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Characteristics of artificial coarse aggregate from High Density Polyethylene (HDPE) plastic waste for highway flexible pavement

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Abstract

Aggregates are a major component of hot mix asphalt and make up about 85% of the total mix volume. The increasing expansion of road infrastructure in Indonesia has led to a depletion of aggregate resources. Conversely, Indonesia is one of the largest producers of plastic waste in Southeast Asia. The aim of this study is to evaluate the potential of high density plastics (HDPE) for use as artificial aggregate material in flexible road pavements. The parameters investigated include softening and melting point, penetration and elongation index, gradation value, specific gravity, absorption and abrasion of the aggregates. The investigations into the physical properties of the artificial aggregates revealed a softening point of 265°C and a melting point of 272°C. The penetration index was 0.77% and the elongation index was 0.70%. The classification values passing through the 3/4" sieve were 100%, 66.88% for the 1/2" sieve and 25.96% for the 3/8" sieve. The specific gravity of the artificial coarse aggregate was 1.629. The absorption of the artificial coarse aggregate was 1.270% and the abrasion value was 0.15%. In sum, the artificial coarse aggregates produced from HDPE plastic waste can serve as a partial substitute for natural coarse aggregates.

1. Introduction

Aggregates are the main component of hot-mix asphalt[1,2]. They make up about 95% of the total weight of the mix or about 70-85% of the total volume of the mix[3,4]. To meet the demand for aggregates, these are traditionally sourced from quarries in certain regions. With the increasing development of road infrastructure in Indonesia, the availability of aggregates as the main source of crushed stone may be exhausted[5]. There is a possibility that Indonesia will face a shortage of aggregates if the exploitation of these aggregates is excessive. Therefore, it is necessary to plan a strong, durable road structure with high resistance to deformation.

Several studies have been conducted to prevent over-exploitation of natural resources in order to preserve the authenticity of the environment and ensure the sustainability of aggregates in the years to come[6–8]. One approach is to reuse organic and inorganic waste by recycling it into new forms or retaining its original form.

Aggregates are classified into two categories: natural aggregates and artificial aggregates[9]. Aggregates consist of crushed stones, gravel, sand, or other materials, whether sourced from natural deposits or artificially produced, and exhibit solid forms in various sizes or fragments. Natural aggregates can be utilized in their natural state or with minimal processing due to their formation through erosion and degradation processes, determining their shapes. In contrast, the formation of artificial aggregates depends on the type and form of the materials used.

The material choices for artificial aggregates are not restricted compared to natural aggregates, as they can leverage waste materials generated from human activities. One such material is High-Density Polyethylene (HDPE). HDPE was selected as the fundamental material to enhance the quality of artificial aggregates, based on its robust, ductile, rigid, high-pressure and temperature-resistant properties[10]. It is also easily moldable, possesses advantages of resistance to water, acids, bases, and other solvents[11]. The selection of HDPE is further motivated by the substantial mismanagement of plastic waste in Indonesia, as documented by The Central Statistics Agency (BPS), reporting approximately 64 million tons of plastic waste annually[12]. Of this, 48% is openly burned, 13% is inadequately managed in official disposal sites, and the remaining 9% pollutes water bodies and oceans.

On the other hand, in the face of abundant plastic presence, a Artificial Report initiated by the World Bank in collaboration with various research institutions revealed that no less than 150 million tons of plastic have contaminated the world's oceans[13,14]. East Asia is identified as the region experiencing the fastest growth in waste production globally. Jambeck et al.[15] states that among the total of 192 countries studied, five countries in the East Asian region are responsible for more than half of the plastic waste in the oceans. Regrettably, Indonesia ranks second among these five countries, following China, and is followed by Vietnam, the Philippines, and Thailand. The total amount of plastic waste from Indonesia that ends up in the sea is estimated to be 187.2 million tons.

In the context of environmental protection, we are looking at the potential use of the properties of high-density polyethylene (HDPE) as an artificial aggregate material in flexible pavements. This endeavor involves investigation with various tests, including analyzing the heating temperature required for HDPE plastic waste fragments to reach the required melting point to form chunks of material, investigating the process associated with the decomposition of HDPE plastic waste chunks into artificial coarse aggregates, and evaluating the physical properties of these artificial coarse aggregates when incorporated into road pavement mixtures.

The study provides insights into the potential use of high density plastics (HDPE) as an artificial aggregate material, increasing the market value of plastic waste and providing an alternative to natural aggregates. This research seeks an approach for the development of artificial aggregates for flexible pavements and provides a solution for the management and recycling of plastic waste.

2. Methods

Raw material in the form of chopped High Density Polyethylene (HDPE) plastic was sourced from plastic waste collectors in Jalan Lingkar Luar, Km 10, Palangka Raya City, Central Kalimantan. The process of producing and testing plastic crisps as artificial coarse aggregate is conducted at Highway Laboratory, Faculty of Engineering, University of Palangka Raya. The physical property tests of other artificial aggregates include softening and melting point test, flatness index and curvature index, specific gravity and absorption test, particle size distribution test and abrasion test.

Chunk molds are made as containers to shape plastic parts that have been melted from solid to liquid. The lump mold is made of a steel plate that is resistant to the heat of melting and conducts heat well so that the mold does not melt when it receives the hot plastic liquid after melting. The mold is made from a 2 mm thick steel plate that is welded into a rectangle with the following dimensions: length = 30 cm, width = 20 cm, height = 10 cm.

Shredded plastic material is first washed to prevent it from mixing with chemicals or other substances. It is then dried under sunlight to facilitate the melting process. The dried plastic fragments are placed in a mold until they reach the top of the mold and then weighed. The result is a weight of 2182.4 grams. During the melting process, the plastic fragments are heated in four stages, each weighing 545.6 grams, with a time interval of around 30 minutes between each stage. Once all the plastic fragments are in the mold, heating is continued until the plastic is evenly liquefied. Around 120 minutes are required to achieve uniform liquefaction. The heating is then stopped and natural cooling is carried out until the plastic liquids solidify (Figure 1a). This stage takes around 14 hours. The fragments are subsequently taken out of the mold and fractured with a hammer to transform into coarse aggregates (Figure 1b).

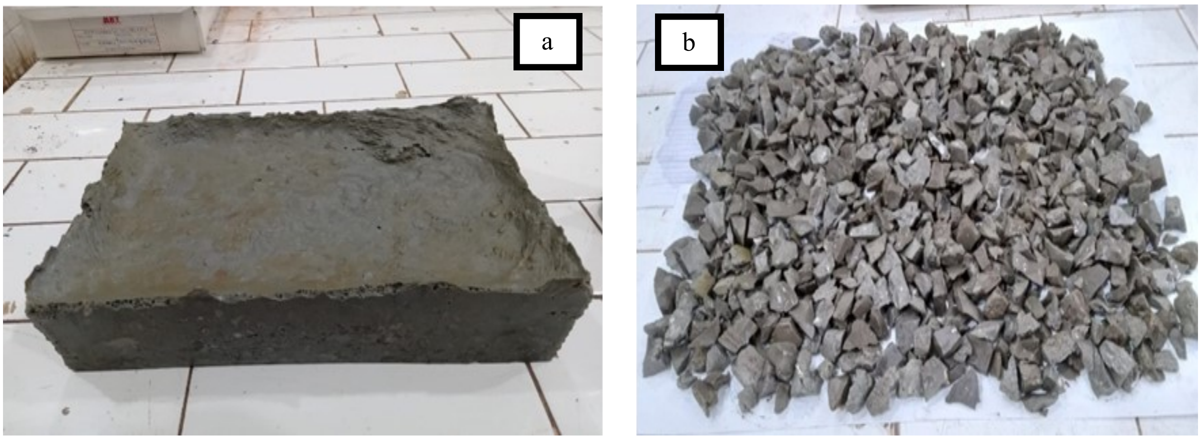

Figure 1. (a) plastic chunk, (b) artificial coarse aggregate

The artificial aggregate is then tested for its physical properties by applying the rules established by the Directorate-General for Highways for natural aggregates to find out whether it can be used for flexible road surfaces.

3. Results and Discussion

Testing the physical properties of artificial coarse aggregates is divided into testing the softening and melting points, the flatness and curvature indexes, specific gravity and absorption, particle size distribution and the abrasion of the aggregate.

3.1. Softening Point and Melting Point

The examination of the softening point is conducted when the melted plastic fragments begin to soften, whereas the examination of the melting point is carried out when the melted plastic fragments start transitioning from a softened state to a molten state. This assessment is performed using a temperature measurement tool such as a thermometer. The results of examining the softening and melting points of HDPE plastic waste fragments can be observed in Table 1.

The softening point and melting point examinations provide crucial insights into the thermal behavior of HDPE plastic waste fragments. The softening point, denoted as the temperature at which the plastic fragments begin to soften, was observed to range between 193°C and 195°C for the examined samples. On the other hand, the melting point, marking the transition from a softened to a molten state, ranged between 200°C and 202°C.

Softening point of HDPE plastic depends on the specific type of HDPE and its molecular weight. In general, however, HDPE starts to soften at around 125°C[16]. This means that at this temperature the

Table 1. Results of examination of the softening point and melting point of the shreds

No	Crushed weight of plastic waste (gr)	Softening point (°C)	Melting point (°C)	Hotmix temperature (°C)
1	2182,4	195	202	145-155
2	2182,4	194	201	145-155
3	2182,4	193	200	145-155
4	2182,4	195	202	145-155
	Average	194,25	201,25	

plastic starts to lose its rigidity and become more pliable, although it is not yet fully melted. At around that point, HDPE can maintain its mechanical properties and dimensional stability for a longer period of time. The melting point of HDPE is around 180°C[17]. This is the point at which the plastic changes from a solid to a liquid state. However, it is important to note that the actual temperature at which HDPE softens or melts can vary depending on the specific material properties. The softening and melting points of HDPE vary slightly depending on factors such as molecular weight, branching and test methods.

Table 2 presents the experimental results detailing the time required to achieve both the softening point and melting point of plastic waste during a controlled heating process. The investigation focuses on plastic waste with a consistent weight of 2182.4 grams. The softening point reaching time and time to reach the melting point are recorded for four separate trials, providing insights into the thermal behavior of the material under study.

Table 2. Time to achieve the softening point and melting point of the chop

No	Weight of plastic waste (grams)	Time to reach softening point (minutes)	Time to reach melting point (minutes)
1	2182.4	20.25	30.20
2	2182.4	19.75	29.80
3	2182.4	20.35	30.25
4	2182.4	19.80	29.75
	Average	20.25	30.20

Time it takes for HDPE plastic to start softening when heated can vary based on several factors, including the specific HDPE formulation, thickness, and the temperature at which it is heated. Our experiment shows that the softening point reaching time ranges from approximately 19.75 to 20.35 minutes, with an average value of 20.25 minutes. These values represent the time it took for the HDPE plastic waste, weighing 2182.4 grams, to start softening under the given experimental conditions. The softening point and melting point test is then carried out on the artificial aggregate produced. The softening point test is measured when the artificial coarse aggregate is heated and begins to soften, while the melting point test is performed when the heated artificial coarse aggregate begins to melt from soft.

Table 3. Results of examination of softening point and melting point of artificial coarse aggregate

No	Artificial coarse aggregate samples	Softening point (°C)	Melting point (°C)	Hotmix temperature (°C)
1	Sample 1	264	271	145-155
2	Sample 2	266	273	145-155
3	Sample 3	268	276	145-155
4	Sample 4	265	272	145-155

Table 4. Time to achieve softening point and melting point of artificial coarse aggregate

No	Artificial coarse aggregate samples (gram)	Time to reach softening point (minutes)	Time to reach melting point (minutes)
1	Sample 1	35.30	45.20
2	Sample 2	34.75	44.75
3	Sample 3	34.80	44.80
4	Sample 4	35.25	45.40
	Average	35.0	45.0

Based on the examination results conducted on HDPE plastic waste fragments and artificial coarse aggregates, a comparison of the temperatures reached for each heating time is presented below (Figure 2).

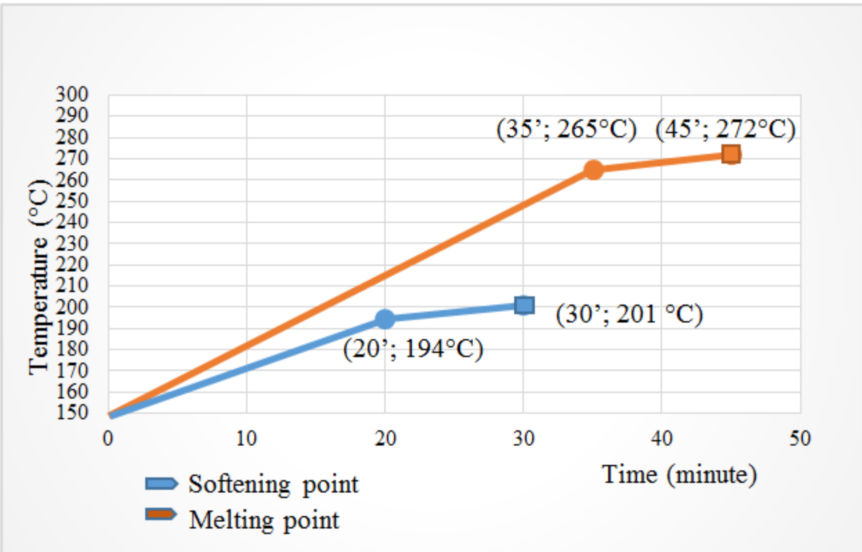

Figure 2. Comparison of softening point and melting point of chopped plastic waste and artificial coarse aggregate as a function of heating time

3.2. Flatness Index and Lumpyness Index

After the plastic chunks have been broken down into coarse aggregates, the next step is to check the uniformity and elongation indices using a thickness gauge (measuring device for the uniformity index) and a calliper gauge (measuring device for the elongation index) as in Figure 3. The uniformity and elongation indices are tested according to the ASTM D-4791-95 method. The use of the measuring device complies with SNI 03-4137-1996 with a maximum permissible percentage of 10%.

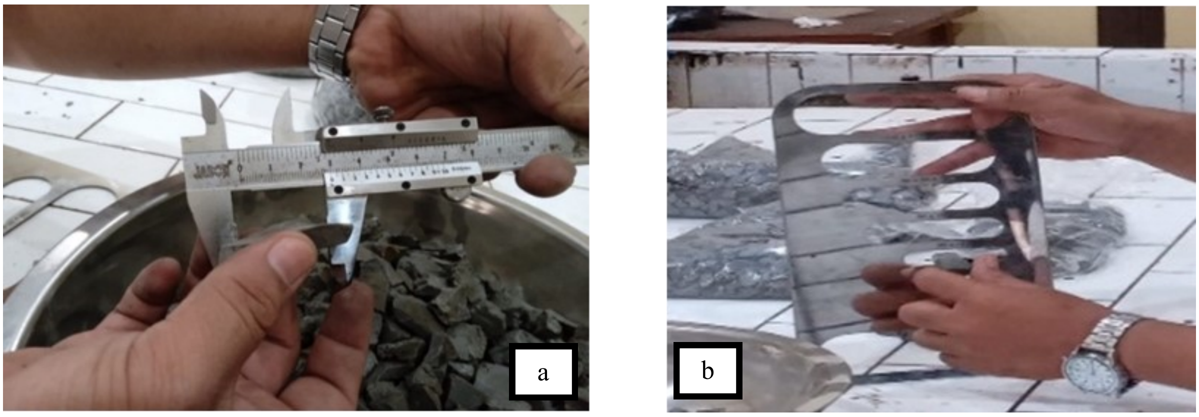

Figure 3. (a) Flatness index examination, (b) Lumpy index check

The results of the examination of the uniformity and elongation indexes for artificial coarse aggregates are in Table 5.

Table 5. Results of the examination of uniformity and elongation indexes

No	Filter	Retained weight (gr)	Retained (%)	Passed the flatness test (gr)	Withstands slime test (gr)
1	1/2	2500	50%	4,9	34,9
2	3/8	2500	50%	33,7	0
Total		M1 = 5000	M2 = 5000		
			M3F = 38,6 M3E = 34,9		
Flatness Index (%) = M3F/M2 = 38,6/5000 x100% = 0,77%					
Lumpyness Index (%) = M3E/M2 = 34,9/5000 x100% = 0,70%					

Remarks:
M1 = Total weight retained (test object)
M2 = Percentage retained (test object)
M3F = Passing the flatness test
M3F = Resistant swelling test

Notes:
Aggregate that passes the flatness test (not fulfilled)
Aggregate that passes the bulge test (not fulfilled)

3.3. Gradation Test of Artificial Coarse Aggregates

Gradation test of artificial coarse aggregates involves subjecting crushed test objects to abrasion testing in stages. The Bina Marga Specifications 2018, Revision 2 of 202018 is used for this test. Three experiments are conducted for sieve analysis of artificial aggregates, as shown in Table 6, Table 7 and Table 8. The test objects are crushed into artificial coarse aggregates, and the sieve analysis is performed to determine the particle size distribution. Pieces of test objects that have been crushed into artificial coarse aggregates are subjected to abrasion testing three times in stages weighing 1000 grams.

Table 6. First experiment for sieve analysis of artificial aggregates

Filter size		Sample I = 1000 gram			
		Retained weight	Total of retained weight	Percentage	
inch	mm			Retained	Pass
#3/4	19	0.00	0.00	0.00	100.00
#1/2	12.7	381.16	381.16	38.12	61.88
#3/8	9.5	355.12	736.28	73.63	26.37
No.8	2.38	220.97	957.25	95.73	4.27
No.30	0.595	23.70	980.95	98.10	1.90
No.200	0.074	14.15	995.10	99.51	0.49
Pan	-	4.90	1000.00	100.00	0.00

Table 7. Second experiment analysis of artificial aggregate sieve

Filter size		Sample II = 1000 gram			
		Retained weight	Total of retained weight	Percentage	
inch	mm			Retained	Pass
#3/4	19	0.00	0.00	0.00	100.00
#1/2	12.7	382.03	382.03	38.20	61.80
#3/8	9.5	354.28	736.31	73.63	26.37
No.8	2.38	218.97	955.28	95.53	4.47
No.30	0.595	24.34	979.62	97.96	2.04
No.200	0.074	15.08	994.70	99.47	0.53
Pan	-	5.30	1000.00	100.00	0.00

Table 8. Third experiment analysis of artificial aggregate sieve

Filter size		Sample III = 1000 gram			
		Retained weight	Total of retained weight	Percentage	
inch	mm			Retained	Pass
#3/4	19	0.00	0.00	0.00	100.00
#1/2	12.7	391.61	391.61	39.16	60.84
#3/8	9.5	356.98	748.59	74.86	25.14
No.8	2.38	221.13	969.72	96.97	3.03
No.30	0.595	17.61	987.33	98.73	1.27
No.200	0.074	9.24	996.57	99.66	0.34
Pan	-	3.43	1000.00	100.00	0.00

Based on Tables 6-8, cumulative sieve values are input into the Sieve Analysis Graph with the aim of determining the size gradation of Artificial Coarse Aggregates, as illustrated in Figure 4.

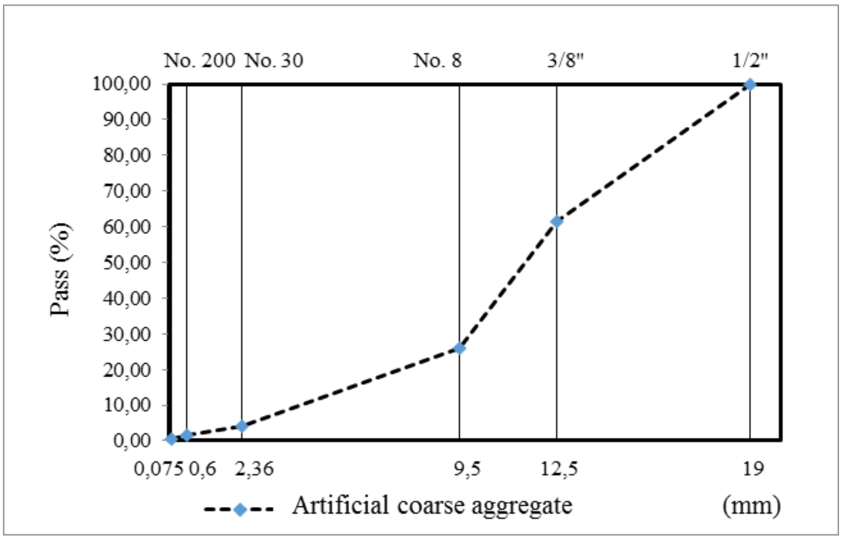

Figure 4. Artificial coarse aggregate sieve analysis

3.4. Specific Gravity and Absorption Examination

This inspection uses the standard of SNI 03-1969-2016, and the results are presented in the Table 9.

Table 9. Results of specific gravity and absorption

Description	Sample (gram)			Average
	I	II	II	
Oven dry test object weight (Bk)	4975.90	4972.00	4972.10	4973.33
Weight of saturated surface test object (Bj)	5063.40	5063.60	5063.50	5063.5
Test object weight in water (Ba)	1985.50	2008.70	1985.50	1993.23
Specific gravity (Bulk)	1.617	1.628	1.615	1.620
Saturated surface dry specific gravity	1.645	1.658	1.645	1.649
Apparent specific gravity	1.664	1.678	1.665	1.669
Absorption	1.758	1.842	1.838	1.813

Table 9 shows the influence of the most important characteristics on the specific weight and absorption of the artificial aggregate made of HDPE. Key parameters such as the weight of the oven-dry test object (Bk), the weight of the test object on the saturated surface (Bj), the weight of the test object in water (Ba), the specific weight (bulk), the specific weight on the saturated surface (dry), the apparent specific weight and the absorption are analyzed. The determined average dry weight in the oven is 4973.33 grams, which indicates the initial weight of the material before exposure to moisture. Under saturated conditions, the material can absorb a maximum weight of 5063.5 grams. This weight in water, which averages 1993.23 grams, is decisive for calculating the apparent specific gravity. The specific bulk density, which averages 1.620, provides information about the density of the material. The specific gravity of the saturated surface, which averages 1.649, indicates the maximum density under saturated conditions when the surface is dry. The apparent specific gravity, which averages 1.669, indicates the ratio between the weight of the material and an equal volume of water at saturation. The average absorption value, expressed as a decimal (1.813), indicates the water absorption capacity of the material, with higher values indicating greater water absorption capacity. Taken together, these results provide a comprehensive understanding of the physical properties of the material so that decisions can be made about its suitability for construction applications.

3.5. Abrasion Test

Examination of the Coarseness of Artificial Coarse Aggregate using the Binamarga 2018 Revision 2 Year 2020 standard on Analysis of Sieves for HRS-WC Road Pavement Mixtures[18]. The results of the abrasion test examination are presented in Table 10.

Table 10 shows that the abrasion value of the artificial coarse aggregate was 0.98% in the first experiment and 0.202% in the second experiment. The abrasion value indicates the percentage of material loss or wear that the artificial coarse aggregate experiences due to abrasive forces. This figure is almost insignificant, suggesting that the abrasion values observed, particularly the decrease from 0.98% to 0.202%, are relatively small or negligible. In other words, the degree of abrasion or degradation experienced by the artificial coarse aggregate under the test conditions can be considered minimal.

4. Conclusion

As the global demand for sustainable and eco-friendly construction materials continues to grow, innovative approaches to recycling and repurposing waste materials have become imperative. This paper delves into the realm of sustainable infrastructure by exploring the characteristics of artificial coarse aggregate derived from High Density Polyethylene (HDPE) plastic waste, with a specific fo-

Table 10. Examination of the abrasion of artificial coarse aggregate

Filter size		Gradation of artificial coarse aggregate			
		Sample I (gram)		Sample II (gram)	
Pass	Retained	Before	After	Before	After
3" (76,2 mm)	2,5" (63,5 mm)	-	-	-	-
2,5" (63,5 mm)	2" (50,8 mm)	-	-	-	-
2" (50,8 mm)	1,5" (37,5 mm)	-	-	-	-
1,5" (37,5 mm)	1" (25,4 mm)	-	-	-	-
1" (25,4 mm)	3/4" (19,0 mm)	-	-	-	-
3/4" (19,0 mm)	1/2" (12,5 mm)	2500.00	-	2500.00	-
1/2" (12,5 mm)	3/8" (9,5 mm)	2500.00	-	2500.00	-
3/8" (9,5 mm)	1/4" (6,3 mm)	-	-	-	-
3/8" (9,5 mm)	1/4" (6,3 mm)	-	-	-	-
1/4" (6,3 mm)	No. 4 (4,75 mm)	-	-	-	-
No. 4 (4,75 mm)	No. 8 (2,36mm)	-	-	-	-
Total Weight (gram)		5000.00	-	5000.00	-
Total retained weight sieve No. 12 (gram)		-	4995.10	-	4989.90
Abrasion (%)		0.098		0.202	
Average abrasion (%)		0.15			

cus on its application in highway flexible pavement. The pressing need for environmentally responsible construction practices has led to the development of alternative materials that not only mitigate the environmental impact of waste but also contribute to the longevity and performance of infrastructure. Our study embarks on a thorough investigation, employing various tests to discern the heating temperature required for HDPE plastic waste fragments to attain the necessary melting point for forming cohesive material chunks.

Based on our examination, the physical properties of the artificial coarse aggregate from HDPE plastic waste have the following characteristics. First, the softening point is 265°C with a heating time of 35 minutes and the melting point is 272°C with a heating time of 45 minutes, calculated from the start of heating. In addition, the flocculation index and the elongation index are 0.77% and 0.70% respectively, thus fulfilling the criteria of the specification SNI 03-4137-1996, which prescribes a maximum deviation of 10%. Next, the achieved gradation of the artificial coarse aggregate shows a passage of 100% through a 3/4" sieve and 66.88% through a 1/2" sieve. Lastly, the bulk density of the artificial coarse aggregate is 1.629, which makes it comparatively lighter than natural aggregate and below the standard SNI 03-1968-1990 (minimum 2.5). However, at 1.270%, the absorption of the artificial coarse aggregate corresponds to the specification of SNI 03-1968-1990, which provides for a maximum permissible absorption of 3%. e) The abrasion of the artificial coarse aggregate is 0.15% and thus corresponds to the Direktorat Jenderal Bina Marga standard[18], which provides for a maximum specification of 40%.

After going through this series of research, several strategic recommendations can be proposed. Firstly, artificial coarse aggregate derived from High Density Polyethylene (HDPE) plastic waste demonstrates significant potential as a partial substitute for natural coarse aggregate in road pavement mixtures. Despite the artificial coarse aggregate's tendency to have lower density and absorption, the practical recommendation is to use natural coarse aggregate to compensate for these shortcomings, thereby enhancing the overall performance of the road pavement mixture. Lastly, for further development, it is suggested that future research consider the use of plastic types other than HDPE. The primary goal is to gain a more comprehensive understanding of the quality of artificial coarse aggregates from various types of plastic waste, guiding the selection of optimal materials to support sustainable construction practices.

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