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Lightweight mortar made with recycled polyurethane foam

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ABSTRACT

This paper presents results of an experimental study on the use of rigid polyurethane foam wastes with cement-based mixtures to produce lightweight mortar. Several mortar grades were obtained by mixing cement with different amounts of polyurethane, aggregate and water. Dosages were varied to replace aggregates with recycled polyurethane, while the amount of water was optimized to obtain good workability. Rigid polyurethane was ground to particle sizes of less than 4 mm prior to use as an aggregate substitute. The characteristics of the test specimens were defined and they were tested in both a fresh and a hardened state. Results show that an increase in the amount of polyurethane affects the mortar, decreasing its density and mechanical properties while increasing its workability, permeability, and occluded air content. These results confirm that mortar produced with recycled polyurethane is comparable to lightweight mortar made with traditional materials.

1. Introduction

Industrial processes generate vast amounts of waste products. The majority of these have no specific use and are dumped on landfill sites. It is therefore necessary to establish recycling procedures or ways of reusing industrial waste in order to minimise its environmental impact. This is the case of polymeric waste from the manufacturing and construction industries. In particular, the automotive industry generates a large amount of waste resulting from the manufacture of rigid polyurethane foam panels. When these are destroyed and crushed, they are converted into low-density particles which can be useful in the manufacture of lightweight materials. The addition of these polyurethane foam wastes to lightweight mortar and concrete is potentially a viable alternative for their disposal [1–4].

The objective of this work is to study the use of industrial by-products in the manufacture of mortar, by comparing the beneficial properties of mortars manufactured with polymer foam to those of mortars manufactured with traditional materials [5,6]. In this regard, the study examines the practical use of polyurethane foam in the manufacture of mortars for the building industry, by setting the criteria for its usage and establishing the basic proportions that will guarantee mortar strength and durability, as well as high performance and placing on-site [7–9].

The steps followed in this research are: to establish the characteristics of the mortar components (the selected polymeric waste, aggregate and commercial cement to be used); to set satisfactory proportions for the manufacture of lightweight mortar (by replacing different percentages of conventional aggregate with polyurethane foam); and to analyse the properties of the mixtures in both a fresh and a hardened state.

2. Materials

In this study, two different types of cement manufactured at the Valderrivas Portland factory in Navarra (Spain) were used. The first, CEM I 42.5 R had a density of 3065 kg/m^3; and the second, CEM IV/B 42.5 N (EN 197-1), a density of 3030 kg/m^3. The chemical composition of both types is shown in Table 1 [10].

River sand, sieved between 0 and 4 mm (Fig. 1), with a density of 2700 kg/m^3 was used. The particle size distribution was obtained according to Spanish Standard EN 13139 [11].

Polyurethane foam waste (PFW) was obtained from the destruction of panels used in the automotive industry. Polyurethane foam waste (PFW) was ground to a particle size of between 0 and 4 mm before being used as an aggregate substitute (see Fig. 1). The apparent density of the PFW was measured on three cubic test specimens. This density was evaluated as 26 ± 2 kg/m^3; the same specification as that given by the panel supplier (25 ± 2 kg/m^3). Chemical composition obtained by the elemental analysis CHNS with an analyser LECO CHNS-932 and with X-ray diffraction (Fig. 2).

2.1. Sample preparation

The operating procedure for the manufacture of lightweight mortar has consisted of manufacturing traditional mortar (a

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Table 1
Chemical cement composition (%).

Components		CEM I	CEM IV
Calcium oxide	CaO	60.40	42.20
Silica	SiO_2	21.30	30.30
Alumina	Al_2O_3	6.10	10.80
Ferric oxide	Fe_2O_3	4.00	3.00
Magnesium oxide	MgO	1.50	2.50
Potassium oxide	K_2O	1.30	1.60
Sodium oxide	Na_2O	0.40	0.80
Sulphuric anhydride	SO_3	2.30	2.00
Others	–	0.70	1.10
Loss on ignition	–	2.00	5.70

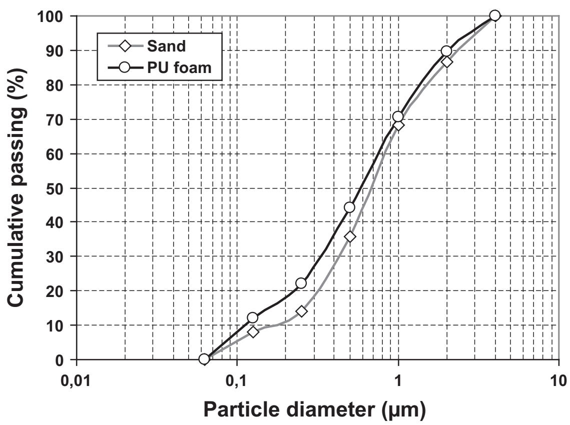

Fig. 1. Particle size distribution of sand and PU foam waste.

mixture of cement, sand and water) and, after, to replace different percentages of sand with ground PFW. The cement/aggregate dosage by weight – aggregate being understood as the total quantity of sand and polyurethane in relation to cement – was 1–3. Though the initial dosages were calculated by weight, the amount of discarded sand was substituted by an equivalent quantity of polyurethane in volume. An amount of added water was necessary to ensure good workability, in accordance with Standard EN 1015-3 [12]. Two series of lightweight mortar have been produced, Series I with CEM I 42.5 R and Series II with CEM IV/B 42.5 N (Table 2).

3. Samples characterization

3.1. Consistency and workability

The consistency of the mixtures, which is defined as the *w*/*c* (water/cement) ratio, was calculated in accordance with Standard EN 1015-3, which sets the amount of water needed to obtain good workability and a plastic state in mixtures, with slump flow test, with reference to an average spreading diameter of 175 mm ± 10 mm.

Though initially one might think that the addition of a significant volume of polyurethane will require relatively high *w*/*c* ratios [13–15], quite the opposite was in fact observed. In other words, a higher proportion of PFW caused a decrease in the *w*/*c* ratio (Table 2). One explanation of this could be that, as the percentage of eliminated aggregate is increased, the mortar component that demands more water is reduced. This leads to an interesting result when considering the applications for these lightweight materials, as the quantity of water used as a proportion will affect some of the subsequent properties of the hardened mortar, such as its mechanical strength or its permeability.

The definition of mortar workability in the fresh state, according to Standard EN 1015-9 [16], is the time in which the mortar will obtain a strength of 0.5 N/mm^2, measured by applying a static force of 14.7 N on the surface of the mortar using a Standard tamper. The workability tests were extended to reach higher loads than those established in the Standard. The results for the different dosages showed similar values for both types of cement. A relevant finding was that as the amount of foam was progressively increased, mortar workability improved. For example, in the case of Series II, by substituting only 25% of the aggregate, the workability improved from 270 min (measured on a reference mortar) to 390 min, i.e. the workable time increased by 120 min compared to the reference mortar (see Fig. 3).

On the one hand, the explanation for this might be that less water was needed because of the aggregate; on the other hand, the polyurethane which is used as a substitute retains a large amount of water due to its high porosity, thus improving the water absorption and the dispersion capacity of the cement [17]. This can imply a big increase in workability. Thus, the result of adding PFW leads to a change in the rheological properties of the material, obtaining mortars with a low tendency to segregation or exudation, which in turn facilitates its application. This information can be considered as an improvement when it comes to handling and placing the material.

3.2. Density in fresh and hardened states

Bulk density was measured in fresh and hardened state, according EN 1015-6 [18] and EN 1015-10 [19], using 40 mm × 40 mm × 160 mm test specimens, following curing at a temperature of 20 ± 1 °C, at a relative humidity of 50 ± 1%.

In the fresh state, the densities fluctuated between approximately 2100 kg/m^3 for reference mortars (I-0 and II-0), 1500 kg/m^3 for I-100 and 1100 kg/m^3 for II-100. This means a reduction of 600 kg/m^3 for a total substitution of aggregate in Series I, which means a decrease of almost 30%, and a reduction of 1000 kg/m^3 for Series II, which is a decrease of almost 50% (Table 2).

Element	Weight (%)
C	65.5
O	19.0
N	7.2
H	6.2
Ca	1.0
Others	1.1
Total	100.0

Fig. 2. Polyurethane foam wastes used and basic chemical composition.

Table 2
Mix proportions and properties in fresh state of the mortar mixtures.

Series no.	Mix no.	Sand replaced by foam in volume (%)	w/c	Mix proportions (kg/m^3)				Fresh density (kg/m^3)	Occluded air (%)
				Cement	Water	Sand	Foam		
Series I	I-0	0	0.82	436.2	357.8	1310	0	2104	4.8
	I-25	25	0.74	506.6	374.7	1141	3.7	2026	5.1
	I-50	50	0.68	598.3	406.7	898.4	8.6	1912	7.6
	I-75	75	0.64	733.3	469.3	550.5	15.9	1769	9.0
	I-100	100	0.62	910.7	561.9	0	26.4	1499	13.0
Series II	II-0	0	0.75	443.7	332.8	1332.5	0	2109	3.5
	II-25	25	0.72	508.0	367.0	1136.4	3.6	2015	4.2
	II-50	50	0.70	571.8	400.4	858.6	8.2	1839	6.6
	II-75	75	0.67	725.1	485.8	544.4	15.7	1771	8.1
	II-100	100	0.61	677.3	413.2	0	19.5	1110	11.9

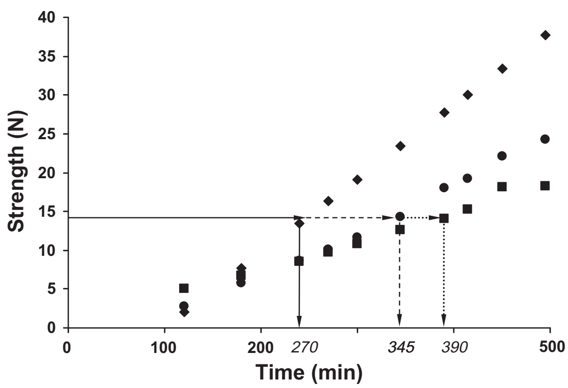

Fig. 3. Workability of different mortars: ♦ II-0; ● II-25; ■ II-100.

In the hardened state, these differences are maintained for 28 days, as well as for 3 months. Moreover, due to the compaction of the material and the curing of the test specimens, the apparent densities decreased in relation to the fresh state by about 200 kg/m^3 in all cases (Table 3).

Though the density of the mortars decreased in time due to the progressive increase in the amount of the PFW, the selected ratios only achieved densities that allow us to consider these materials as lightweight mortars with regard to their use (having a maximum density of less than 1500 kg/m^3 in the hardened state), when the aggregate is substituted in its entirety.

3.3. Air void content

With regard to Series I and II, as the proportion of polymeric foam increased, so did the percentage of occluded air, as defined in Standard EN 1015-7 [20], because there are greater quantities of pores present in the mixture (see Table 2). Due to their size, the air bubbles formed in the fresh mortar act as particles smaller than 4 mm, but have the advantage of a better form coefficient, being elastic and deformable, which allows them to slide without creating friction [21]. As expected, the results indicate that by moving from reference test specimens to mortars without aggregate implies an increase of approximately 8% in occluded air for both cements.

Table 3
Hardened density for Series I and II.

	Mix no.	Density at 7 days (kg/m^3)	Density at 28 days (kg/m^3)	Density at 3 months (kg/m^3)
Series I	I-0	2017	1932	1930
	I-25	1997	1887	1890
	I-50	1879	1806	1791
	I-75	1691	1657	1623
	I-100	1467	1273	1241
Series II	II-0	2040	2000	1994
	II-25	1980	1949	1763
	II-50	1735	1635	1611
	II-75	1660	1524	1491
	II-100	1092	1025	1084

3.4. Permeability to water vapour

In the construction industry, one speaks of the need for mortars to transpire, where the concept of ''transpiration'' refers to these materials' water vapour permeability. The importance of permeability is understood when associated with the pathology of condensation and humidity increase, which occurs for other reasons whenever there is a lack of permeability.

The methodology for the determination of water vapour permeability in a stationary state in stucco and plaster mortars is defined in Standard EN 1015-19 [22]. The Standard specifies that to find the permeability value, it is first necessary to calculate the permeance, which is the water vapour flow that passes through one area unit under equilibrium conditions for each unit of vapour pressure difference on both sides of the mortar. Afterwards, water vapour permeability is calculated as the result of multiplying permeance by the thickness of the test specimen.

To determine the permeability of all the samples, we prepared and tested five test specimens and used the average value, represented in Fig. 4 for each of the different mortar grades. In that graph, the continuous increase in permeability may be observed until it reaches a maximum value when the amount of sand is substituted in its totality; a maximum which trebles the permeability of the reference mortars for Series II and increases it by a factor of 5.5 for Series I. This progressive increase in permeability may be due to various factors. Polyurethane is a porous material, which means that it has relatively high mean diameters in the capillary network, which in turn eases the passage of water vapour [23,24]. Also, the foam is highly reticulated, which means that it provides the presence of conduits or capillaries that are distributed throughout the mortar, connecting one to each other to form a fine network through which water vapour flows easily. All these factors allow us to consider these mortars as lightweight materials free of condensation in the form of liquid water in practically any climatic condition, which perform well with respect to water vapour diffusion.

3.5. Mechanical properties

Numerous works may be found that establish the mechanical properties of lightweight mixtures manufactured with polyurethane aggregates. Unlike the case of conventional mortar, in

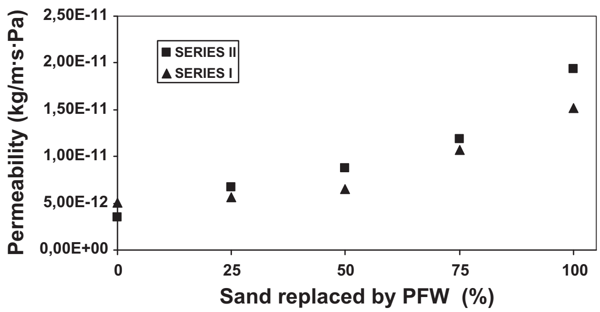

Fig. 4. Water vapour permeability.

lightweight mortar the break failures occur in the lightweight aggregates and in the lightweight aggregate–paste interface [25]. In spite of the fact that different adhesion between aggregate and paste is difficult to detect, the explanation for this phenomenon can be attributed to the fact that the high water absorption of these porous foam compounds reduces the amount of water available to the mix, and the aggregate–paste interfacial area becomes denser [26–28]. This does not happen in the synthetic ceramic aggregates where an increase in the water absorption, and thus in the interfacial contact area, may be observed. Thus, the effect of aggregate type on lightweight mortars can have an effect on its mechanical properties.

Flexural strength and compressive strength was measured at 7 days, 28 days and 3 months, as per Standard EN 1015-11 [29], using an MTS hydraulic press. Five different test specimens were tested under flexion for each combination and ten under compression. The test specimens measured 40 mm × 40 mm × 160 mm, and the bottom support rollers were separated at intervals of 100 mm. The resulting fragments in this test broke under compression using a load surface of 40 mm × 40 mm. The mean values obtained are shown in Fig. 5 where, as expected, the breakage strength decreases in proportion to the amount of polyurethane present in the mixture. Regarding mechanical properties, we can observe that compressive strength is about 60% lower for samples without sand (I-100 and II-100), in relation to the reference test specimens (I-0 and II-0). At 28 days, within which time the complete development of mechanical strength may be assumed, this difference was reduced to 50%, and it was stable in 3-month-old test specimens. This means that the recovery and stabilization of the material takes place when the curing process is complete. The values obtained for the flexural tests showed similar results, with a loss of strength of approximately 55% when there was a total substitution of the aggregates with PFW.

PFW is a compressible material that has high porosity, which means greater water absorption in its pores and a lesser need for the cement–polyurethane paste mixture, which in time results in a reduction of the mechanical properties of flexural and compressive strengths. One has to consider the addition of air, as porosity leads to reductions in mechanical strength in the order of between 3% and 5% for each 1% of added air. This loss of strength is compensated in part by diminishing the *w*/*c* ratios due to the plasticity effect mentioned earlier. On the other hand, PFW has a certain flexibility that gives the mixture good resistance to fissures which, in turn, makes it capable of absorbing small structural movements without breaking up, maintaining its adhesion to the supporting structure.

In fact, mechanical properties could be explained for the presence and amount of foam, but not the quality of the interfacial zone between paste and aggregate, which, in turn, strongly influences the mechanical behaviour of mortars. The interfacial transition zone is probably higher in the case of recycled aggregates, due on the one hand to a bigger size (Fig. 6) of foam and on the other

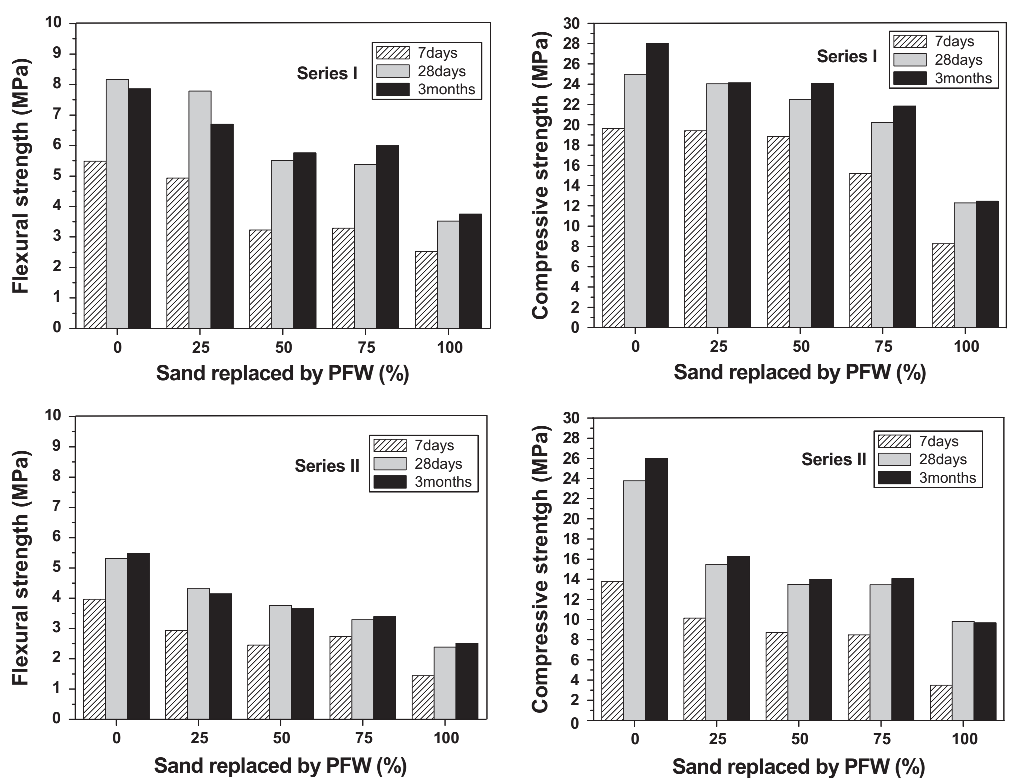

Fig. 5. Evolution of mechanical properties with age.

hand to a bigger transition zone because of the water being given back by the recycled aggregate particles that absorbed high amount of water [30].

Another innovative aspect of these materials lies in their behaviour with regard to surface load tests or compressive strength tests. This is because, when subjected to a progressive load at a constant velocity, they acquire sustainable plasticity and deformability qualities in all cases, resulting in high structural compactness which, prior to breakage and depending on the quantity of foam, allows a reduction in thickness in the direction of the force of between 15% and 35% compared to the initial dimensions. Fig. 7 shows the compactness data of the mortars after carrying out the compression test on Series I. In addition, the specimens went onto show a small dimensional recovery once its load was removed. This property could be taken advantage of, for instance, in joints where a certain amount of flexibility is necessary to absorb small load movements.

3.6. Thermal characterization

Thermogravimetric analysis (TGA) was used to determine the polymer content in the composites and its distribution and could be used for make a quality control of lightweight mortar formulate. TGA data were recorded under nitrogen atmosphere on a Mettler-Toledo TGA/SBTA851 analyser from 15 mg of sample at a scan rate of 10 °C/min from 100 °C to 800 °C. Fig. 8 shows TGA patterns of all the mortars of Series I, with I-0 used as reference, showing a partial degradation of the mortars proportional with amount of polymer included for different dosages between 350 and 550 °C, typical of the thermal degradation of this polyurethane group, whose presence enhances the flexibility composite strength [31]. When the polymer content increases, the mortar porosity becomes greater, decreasing significantly its mechanical properties, as we have observed previously.

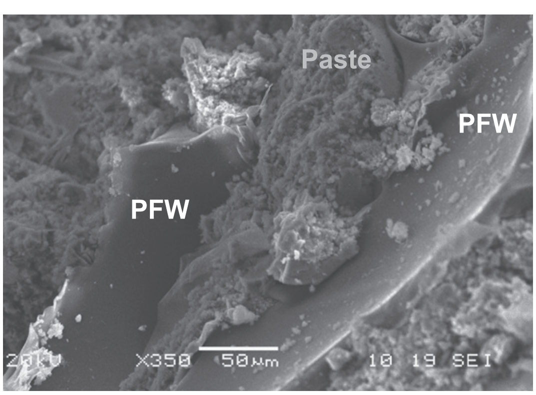

Fig. 6. SEM image (50×) of the interface between cement paste and polyurethane foam waste (PFW).

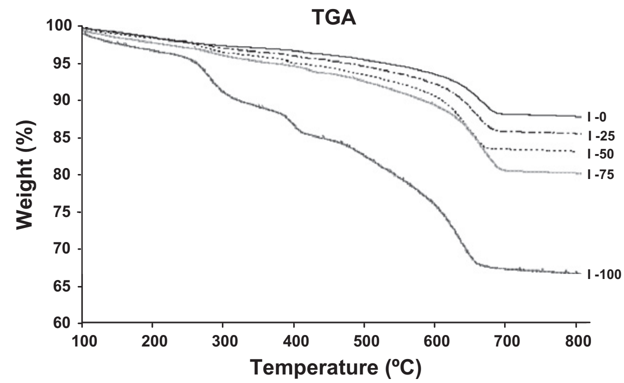

Fig. 8. TGA in nitrogen for different dosages of CEM I.

4. Conclusions

In summary, the manufacture and characterization of quality lightweight mortars has been performed in a simple way, beginning with the progressive elimination of aggregates which were substituted by ground rigid polyurethane foam waste (PFW) materials, with a view to finding compound materials that comply with current legislation, which could become attractive for use in industry. On the basis of these results, it may be established that the quantity of foam present in the composition is the most important factor to explain the variation in the subsequent properties of these composites.

We have established that the *w*/*c* ratio decreases according with the increase of the amount of sand replaced by foam. On the other hand, the time period of mortar workability increases considerably, by 120 min when replacement of sand by PFW is total.

In the fresh state, the densities varied between approximately 2100 kg/m^3 in both reference mortars (I-0 and II-0) and 1500 kg/m^3 for mortar I-100 and 1100 kg/m^3 for mortar II-100. This means there is an increase in occluded air of around 8% in both mortars. In the hardened state, and due both to the compactness of the material as well as the curing process, the apparent densities decreased in comparison to the fresh state and at 28 days the decrease was about 200 kg/m^3 in all the samples.

Considering a possible application of these recycled materials within masonry mortars, small vapour diffusion or permeability can lead to a deficient transpiration in materials recovered with these mortars, which could produce undesirable condensation of water. Hence, ensuring a high vapour permeability is considered an advantage as it improves the vapour balance between phases. Permeability trebled in relation to the reference mortar for Series II, and increased by a factor of 5.5 for Series I. This implies the possible presence of a capillary network due to the PFW, which not only maintains good water diffusion but even improves it.

Mechanical strength decreased by less than 50% in mortars I-100 and II-100 in comparison to I-0 and II-0. On the other hand, the deformability of these materials is of interest as the compression

Sample	Compactness (%)	Recovery (%)
I-0	0	0
I-25	10	4
I-50	16	4
I-75	25	5
I-100	35	5

Fig. 7. Mortar compactness data for Series I and picture of specimen I-100 after compressive strength testing.

straining prior to failure is between 35% and 10%, and the small subsequent recovery of around 5% in all cases means that these composites are not only satisfactory for non-structural use (dividing walls, partitions, etc.) but potentially also for applications that require an amount of shock absorption (such as joints).

We may therefore conclude that it is technically possible to use polymeric foams from industrial waste materials in the manufacture of cement-based mortars and that these could be of use in the building industry. At the same time, these are environmentally friendly materials that will contribute to sustainable development. Further work will focus on the potential applications of these materials, with the aim of determining their adhesion to other materials and their durability through other forms of testing.

Acknowledgements

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