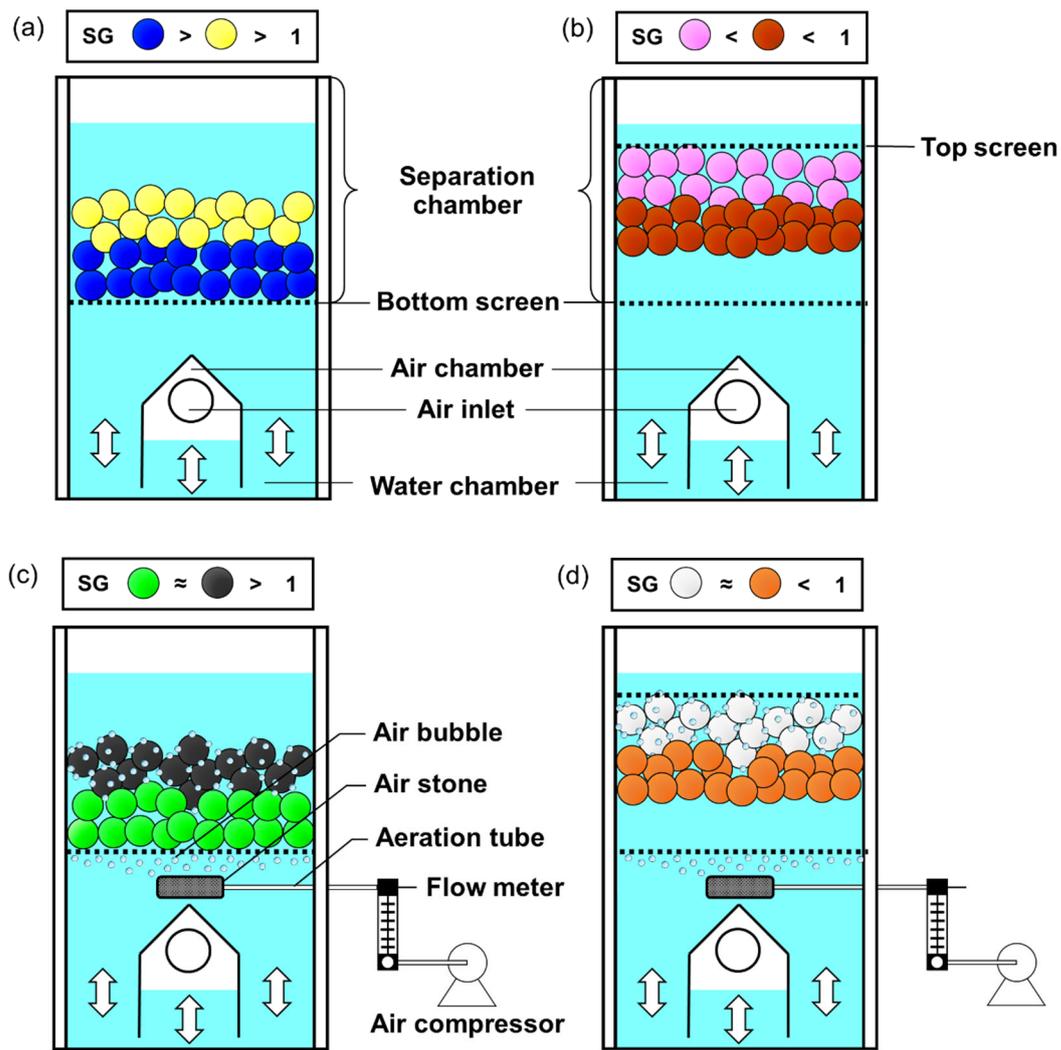
92 The authors have developed the RETAC jig (Fig. 1 (a)) for plastic recycling and
93 modified the RETAC jig into a reverse jig (Fig. 1 (b)) and a hybrid jig (Fig. 1 (c)) (Hori
94 et al., 2009a, 2009b; Ito et al., 2010, 2019a, 2019b, 2020; Tsunekawa et al., 2005, 2012).

95 The reverse jig can separate plastics floating on the water surface (Ito et al., 2010) while
96 the hybrid jig can separate plastics having similar specific gravities by attaching air
97 bubbles selectively onto hydrophobic plastics (Hori et al., 2009b). Using this jig
98 technologies, it is possible to separate several kinds of plastics by incorporating them in
99 various recycling unit operations (Fig. 2). For example, plastics can be separated by sink-
100 float separation using water to recover float and sink products. The sink product ($SG >$
101 1.0) then goes to either a RETAC jig or a hybrid jig depending on the SGs of plastics
102 (Jeon et al., 2019; Phengsaart et al., 2018, 2020; Tsunekawa et al., 2005). Meanwhile, the
103 floating products ($SG < 1.0$) can be treated by the reverse jig if the difference in SGs
104 between plastics is substantial. Unfortunately, these previous variants of the RETAC jig
105 cannot treat floating plastics having similar SGs like PE and XLPE.

106 To address this issue, we developed the reverse hybrid jig (Fig. 1 (d)) to separate

107 floating plastics having similar SGs. In addition, the effects of particle size on separation
 108 efficiency and how wetting agents and water pulsation affect bubble attachment during
 109 reverse hybrid jig separation were elucidated in this study.

110

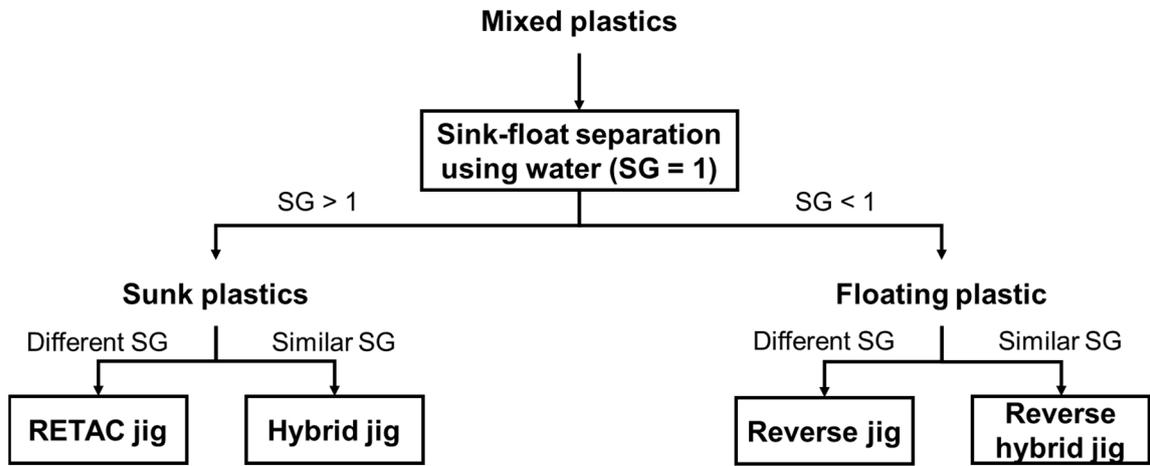


111

112 Fig. 1. A schematic illustration of (a) RETAC jig, (b) reverse jig, (c) hybrid jig, and (d)

113 reverse hybrid jig.

114



115

116 Fig. 2. Flowchart of plastic separation using advanced jig technology.

117

118 **2. Outline of the reverse hybrid jig**

119 The TACUB (BATAAC) jig is widely used in coal cleaning and the RETAC jig
120 (Fig. 1(a)) is a modified TACUB (BATAAC) jig for plastics sinking in water (Tsunekawa
121 et al., 2005). A reverse jig (Fig. 1 (b)) was developed to separate plastics floating on water
122 (Ito et al., 2010). The hybrid jig (Fig. 1 (c))—a combination of jig and flotation
123 technologies—is a modified RETAC jig for separation of hydrophobic and hydrophilic
124 plastics having similar specific gravities by attaching air bubbles selectively onto the
125 hydrophobic plastics (Hori et al., 2009b). In this study, a reverse hybrid jig (Fig. 1 (d))
126 was developed to separate floating plastics having similar SGs but different wettability.

127 Fig. 1(d) shows a schematic diagram of the reverse hybrid jig where particles
128 move up and down under the top screen, and the particles are separated based on
129 differences in levitation velocity (Ito et al., 2010). The top screen is made up of a metal
130 mesh (1×1 mm openings). An aeration tube fitted with air stones is installed under the
131 separation chamber and an air pump is connected to the tube. Ragging materials—6 mm
132 diameter alumina balls—were placed on the bottom screen to create uniform water flow
133 and air bubble distribution within the separation chamber. When bubbles attach
134 selectively onto hydrophobic particles, the apparent specific gravity (SG_{apparent}) becomes
135 lower and the reverse hybrid jig can potentially separate particles based on the differences

136 in their SG_{apparent} similar to those reported by Ito et al. (2020) for the hybrid jig.

137

138 **3. Materials and methods**

139 **3.1 Samples**

140 Polyethylene (PE, SG = 0.92) and cross-linked polyethylene (XLPE, SG = 0.93)
141 were used in this study and the samples were obtained from an electric wire recycling
142 plant (Kuniosa Metal Co. Ltd., Japan). The samples were crushed by an orient mill
143 (VH16, Seishin Enterprise Co. Ltd., Japan) and sieved to obtain 4 size fractions (+2.8–4.0
144 mm, +4.0–5.6 mm, +5.6–6.7 mm and +6.7–8.0 mm).

145

146 **3.2 Reagents**

147 Methyl isobutyl carbinol (MIBC, Wako Pure Chemical Industries Ltd., Japan)—
148 a reagent widely utilized in flotation as a frother to stabilize bubbles in solution—and
149 tannic acid (TA, Wako Pure Chemical Industries, Ltd., Japan)—a wetting agent
150 (sometimes called collector or depressant, depending on its role)—were used in the
151 reverse hybrid jig separation experiments.

152

153 **3.3 Reverse hybrid jig separation experiments**

154 Reverse hybrid jig separation experiments were carried out under the following
155 conditions: displacement of 20 mm, frequency of water pulsation equal to 30 cycles/min,

156 conditioning time of 5 min (air generation without water pulsation), and separation time
157 of 3 min (air generation with water pulsation). The amounts of samples, water, air flow
158 rate, MIBC dosage and TA dosage are shown in Table 1. After the reverse hybrid jig
159 separation, products were divided into six layers from the top and collected using a
160 vacuum sampling system. Materials in the layers were separated by hand to determine the
161 purity of each layer.

162

163 Table 1. Experimental conditions of the reverse hybrid jig separation.

Variables	Conditions	164
PE	150 g	
XLPE	150 g	
Water	18 L	
MIBC	20 ppm	
TA	0–500 ppm	
Air flow rate	500 mL/min	
Conditioning time	5 min	
Separation time	3 min	

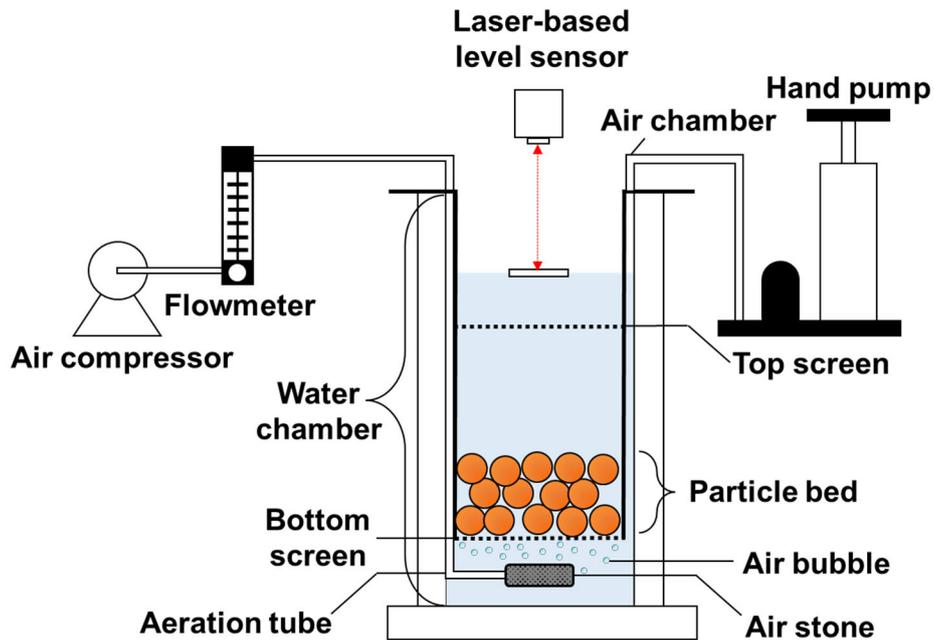
165

166 **3.4 Measurements of attached-bubble volume**

167 In our previous study, we developed a special laser-assisted measurement setup
168 for the determination of attached-bubble volume on plastic particles during water
169 pulsation to estimate suitable conditions for surface modification (Ito et al., 2020; Fig. 3).

170 In this setup, air bubbles are introduced by a pump under the particle bed, and
171 when bubbles attached to particles, an equivalent water level rise is recorded. This water
172 level rise is accurately measured and recorded by the laser-based level sensor system (IL-
173 S100, Keyence Corporation, Japan), and the attached-bubble volume can then be
174 calculated from changes in water level inside the separation chamber before and after
175 bubble introduction. Measurements of attached-bubble volume were carried out under
176 static and pulsed water conditions (Ito et al., 2020).

177



178

179 Fig. 3 A schematic diagram of the laser-assisted measurement setup for the determination
 180 of attached-bubble volume.

181

182 3.4 Surface tension and bubble size measurement

183 Surface tension of water with different TA dosages was measured using a
 184 temperature-controlled reaction vessel connected to a tensiometer (Krüss K100, Krüss
 185 GmbH, Germany). Bubble size measurement in reverse hybrid jig separation chamber
 186 were carried out at different concentrations of TA and captured using a high-speed digital
 187 camera. The captured images were analyzed using an image analysis software (WinRoof
 188 v.5, MITANI Corporation, Japan) for 100 bubbles (10 random bubbles from 10 images).

189

190 **4. Results and discussion**

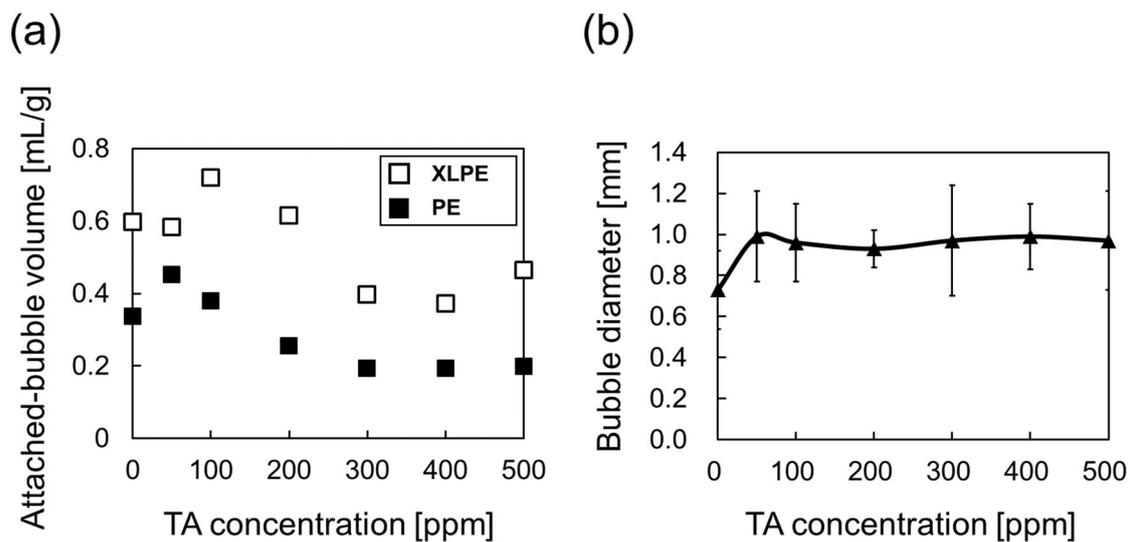
191 **4.1 Effects of bubble attachment on reverse hybrid jig separation**

192 **4.1.1 Effects of tannic acid addition**

193 Fig. 4a shows the volume of bubbles attached to the +5.6–8.0 mm PE and XLPE
194 with and without TA. The attached bubble volume measured for XLPE was higher than
195 that of PE regardless of TA concentration and the biggest difference was observed at 200
196 ppm. The attached bubble volumes to PE and XLPE were also higher at low TA
197 concentrations (50–100 ppm) and decreased with increasing TA concentrations. This
198 suggests that plastics become hydrophilic because of the addition of TA but TA addition
199 caused the sizes of bubbles to increase (Fig. 4b). The bigger bubble size may explain the
200 higher attached bubble volume on the plastic surface (Fig. 4(a)).

201 Separation tests with a reverse hybrid jig were carried out for mixtures of PE and
202 XLPE (150 g each) under various TA concentrations but the purity of the recovered
203 products was low (XLPE: 54 % as top (1st) layer, PE: 43 % as bottom (6th) layer, TA 250
204 ppm) (Fig. 5(a)), which could be attributed to excess attached bubble volume on particles.
205 By visual observation during the reverse hybrid jig separation, some of the attached-
206 bubbles detached from particles when water pulsation is applied. To further understand
207 this phenomenon, the effects of water pulsation on bubble detachment behavior from the

208 plastic surface was investigated in the next section.



209

210 Fig. 4. (a) attached-bubble volume as a function of TA concentration and (b) bubble

211 diameter as a function of TA concentration.

212

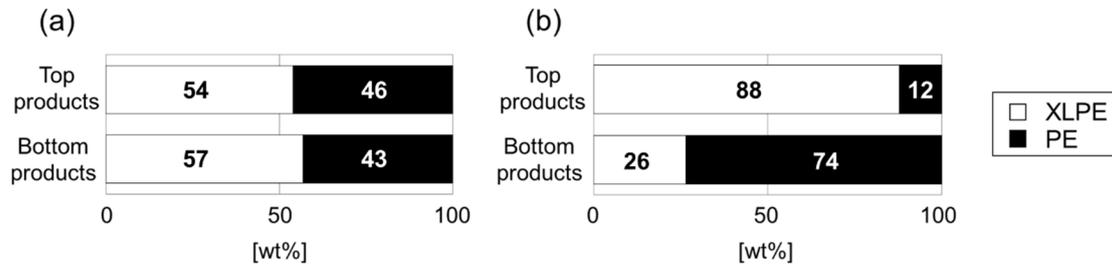
213 **4.1.2 Detachment behavior of attached bubbles and reverse hybrid jig separation**
214 **using a two-step approach**

215 The effects of water pulsation on the detachment behavior of bubbles attached
216 to plastic surfaces were investigated using a special laser-assisted measurement setup (Fig.
217 3). Air bubbles were introduced for 3 minutes to facilitate attachment to plastic particles
218 (Ito et al. 2020). After which, the air pump was turned off and water pulsation was applied
219 using a hand pump and changes in the attached-bubble volume were measured at 250
220 ppm of TA. The results showed that attached-bubble volume decreased with the number
221 of water pulsation and became constant after 4 pulsations (Fig. 6) and based on these
222 results the SG_{apparent} of XLPE and PE are 0.86 and 0.92, respectively (Ito et al., 2020).

223 Therefore, reverse hybrid jig separation was carried out using a two-step
224 approach: (i) jigging with air introduction for 5 minutes, and (ii) jigging for 3 minutes
225 without air introduction. Fig. 5 shows the improvement of purity of products using the
226 two-step method (Fig. 5 (b)); that is, 88% XLPE was recovered as top products (1st layer),
227 a 34% improvement from 54% obtained using the one-step approach (Fig. 5 (a)).
228 Similarly, PE purity in bottom products (6th layer) increased from 43% to 74% using the
229 two-step approach. These results suggest that the plastics were separated by differences
230 in bubble detachment behavior and by controlling bubble introduction into the separation

231 chamber, effective separation could be achieved. For the reverse hybrid jig, both
 232 attachment and detachment of bubbles are important parameters. However, the number
 233 of attached bubbles on particles is a function of particle size, so to further understand the
 234 bubble attachment-detachment process, the effects of particle size on reverse hybrid jig
 235 separation was investigated in the next section.

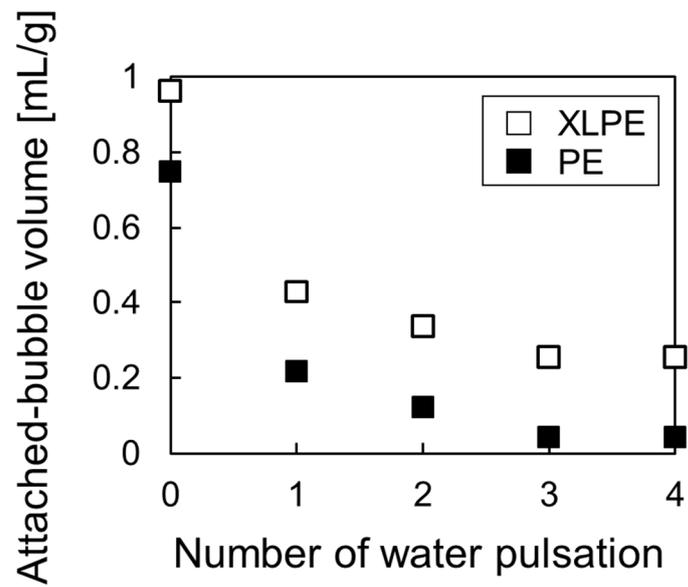
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237

238 Fig. 5 Distribution of XLPE and PE in top (1st layer) and bottom (6th layer) products after
 239 the reverse hybrid jig separation (a) one-step approach (air introduction without jigging
 240 for 5 min and jigging with air introduction for 3 min), and (b) two-step approach (jigging
 241 with air introduction for 5 min and jigging without air introduction for 3 min.).

242



243

244 Fig. 6 Attached-bubble volume on PE and XLPE as a function of water pulsation without

245 air introduction

246

247 4.2 Effects of particle size on reverse hybrid jig separation

248 Crushed plastic samples were divided into 4 size fractions (+2.8–4.0 mm,
249 +4.0–5.6 mm, +5.6–6.7 mm, and +6.7–8.0 mm) and reverse hybrid jig tests using the
250 one-step approach were carried out for mixtures of PE and XLPE (150 g each) of each
251 size fraction (Fig. 7). The results showed that the purity of XLPE in the top products (1st
252 layer) and the purity of PE in the bottom products (6th layer) increased with increasing
253 size and higher purity products were obtained in the coarser size fraction at a TA
254 concentration of 250 ppm. These results could be explained by the terminal velocity of a
255 particle with attached bubbles. In conventional jig separation, separation occurs because
256 of the difference of particle settling velocities while in the reverse jig (also reverse hybrid
257 jig), separation of particles is facilitated by the difference of their levitation velocities (Ito
258 et al., 2010; Phengsaart et al., 2020). Jig separation (or reverse jig) could achieve better
259 separation efficiency when the difference of terminal settling velocity (or terminal
260 levitation velocity) is larger. During particle settling (or levitation), there is initially no
261 size effect because of the similar initial velocities of particles. With time, however, the
262 particle's acceleration becomes zero and particles reach their terminal velocities, a
263 parameter that is influenced by particle size as shown in Eq. 1 (in laminar flow).

$$264 \quad v_{\infty H}^* - v_{\infty L}^* = (\rho_H - \rho_L) \frac{gD^{*2}}{18\mu} \quad \text{Eq. 1}$$

265 where $v_{\infty H}^*$ is the terminal velocity of a heavy particle with spherical shape [m/s]

266 $v_{\infty L}^*$ is the terminal velocity of a light particle with spherical shape [m/s]

267 ρ_H is the density of heavy particle [kg/m³]

268 ρ_L is the density of light particle [kg/m³]

269 g is the gravitational acceleration [m/s²]

270 μ is the viscosity of fluid [Pa·s]

271 D^* is the equivalent volume diameter [m]

272 Note: the terminal velocity difference ($v_{\infty H}^* - v_{\infty L}^*$) is larger when the plastic size (D) is

273 coarser.

274 For jig separation with the presence of bubbles (hybrid and reverse hybrid jig),

275 the terminal velocity difference is also influenced by the number of attached bubbles on

276 the particle surface that changes their apparent SGs (Hori et al., 2009b; Ito et al., 2020).

277 Because the average bubble size is around 1 mm (Fig. 4(b)), fewer bubbles could attach

278 to fine particles, so the difference of apparent density becomes small in the fine fraction

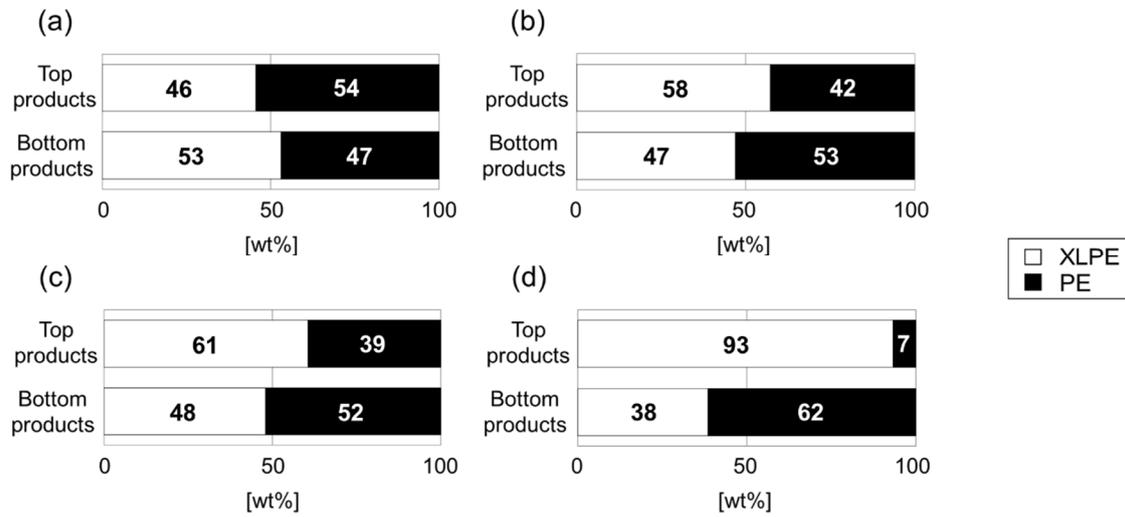
279 causing little terminal velocity difference ($v_{\infty H}^* - v_{\infty L}^*$). This indicates that the terminal

280 velocity difference ($v_{\infty H}^* - v_{\infty L}^*$) is larger when the plastic size (D) is coarser, which is

281 in line with the results of reverse hybrid jig separation shown in Fig. 7. These results also

282 suggest that the terminal velocity calculated from apparent density is an important

283 parameter for reverse hybrid jig separation.



284

285 Fig. 7. The distribution of XLPE and PE in top products (1st layer) and bottom products

286 (6th layer) after the reverse hybrid jig separation in 250 ppm TA solution (one-step

287 approach) of PP and XLPE with (a) +2.8–4.0, (b) +4.0–5.6, (c) +5.6–6.7 mm, and (d)

288 +6.7–8.0 mm size fraction.

289

290 **5. Conclusions**

291 In this study, we developed a novel method to separate floating plastics having
292 similar SGs called the “reverse hybrid jig”. The separation of PE and XLPE from waste
293 eco-cable was successfully carried out using this advanced jig separation technique.
294 Moreover, product purity was improved by employing a two-step approach: (1) jigging
295 with air introduction, and (2) jigging without air introduction. The reverse hybrid jig
296 separation efficiency was strongly influenced by both bubble attachment to and
297 detachment from plastic particles. In addition, the effects of particle size and apparent
298 SGs on the levitation velocities and separation efficiency were discussed in line with the
299 results of the reverse hybrid jig separation with different size fractions.

300

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305

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