Adhesives for Bead Fusion of Recycled Expandable Polystyrene

S. W. Lye, H. S. Aw, S. G. Lee

Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, China

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ABSTRACT: Expandable polystyrene (EPS) is a plastic cellular material that is commonly used in the packaging industry. Its growing uses have led to environmental concerns over resource sustainability and the dwindling availability of landfill spaces. Although existing approaches to control and manage EPS wastes are available, much effort is still needed to recycle as much of the used materials via developing new processes or applications. This article looks into a new approach using adhesives to promote EPS bead fusion. Two sets of test specimens made of 100% recycled EPS using spray adhesive and powder adhesive were investigated. Their mechanical behaviors of these two adhesive EPS samples were studied. These specimens were compared with the commercially available ones produced using steam injection molding and direct microwave molding. From the findings, the powder adhesive specimens were found to be quite comparable to the steam-injected ones in terms of better cushioning property, shape definitions, smaller dimensional and density variations than those of sprayed adhesive and microwave ones. The results highlight that powder adhesive mixed with 100% recycled EPS offer a new "green" approach in EPS production with low initial capital outlay and shorter production lead time. © 2002 Wiley Periodicals, Inc. J Appl Polym Sci 86: 456–462, 2002

Key words: powder adhesive; recycling; bead fusion

INTRODUCTION

Expandable polystyrene (EPS) beads, composed of small spherical-shaped particles containing about 98% air, are commonly used in the cellular plastics or polymer market. A cellular plastic is defined as a plastic whose apparent density decreased substantially by the presence of numerous cells disposed throughout its mass.[1] According to the Packaging Council, the total world production capacity for polystyrene in 1997 including both solid and expandable beads was estimated to be 14 million metric tons, and its global polystyrene demand for 1997–2005 was expected to grow by 4.5% annually.[2] On the production of EPS foams in the United Kingdom (UK),[3] it had grown by an annual rate of 6.9% between 1993–1996, and forecasted to grow further by 3.9% annually between 1997–2010. In United States, the amount of EPS foams sold for packaging alone had also grown from 202 million pounds in 1998 to 211 million pounds in 1999.[4] In Asian countries, significant production increases of EPS between 1998 and 1999 were also registered, as shown in Table I.

The significant increase in the use of EPS had led to a growing concern over the effects it had on the environment and the dwindling landfill space. One effective waste management approach involves reusing and recycling of EPS products, thereby delaying their final state of disposal. It has been reported that as much as 30% of EPS loose fills (also known as "peanuts" because of its shape) are being reused. Some makers of loose fill "peanuts" have even set up a network of collection sites for reuse and recycling of their polystyrene products. This has helped to divert more than 28 million pounds of EPS packaging from the landfills in 1997.[5]

Despite the recycling efforts, a lot of EPS waste still goes to landfills. This is for several reasons. First, successful models of in-house collection programs where large amount of expanded polystyrene could be gathered from wholesale markets, supermarkets, department stores, restaurants, electrical appliances stores, and at factories of machinery manufacturers are largely absent.[6] Second, the costs of recycled materials are not significantly cheaper than the raw materials. Recycled EPS also tend to have an inferior set of material properties than raw ones, thereby hampering demand. This is for current EPS foams are commonly produced using the steam injection-molding process. The maximum amount of recycled EPS used to mix with raw EPS beads to produce the moldings is only 50–60%.[7,8] Such recycled EPS beads usually contained minimum or no pentane gas in them, and any expansion is minimal, resulting in poorer bead fusion. Thus, these recycled materials, which typically weigh 20–30% lighter, need to undergo through a densifier pretreating the beads with pentane gas to restore them back to near their original density.[7,9,10] The result is

Correspondence to: S.-W. Lye (mswlye@ntu.edu.sg).

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that firms are reluctant to increase their ratio between recycled and raw materials in the manufacture of EPS foams and products.

Finally, the application areas where EPS is employed are dictated by the nature of the process. Presently, steam-injection molding and extrusion are the two key processes that make use of the recycled materials for mass manufacture of EPS products. Such processes are not suitable in handling of one-off or small batch prototyping and molding. Other processes to promote bead fusion include direct molding[11–14] and use of additives such as salt solution, paper, wax, and oil. Salt solution and oil[13,15] are added to the EPS beads to increase the boiling temperature of the water or increase the heat required thereby enabling fusion to occur. For paper,[16] the material is meshed with recycled EPS to form into a mold that is then left to cure. Wax is used primarily to increase the surface and body compressive and tensile strengths of the molded products.[17] Such approaches have been in existence for a while but are not well received by the industry.

Adhesives for recycled EPS bead fusion

Adhesives come in many forms such as structural adhesives, automotive adhesives, plastic adhesives, foam adhesives, and wood adhesives. This is the result of recent adhesive research and development effort. For foam adhesives, a review has found that the adhesives suitable for use on EPS are of two main types namely in solvent[18,19] and hot melts.[20,21] The first adhesive type exists in water-based or fluid-based form, whereas the second type is in pallet or powder form, which melts when subjected to heat. Despite their availability, the review found that adhesives are not used to promote bead fusion in the manufacture of EPS molds. The ensuing sections discuss the mechanical properties of samples produced using adhesives and are then compared with specimens made via steam injection molding and microwave molding.

TABLE I
Production of EPS in Asia Countries 98/99[4]

Country	Production (units: tons) 1998	1999	Increment
China	300,000	520,000	42.3%
Hong Kong	35,000	54–72,000	35.2–51.4%
India	—	25,000	—
Japan	213,000	212,000	−0.47%
Korea	137,482	174,426	21.2%
Malaysia	19,000	23,000	17.4%
Philippines	7,000	7,000	—
Singapore	9,000	8,350	−7.22%
Taiwan	35,150	36,000	2.4%
Thailand	18,000	39,000	53.8%

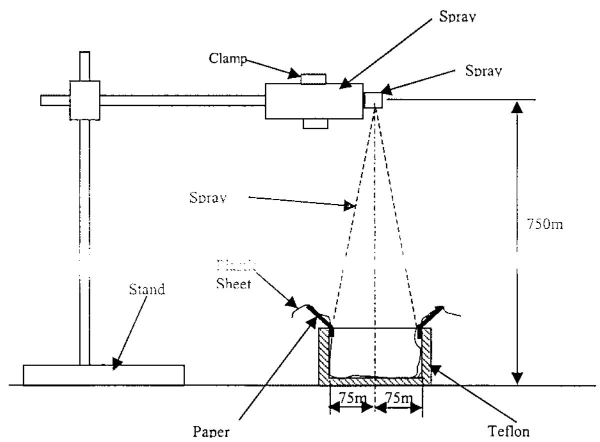

Figure 1 Experimental setup for preparation of spray adhesive test samples.

Experimental setup and sample preparation

To evaluate the material performance, four sets of test samples were prepared, namely fusion by adhesives in solvent and powder form, by microwave and the steam injection molding, here refered as the standard.

The first set of test samples of size 150 × 150 × 50 mm was produced using a Teflon mold. Sieved ground recycled EPS, having a bead size of about 2–3 mm in diameter, was introduced into the mold. A solvent-based adhesive, 3M #77 low Mist Super Spray Adhesive,[18] was manually sprayed in tiny droplets onto a layer bead thickness containing 100% ground recycled EPS. The low Mist Spray Adhesive is a sprayable, synthetic elastomer-based adhesive that can be used to bind most lightweight materials such as thin decorative films, foils, and fabrics for wide surface coverage. The solvent used is aliphatic hydrocarbons. Its preferred bonding temperature is at 65°C and above, with a drying time less than 10 min. The experimental setup for the preparation of test samples can be found in Figure 1.

The amount of ground recycled EPS (g) to adhesive (g) is found to observe a weight ratio of about 1.1 for optimal cushioning performance. This ratio was derived from a two-factorial design of experiment analysis being carried out to identify the key process parameters. The response surface methodology was then used to determine the optimal mixture between the amount of recycled EPS and adhesive. The weight ratio between EPS and adhesive is mainly attributed to EPS being substantially lighter than the solvent adhesive used, even though only a small amount of adhesive is sprayed onto the recycled EPS. After spraying the required amount of adhesive, the layering process repeats itself until the required thickness is reached. The specimen is then left to cure and later removed from the mold. Through this layering process, adequate mixing between the adhesive and the ground recycled EPS can be made.

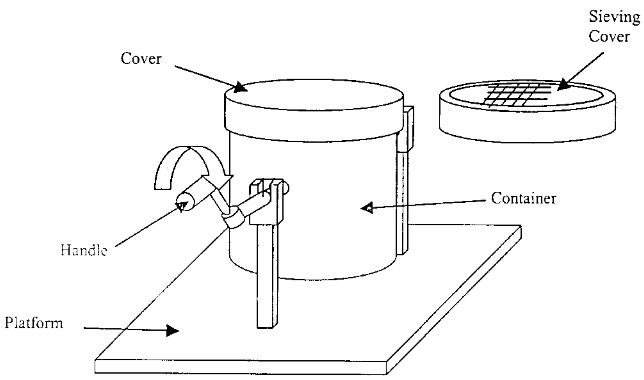

Figure 2 Mixing container for recycled EPS and powder adhesive.

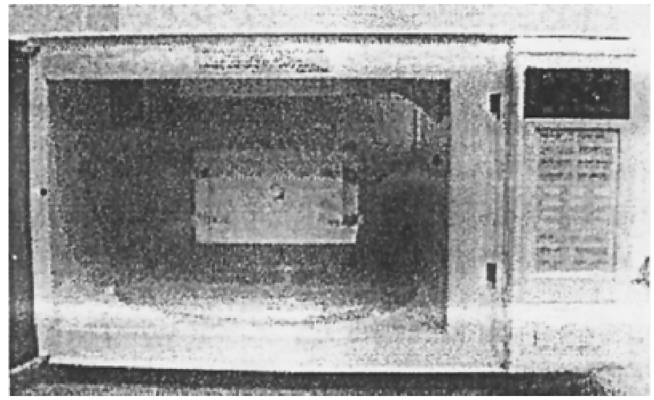

Figure 4 Specimen in Teflon mold in the microwave oven.

In the second set of test samples, the recycled EPS beads is to be lightly coated with a layer of clear thermographic adhesive powder obtained from Thermoboss Company[22] made of fatty acid dimer-based polyamide resin. This is done by introducing the ground recycled EPS with the powder adhesive into a container as shown in Figure 2. A rotating handle is used to rotate the container to facilitate even mixing of the powder adhesive with the EPS beads. The container cover is then replaced with a sieving meshed cover. By positioning the sieving cover at the bottom of the container and gently tapping at it, excessive adhesive from the mixture would then be sieved out from the container where it could be collected and reused later on for future batch mixing. From prior tests conducted, the optimal weight mix is found to be for every gram of recycled EPS; about 0.1 g of powder adhesive would be required. This weight ratio is substantially lower than the solvent-based adhesive ones, owing to the powder lightweight. After mixing, the mixture is introduced into a mold of a size 150 × 150 × 50 mm and compacted. The mold is then heated up to a temperature of about 85–90°C sufficient for the adhesive to melt, thereby encouraging bead adhesion or fusion. The melting temperature of EPS beads is 100°C. Upon cooling, the test samples are then removed from the mold.

In the third test set, a square Teflon mold of 16-mm wall thickness as shown in Figure 3 is used to produce specimens of 150 × 150 × 50 mm according to BS EN ISO 4651.[23] The specimens were to be cured in a 700-kW model ER-761ME Goldstar domestic microwave oven of 395 × 250 × 396 mm capacity. The sample preparation process involves mixing 45 g of recycled EPS with 400 mL of water at set intervals to be poured into the Teflon mold. The mixture of water and recycled EPS is subjected to uniform heating. A minimum gap is left on top of the mold cover to enable water to flow out during expansion. The mold is placed onto the rotational table inside the microwave oven, as shown Figure 4. Subject to a uniform heating for a few minutes at 700 Watts, this would result in a rise in temperature of the mold to within a range of between 80 and 90°C, thereby permitting the recycled EPS beads to soften and fusion among the EPS beads to occur. The mold cover is lifted up and the mold is then left to cool at room temperature (23°C) for 3 min before the specimen is removed from the mold. Before undergoing any test, the samples are left in the open, preferably at 23 ± 2°C, for 16 h to allow curing or stabilization to take place.

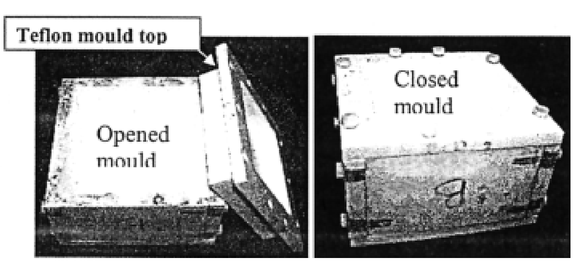

Figure 3 Teflon mold.

The fourth set of test samples was purchased from EPS foam producers that were then cut to the required size of 150 × 150 × 50 mm. Such foams are made of raw EPS beads. In this work, the samples have a density of 19 kg/m^3.

Experimental testing

Experimental tests were carried out on the various test samples to determine their material performance in terms of cushioning, creep, flexural strength, dimensional consistency, and density uniformity.

Cushioning relates to the material ability to absorb impact shock, thereby offering protection to the product. In this work, the Lansmont Cushion Test System, as shown in Figure 5, was used to perform free fall drops at heights of 0.5 and 0.75 m over a static stress range of between 0–18 kPa. Each set of drop contains the average values over three repeated drops relating to the maximum deceleration and displacement for a

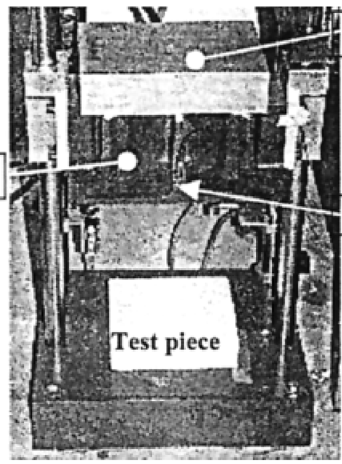

Figure 5 The Lansmont Cushion Tester System to determine Cushioning performance.

given test sample. The maximum deceleration and maximum displacement are the peak deceleration largest displacement experienced by the test sample according to BS EN ISO 4651 following impact, respectively.

On creep, investigation is made of the test sample's ability to resist deformity when subject to a compressive load over a period of time. The test involves placing a platform of size 200 × 200 mm, having a deadweight of 20 kg on top of a given recycled sample for 3 days, as shown in Figure 6. The amount of displacements is then measured at step time intervals as stipulated by ASTM 2221.[24]

Flexural strength of a material is the measure of resistance to bending, and is mainly dependent on the bonding strength among the recycled beads. In this work, a three-point bending test using the Instron 5569 machine is to be conducted on the samples of 120 × 25 20 mm in size. This is shown in Figure 7. Flexural strength test was, however, not performed on the spray adhesive sample, owing to difficulties faced in collecting accurate readings.

Dimension consistency relates to the size variations of the 12 samples produced for each test set. The lengths, widths, and thickness of each set of samples were measured and their corresponding mean values

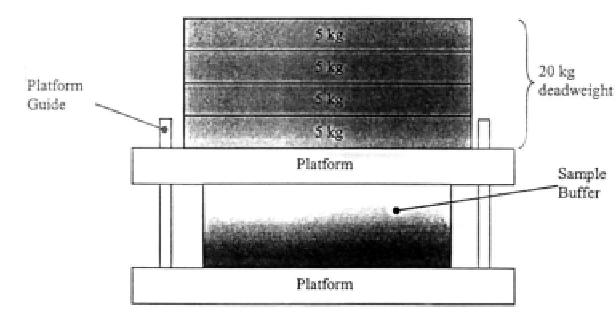

Figure 6 Experimental setup for creep property testing.

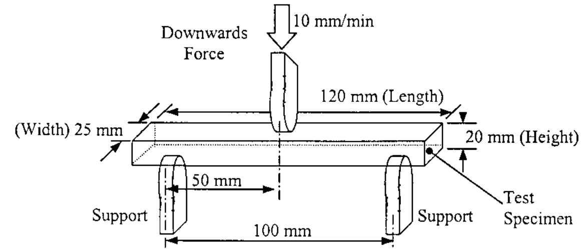

Figure 7 Flexural strength test setup.

and size variation computed. A comparison between the sets of test samples was then made.

Density uniformity concerns the homogeneity of the ground recycled EPS samples produced. Twelve samples were used in the analysis in which the weight of each sample is to be divided by its mean volume to derive the material density. The population variance, σ^2, and standard deviation, SD, of the specimens for a given set of samples was then calculated and compared with the other samples.

RESULTS AND DISCUSSION

This section discusses the material performance in terms of cushioning, creep, flexural strength, dimensional consistency, and density uniformity on the two adhesive bead fusion processes. A comparative study of the material performance of the adhesive samples produced based on steam injection molding and microwave molding is also made.

Cushioning properties

Figure 8 shows the impact cushioning curves for the four sets of test samples. Except for the steam injection molded ones, all the other test samples are made using

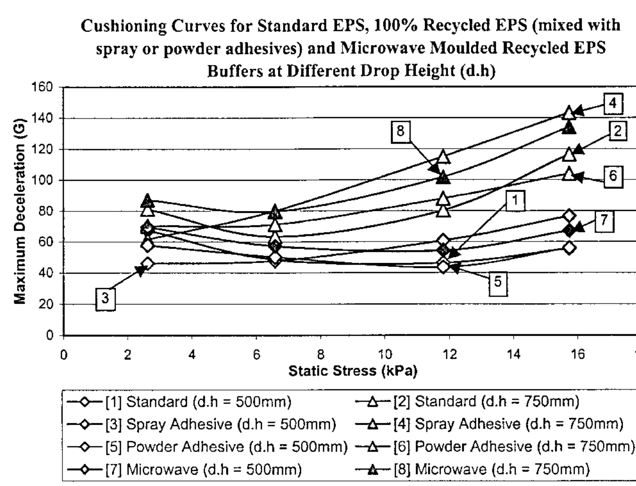

Figure 8 Maximum deceleration curves of standard and ground recycled EPS with spray and powder adhesive moldings at different drop heights.

100% ground recycled EPS. It was observed that all the four test samples exhibited a "U" impact cushioning profile with the larger impact values registered at higher drop heights. This implies that the cushioning curve profiles of the adhesive samples are consistent with the standard EPS ones produced by the steam injection molding process. Of these samples, the maximum deceleration values derived from the powder adhesive samples (curves 5 and 6) resemble more closely to those of standard EPS samples (curves 1 and 2). The results also show that, at drop heights of 0.5 and 0.75 m, the powder adhesive and standard EPS samples consistently offer better impact cushioning properties than those produced by spray adhesive and microwave. It was also observed that the gap between the samples produced by spray adhesive and microwave, and the standard ones widens at higher drop heights. A much thicker spray adhesive or microwave specimen when compared to the usual would have to be used at higher drop heights.

Figure 8 also highlights that the powder and spray adhesive EPS samples exhibit better cushioning properties at low static stresses. One probable reason is that the adhesives used to join the beads together result in a relatively larger bead spacing than those of standard EPS samples. More air entrapments exist in the adhesive samples, offering better cushioning properties than the more rigid standard EPS ones at low static stresses. Microwave samples, however, found to register higher impact readings throughout the range of static stresses.

Figure 9 shows the displacement results for the four sets of samples. Displacement is a measure of the difference between the initial thickness of the buffer and its thickness at the fifth-minute interval after the third drop. In this respect, three trends can be observed. The first trend reveals that at higher static stress, larger displacement is observed. This is because static stress has an inverse relationship to cushioning area for a given weight. The implication is that a larger static stress is translated to mean a smaller cushioning area leading to less impact force being absorbed by the sample material. The remaining force would therefore be transmitted to the product.

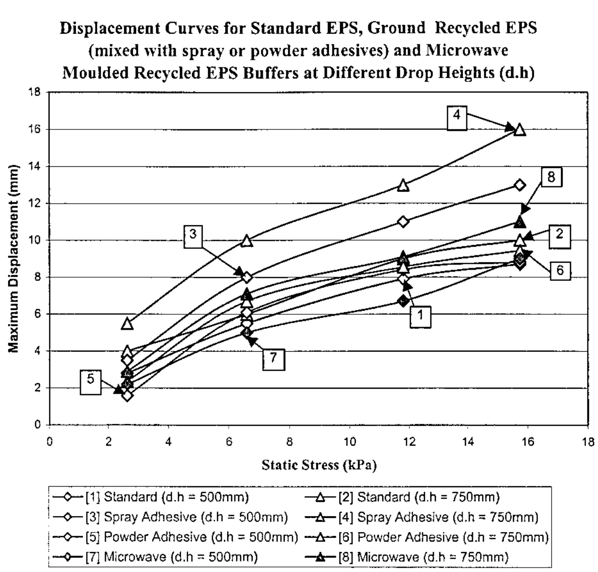

Figure 9 Maximum displacement curves of standard and ground recycled EPS with spray and powder adhesive moldings at different drop heights.

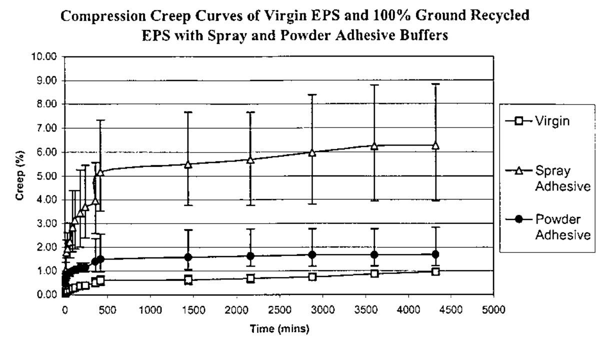

Figure 10 Compressive creep curves of the standard and ground recycled EPS with spray and powder adhesive samples under 20 kg of load.

The second trend is that curves at drop height of 500 mm (1, 3, 5, and 7) register smaller displacements than curves (2, 4, 6, and 8) at 750 mm. This is because an object dropped at a higher height would naturally exert a larger impact force on the samples, leading to a larger indentation or displacement made on the material.

The third trend is that the amount of displacements between powder adhesive EPS and microwave samples (curves 5–8) and the standard EPS ones (curves 1 and 2) are about the same. EPS samples produced using spray adhesive are, however, less resilience, as they register larger displacements consistently than standard ones.

Creep properties

The results of the creep tests conducted on three sets of samples are found in Figure 10. All the curves register linear displacements initially that tapered off over time. The displacements for ground recycled EPS buffers made using spray adhesive and powder adhesive were found to be 6.6 and 2.3 times, respectively, more than that of standard EPS moldings. This can be explained owing to the quality of bead fusion. Samples produced using powder adhesive are found to have a more compact structure and better bead fusion than the spray adhesive ones. When subjected to compression, less air is being squeezed out from the powder adhesive samples compared to the spray adhesive ones. The variance in the spray adhesive samples is

TABLE II
Results of the Flexural Strength of the Ground Recycled EPS with Powder Adhesive and Standard EPS Mouldings

	Maximum flexural strength (*N*)		
Sample	Standard EPS (19 kg/m^3)	Recycled EPS (42.7 kg/m^3)	Recycled EPS (54.5 kg/m^3)
Mean	22.27	4.26	9.98

also found to be larger than standard EPS and powder adhesive ones. This could be due to the nature of the spray adhesive process, which results in a more heterogeneous mix compared to the powder adhesive one.

Flexural strength

Table II reveals the results of the flexural strength tests conducted on two sets of powder adhesive samples of densities 42.7 and 54.5 kg/m^3. The strength reading highlighted in the table reflects the mean value taken over five test samples. From Table II, it can be seen that both sets of powder adhesive samples were found to possess a weaker flexural strength than the standard EPS ones. This is due to the weak material bonding. When a denser material (54.5 kg/m^3) is used, the flexural strength improved quite substantially doubling from that of 0.25 times the flexural strength of standard EPS (42.7 kg/m^3). One probable reason is the denser material resulted in a more compact cellular structure, thereby fostering better bonding strength. Nevertheless, it must be said that a denser material offers poorer cushion protection. The findings meant that powder adhesive samples are to be used in applications where the height to thickness ratio needs not be large.

Dimensional consistency

Table III shows the dimensional variations for the three types of samples produced using spray adhesive, powder adhesive, and microwave. The result for each sample type reflects the mean value based on readings taken from 12 test samples. From Table III, the mean height of the spray adhesive sample was found to have a dimensional deviation of 10.3%, which is substantially higher than 1% expected from standard EPS ones. One explanation could be due to the unconstrained postexpansion in the vertical direction. The side lengths were, however, quite acceptable, having deviations of between 1–2%. To minimize the height deviations among the specimens, one approach is to increase the holding time and leave the lid on so as to keep the postexpansion of the sample to a minimum. For the powder adhesive and microwave samples, the sample dimensions are found to be consistent and within the acceptable deviation of 1–3% as stipulated by BS EN ISO 4651.

TABLE IV
Density Variations of the Different EPS Samples

	Standard EPS	Spray adhesive	Powder adhesive	Microwave
Mean Density, (kg/m^2)	19.0	34.12	42.71	53.1
Population variance σ^2	0.31	1.99	0.42	0.78
Std deviation SD (%)	2.9	4.12	1.51	1.7

Uniformity of density

Table IV shows the mean densities for the four test samples along with their corresponding variance s^2 and standard deviation SD. From the table, the density variations for spray, powder adhesive, and microwave samples are found to be 4.2, 1.5, and 1.7%, respectively. These values compared favorably with the 3% deviation obtained for standard EPS samples. However, the corresponding mean densities for the spray, powder adhesive, and microwave samples are 34.1, 42.7, and 53 kg/m^3, respectively. These densities are higher than the standard EPS samples owing to additional use of adhesive or the materials are being compacted more intensely to enable fusion to occur.

CONCLUSIONS

Ground recycled EPS samples mixed with spray and powder adhesive moldings were subjected to five me-

TABLE III
Dimensional Variations of Samples Produced by Spray Adhesive, Powder Adhesive, and Microwave

	Spray adhesive			Powder adhesive			Microwave		
	Length	Breadth	Height	Length	Breadth	Height	Length	Breadth	Height
Actual Dim. (mm)	147	150	50.0	75.14	37.86	50.85	147	150	50.0
Mean Dim (mm)	149	149.27	54.96	74.15	37.32	50.44	144.88	145.63	49.53
Pop. variance σ^2 (mm^2)	5.07	1.36	26.52	0.94	0.74	0.20	6.98	20.12	0.24
Std. Deviation SD (%)	1.54	0.78	10.3	1.29	2.24	0.87	1.79	2.99	0.98

chanical tests. Preliminary tests have found that the powder adhesive moldings can offer quite similar material performance except for flexural strength and weight when compared with standard EPS moldings. The powder adhesive samples faired better than the spray adhesive and microwave samples. The results highlight the potential of processing recycled EPS products using powder adhesives. Some notable advantages derived from such approach include catering to small batch production, facilitating product and package integration, and operations, lower initial capital outlay, and shorter product lead time, as expensive molds could be minimized.

A comparative performance between various EPS process specimens was made and these were summarized below.

1. On creep, the amount of compression for ground recycled EPS moldings with spray and powder adhesives were found to be 6.5 and 1.69%, respectively. These values are quite acceptable despite their being higher than that of standard EPS ones (1%), which uses raw beads. When the ground recycled adhesive samples are compared with ECO-Foam, an alternative packaging material, they were found to be comparable if not better. This is for Eco-Foam registers a compression creep of 6.8% based on a lower loading weight (1 P.S.I.) and subjected to a shorter duration of time (24 h).[25]
2. Adhesive fused samples do provide good flexural strength. Its flexural strength can be increased with a denser material, but this would lower its cushioning properties.
3. On dimensional accuracy and consistency, powder adhesive samples produced repeatable registering about 1–2.5% deviation. This compares quite well with standard EPS ones.
4. The mean densities of the spray and powder adhesives were found to be denser or heavier than standard EPS samples. Such adhesive fused samples are to be applied in areas where it can offer unique advantages such as one-off protective packaging molds over current available processes that can aptly deal with small batch production, short lead prototyping, and multisection multiproduct packaging.

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