IJMECIE International Journal of Mechanical, Electrical and Civil Engineering
E-ISSN: 3047-4531
P-ISSN: 3047-4523

Research Article

Experimental Study of Artificial Coarse Aggregate Materials Made from Fly Ash

Rajiman[1]*, Ronny Hasudungan Purba[2], Inggit Anugriyya Netriza[3]

[1-3] Faculty of Engineering, Bandar Lampung University, Indonesia
* Corresponding Author: e-mail: rajiman.mt@gmail.com

Abstract: In general, infrastructure development requires materials from nature and one of them is natural coarse aggregate of crushed stone. The rapid development of infrastructure in Indonesia has resulted in the depletion of the natural coarse aggregate. Therefore, other efforts are needed in terms of using coarse aggregate as a construction material. So in this study the aim is to make artificial coarse aggregate made from fly ash. The results showed that this artificial coarse aggregate met the requirements of the General Specifications of Bina Marga 2010 rev 3 as a construction material, namely for an abrasion value of 40% and water absorption of 3%. In this study, 5 types of comparisons were carried out, namely, 70:30%, 60:40%, 50:50%, 40:60%, 30:70 and for the type of composition comparison 70:30% (70% fly ash:30% cement).) the abrasion value is still below 40%, and the amount of water absorption is below 3% so that this artificial coarse aggregate still meets the standard specifications of General Highways 2010 rev 3. Based on the price comparison that has been made between artificial coarse aggregate and natural coarse aggregate of crushed stone , shows a price disparity of Rp. 35,779 - Rp. 58,779. Thus, this artificial coarse aggregate is one solution that can be developed to reduce the environmental impact due to the presence of fly ash which is quite abundant in Indonesia.

Keywords: Abrasion; Aggregate; Cement; Fly Ash; Water Absorption

Received: August 16, 2025
Revised: October 11, 2025
Accepted: December 6, 2025
Published: January 31, 2026
Curr. Ver.: January 31, 2026

1. Introduction

Fly ash is a residue resulting from coal combustion in steam power plants, and its quantity continues to increase annually. In Indonesia, fly ash production is significantly abundant due to the growing national coal consumption by PT PLN (Persero). Wardani (2008) explains that fly ash is primarily composed of silica, alumina, and iron oxides. According to *Manual of Concrete Practice* (1993) Part 1 226.3R-3 and ASTM C 618, fly ash is classified into Class F and Class C. These characteristics make fly ash a potential alternative material in construction applications.

According to Wardani (2008), the classification of fly ash is determined by its calcium oxide content and pozzolanic properties. Class F fly ash generally has low CaO content and exhibits pozzolanic behavior, requiring additional activators to achieve optimal reactivity. This is consistent with the requirements outlined in ASTM C 618 regarding chemical and physical properties. The utilization of fly ash in construction not only reduces environmental waste but also enhances the value of combustion by-products. Therefore, innovation in processing fly ash into artificial aggregates becomes increasingly important.

Concrete, as a primary structural material, consists of cement, coarse aggregate, fine aggregate, and water. The strength of concrete is strongly influenced by the quality of aggregates, as they constitute approximately 70–75% of the total concrete volume. Through hydration reactions, Portland cement binds aggregate particles into a compact mass. However, continuous exploitation of natural aggregates may eventually lead to resource depletion. This condition encourages research into environmentally friendly alternative aggregates.

DOI : https://doi.org/10.61132/ijmecie.v3i1.389

The use of waste materials as artificial aggregates has been widely investigated over the past two decades. Adi (2016) demonstrated that metakaolin can serve as an alternative base material in the production of artificial lightweight aggregates. The study confirmed that combining pozzolanic materials improves the mechanical characteristics of aggregates. This finding suggests that fly ash can similarly be modified into artificial aggregates with properties comparable to natural aggregates. Thus, waste-based approaches offer sustainable construction solutions.

Putri et al. (2018) examined the effect of artificial aggregate variation on optimum asphalt content in wearing course pavements. The results indicated that artificial aggregates performed adequately in pavement structures. Sudrajat (2016) evaluated fly ash-based artificial aggregates under various curing temperatures. The study revealed that curing temperature significantly influences aggregate strength and abrasion resistance. These findings highlight the critical role of production processes in determining final aggregate quality.

In the context of geopolymer materials, Palomo et al. (1999) explained that fly ash can be alkali-activated to form alternative cementitious binders. Their study described alkali-activated fly ash as a “cement for the future.” Further research by Junaid et al. (2015) showed that geopolymer concrete using fly ash aggregates exhibits good performance after exposure to high temperatures. This approach demonstrates the versatility of fly ash utilization in various binding systems. Therefore, combining fly ash with cement or alkali activators is a promising strategy.

Various production methods for artificial aggregates have been developed, including granulation and cold-bonding processes. Frankovi et al. (2015) produced lightweight aggregates from fly ash using the cold-bond process for lightweight concrete applications. Hilda Yuliana et al. (2019) found that granulator slope significantly affects geopolymer aggregate characteristics. Shahane and Patel (2021) emphasized that curing methods strongly influence the properties of cold-bonded fly ash aggregates. These studies provide multiple alternatives for artificial aggregate manufacturing.

Srinivasan et al. (2016) utilized fly ash, rice husk ash, and iron ore dust in the production of artificial aggregates. George and Revathi (2020) reported that artificial coarse aggregates can be successfully applied in structural concrete. Kayathri et al. (2014) investigated the use of copper slag and fly ash as partial replacements for fine aggregates. Meanwhile, Arifi (2020) evaluated fly ash as a supplementary cementitious material in recycled aggregate pervious concrete. Collectively, these studies confirm the significant potential of fly ash in construction industries.

Regarding durability, Domagała (2020) reported that sintered fly ash aggregates demonstrate good resistance to freeze–thaw cycles. Sunil et al. (2021) found that alkali-activated coarse aggregates made from fly ash and slag exhibit stable mechanical performance. Nevertheless, key parameters such as specific gravity, water absorption, and abrasion resistance must still comply with technical standards. Specific gravity and water absorption testing refer to SNI 1969:2008. Abrasion resistance testing follows SNI 2417:2008.

Based on these previous studies, it can be concluded that the development of fly ash-based artificial aggregates has strong scientific foundations. The combination of fly ash with cement or alkali activators has been proven to produce aggregates with characteristics approaching those of natural aggregates. The main challenges lie in optimizing composition, production methods, and porosity control to meet technical standards. Therefore, this research focuses on producing fly ash-based artificial coarse aggregates with composition variations and performance evaluation according to national standards. This approach is expected to contribute to reducing coal waste while minimizing the excessive exploitation of natural aggregates in a sustainable manner.

2. Literature Review

This section must contain a state-of-the-art explanation. It can be explained in several ways. First, you can discuss several related papers, both about objects, methods, and their results. From there, you can explain and emphasize gaps or differences between your research and previous research. The second way is to combine theory with related literature and explain each theory in one sub-chapter.

Artificial Aggregate

Artificial aggregate is an engineered material designed to substitute natural aggregate in construction applications, particularly in road pavement layers. In flexible pavement structures, aggregates constitute approximately 90–95% of the total weight of the mixture, making them the dominant component. Therefore, the mechanical performance of pavements largely depends on the quality of aggregates used. The load-bearing capacity, durability, and service life of pavement systems are directly influenced by aggregate characteristics. For this reason, artificial aggregate must meet strict technical requirements.

The role of aggregates in pavement structures is to provide strength, stability, and resistance to deformation under traffic loads. Aggregates function as a skeleton within asphalt or concrete mixtures, distributing loads evenly throughout the structure. If the aggregate quality is poor, premature pavement failure such as rutting or cracking may occur. Consequently, the development of artificial aggregates must ensure comparable or improved performance relative to natural aggregates. This includes meeting standards for abrasion resistance and water absorption.

Artificial aggregates are produced through controlled processes using industrial by-products or waste materials. These materials may include fly ash, slag, bottom ash, or other mineral residues. Through granulation, sintering, or cold-bonding methods, the raw materials are shaped into aggregate particles. The manufacturing process allows better control over particle size distribution and internal structure. As a result, artificial aggregates can be tailored to meet specific engineering requirements.

According to Silvia Sukirman (1999), aggregates can be classified into three major groups based on their origin, processing method, and particle size. Based on origin, aggregates are divided into natural and artificial types. Natural aggregates are obtained directly from rivers, quarries, or crushed stone sources. Artificial aggregates, on the other hand, are produced through mechanical or chemical processing. This classification highlights the distinction between naturally occurring materials and engineered products.

Based on processing methods, aggregates may be categorized as crushed, screened, or manufactured. Crushed aggregates are obtained by mechanically breaking larger rocks into smaller pieces. Manufactured aggregates involve additional processes such as heating, bonding, or chemical activation. Artificial aggregates typically fall under the manufactured category due to their engineered production stages. The processing method significantly influences aggregate strength and surface texture.

Classification based on particle size divides aggregates into coarse aggregates, fine aggregates, and filler materials. Coarse aggregates are generally retained on a 4.75 mm sieve, while fine aggregates pass through it. Filler materials consist of very fine particles that fill voids between larger aggregates. Artificial aggregates can be produced in various sizes to match specific design requirements. Proper grading ensures adequate compaction and stability in pavement layers.

The physical properties of artificial aggregates must satisfy technical standards to ensure structural reliability. Important parameters include specific gravity, porosity, abrasion resistance, and water absorption. Low abrasion values indicate good resistance to mechanical wear. Low water absorption reflects a dense internal structure with minimal voids. These properties determine the long-term durability of pavement systems.

One advantage of artificial aggregates is their potential environmental benefit. By utilizing industrial waste materials, artificial aggregates help reduce landfill disposal and environmental pollution. Additionally, they minimize the exploitation of natural stone resources. This contributes to sustainable construction practices and resource conservation. Environmental considerations are increasingly important in modern infrastructure development.

Another important aspect of artificial aggregates is their economic feasibility. Although production costs may initially be higher, large-scale manufacturing can improve cost efficiency. The use of locally available waste materials can also reduce transportation expenses. Over time, artificial aggregates may become competitive alternatives to natural aggregates. Economic evaluation is therefore essential in assessing their practical application.

In conclusion, artificial aggregates play a significant role in supporting sustainable and durable pavement construction. Their classification based on origin, processing method, and particle size provides a framework for understanding their characteristics. Proper design and quality control are crucial to ensure performance comparable to natural aggregates. With continuous technological development, artificial aggregates have strong potential to replace or supplement conventional materials. Thus, they represent an important innovation in modern civil engineering practice.

Fly Ash

Fly ash, also known as pulverized fuel ash, is a by-product generated from the combustion of coal in thermal power plants. In Indonesia, coal-fired power stations operated by PT PLN (Persero) contribute significantly to the production of fly ash due to high electricity demand. During the combustion process, fine mineral impurities in coal melt and are carried upward with flue gases. As these particles cool, they solidify into very fine spherical particles. These particles are then collected before being released into the atmosphere.

Physically, fly ash appears as a fine, powdery material with a texture similar to Portland cement. Its particles are generally spherical in shape, which contributes to improved workability when used in cementitious mixtures. The color of fly ash ranges from light gray to dark gray depending on its chemical composition and carbon content. Because of its fineness, fly ash can easily disperse in mixtures and fill micro-voids between aggregate particles. This characteristic makes it suitable for various construction applications.

Fly ash is primarily composed of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and varying amounts of calcium oxide (CaO). The chemical composition depends on the type of coal used and the combustion conditions. Based on standard classifications such as ASTM C 618, fly ash is categorized into Class F and Class C. Class F fly ash has low calcium content and exhibits strong pozzolanic properties, while Class C contains higher calcium and may have self-cementing properties. These differences influence its performance in construction materials.

The collection of fly ash is typically carried out using electrostatic precipitators or mechanical dust collection systems. As described by Hidayat (1986), electrostatic precipitation is an efficient method that uses electrically charged plates to attract and capture fine ash particles from flue gases. This system prevents harmful emissions from being released into the environment. The collected fly ash is then stored in silos for further processing or utilization. Proper handling is necessary to maintain its quality and prevent environmental contamination.

Due to its pozzolanic properties, fly ash has become an important supplementary material in the construction industry. When mixed with water and calcium hydroxide, it reacts to form additional cementitious compounds that enhance strength and durability. Beyond its use as a cement replacement, fly ash can also be processed into artificial aggregates or geopolymer materials. Its utilization not only improves material performance but also reduces environmental waste. Therefore, fly ash represents both a challenge in waste management and an opportunity for sustainable construction innovation.

Curing

Curing is a treatment process applied to concrete to maintain adequate moisture and temperature conditions so that it does not lose water too quickly. This process is carried out immediately after the finishing stage and once the initial setting time has been reached. Proper curing ensures that hydration reactions continue effectively within the cementitious matrix. Without sufficient curing, concrete may experience premature drying, leading to reduced strength. Therefore, curing is a critical step in achieving optimal material performance.

The primary objective of curing is to ensure optimal hydration of cement compounds, including any additives or supplementary materials used in the mixture. Adequate hydration allows the formation of strong and stable bonding structures within the material. In addition, curing helps prevent excessive shrinkage caused by rapid or uneven moisture loss. Such shrinkage can result in surface cracking and internal microcracks. Maintaining balanced moisture conditions is therefore essential for durability.

Temperature control during curing is also important because hydration reactions are temperature-dependent. Extremely high temperatures may accelerate evaporation and cause thermal cracking. Conversely, very low temperatures may slow down hydration and delay strength development. Controlled curing conditions provide a stable environment for proper chemical reactions. This balance ensures that the material reaches its designed mechanical properties.

In this research, curing was applied to artificial coarse aggregates to maintain their internal moisture content. Similar to conventional concrete curing, the purpose was to support the bonding process between fly ash and the added cementitious or chemical additives. Maintaining adequate moisture prevents uneven drying that could create internal voids. A consistent curing process enhances the density and structural integrity of the artificial aggregate particles. As a result, the aggregates are expected to exhibit improved strength and durability.

Proper curing of artificial aggregates also minimizes the risk of cracking caused by differential moisture loss. When water evaporates too rapidly from the surface, internal stresses may develop within the aggregate structure. By controlling curing conditions, these stresses can be reduced significantly. This ensures that the fly ash and additive compounds react uniformly throughout the particle. Ultimately, effective curing contributes to producing high-quality artificial coarse aggregates with minimal defects.

Abrasion

Abrasion refers to the resistance of aggregates to wear, friction, and mechanical degradation due to impact and rubbing actions. In pavement and concrete applications, aggregates are subjected to repeated traffic loads and environmental stresses. Therefore, high abrasion resistance is essential to ensure long-term durability. Aggregates with poor abrasion resistance tend to break down easily under loading conditions. This can lead to reduced structural performance and premature failure.

The abrasion test is commonly conducted using the Los Angeles abrasion machine. This test measures the percentage of material loss after aggregates are subjected to rotation with steel balls inside a drum. The lower the percentage of wear, the better the aggregate quality. The procedure for abrasion testing in Indonesia follows SNI 2417:2008. Compliance with this standard ensures that aggregates meet minimum performance requirements for construction use.

Abrasion resistance is closely related to the internal structure and bonding strength of aggregate particles. Dense aggregates with strong internal cohesion generally exhibit lower abrasion values. Conversely, aggregates with high porosity or weak bonding tend to experience higher material loss. For artificial aggregates, proper material composition and curing are crucial to achieving adequate abrasion resistance. The production method directly influences the final mechanical properties.

In this research, abrasion testing was performed to evaluate the mechanical durability of artificial coarse aggregates made from fly ash. The test results were compared with the maximum allowable abrasion value specified in national standards. Variations in fly ash and cement composition were analyzed to determine their influence on wear resistance. The findings help identify the optimal mixture proportion that provides sufficient strength. This ensures that the artificial aggregates are suitable for structural applications.

Overall, abrasion testing serves as a key indicator of aggregate performance in road pavement and concrete structures. High resistance to abrasion contributes to improved durability and extended service life. For artificial aggregates, achieving acceptable abrasion values demonstrates their potential as substitutes for natural aggregates. Therefore, abrasion evaluation is an essential parameter in assessing the feasibility of fly ash-based aggregate development.

Absorption

Water absorption testing is an important parameter in evaluating concrete quality, particularly in relation to material density and durability. The water absorption value indicates the ability of concrete to absorb water through the pores within its internal structure. The lower the water absorption value, the more impermeable the concrete is, and the greater its potential resistance to environmental attacks such as water infiltration, chloride ion penetration, and freeze–thaw cycles. Mathematically, water absorption (WA) is calculated using the equation $WA = (Bb - Ba)/Ba \times 100\%$, where Ba represents the initial dry weight before immersion and Bb represents the weight after immersion. This parameter serves as an indirect indicator of concrete porosity.

According to Zhang & Zhong (2014), the overall compressive strength of concrete is strongly influenced by its surface condition and internal structure. A denser and more homogeneous microstructure produces higher compressive strength and lower water absorption values. Therefore, absorption testing is frequently used to describe the bonding quality between particles within concrete. However, in certain artificial aggregate applications, aggregate strength cannot be evaluated solely based on water absorption parameters. Additional mechanical tests are required to obtain comprehensive performance data.

The utilization of fly ash as a primary material in the production of artificial aggregates has been widely studied in recent years. Putri et al. (2018) used a pan granulator method with a composition of 75% fly ash and 25% alkali activator. The mixture gradation was adjusted according to the Bina Marga Technical Specifications 2010 Revision 3 for asphalt wearing courses. The results demonstrated that fly ash-based artificial aggregates have strong potential as alternatives to natural aggregates, particularly in supporting sustainable construction practices.

Sudrajat (2016) evaluated fly ash-based artificial aggregates under various curing temperature conditions. The manufacturing process employed a pan granulator with a diameter of 120 cm, a slope of 40°, and a rotational speed of 26 rpm. The binder consisted of an alkali activator solution made from sodium silicate (Na_2SiO_3) and sodium hydroxide ($NaOH$). Variations in curing temperature were found to significantly influence the density and strength of the artificial aggregates produced. This indicates that thermal treatment plays a crucial role in determining aggregate performance.

Another study by Adi (2016) focused on combining metakaolin and fly ash in different compositions to obtain the optimum mixture for artificial lightweight coarse aggregates. The parameters tested included compressive strength, bulk density, and porosity. The results showed that mixture composition greatly determines the internal structure of aggregates. Higher porosity levels were directly proportional to increased water absorption values. Therefore, careful proportioning is essential to control aggregate performance.

Frankovi et al. (2015) explained that a granulation process with a 60° slope and a mixer speed of 48 rpm produced relatively uniform aggregate pellets. During granulation, water was sprayed to assist the formation of particle clusters. This technique influenced pore distribution within the aggregates, which in turn affected their mechanical properties and water absorption behavior. Proper granulation improves particle compactness and reduces excessive void formation.

Güneyisi et al. (2013) investigated the agglomeration process of fly ash aggregates by spraying water for the first 10 minutes to form clusters, followed by continued rotation until hardening occurred. Only aggregates retained on a 4 mm sieve were selected for testing. The process influenced particle size and compactness levels, which subsequently affected water absorption and mechanical resistance. The findings emphasize the importance of particle selection and processing control in artificial aggregate production.

Research on the durability of structural lightweight concrete made from sintered fly ash aggregates was conducted by Domagała (2020). The study evaluated 12 concrete series in terms of water absorption, permeability, and freeze–thaw resistance. Microstructural analysis was performed using Scanning Electron Microscopy (SEM). The results indicated that a denser microstructure produced lower water absorption values and improved durability performance. This confirms the relationship between internal structure and durability.

The use of coal waste such as bottom ash as artificial aggregate material was also examined by Ediantonius Lubis et al. (2015). The optimum composition obtained was 1 part cement : 3 parts fly ash : 20 parts bottom ash with a water requirement of 25–35% of the bottom ash weight. The water absorption value of the artificial aggregate in SSD condition reached 23.25%, indicating relatively high absorption due to pore formation during production. This suggests that pore structure control remains a major challenge in artificial aggregate development.

Overall, previous studies demonstrate that the utilization of fly ash, bottom ash, and geopolymer materials in artificial aggregate production has significant potential for environmentally friendly construction. Nevertheless, water absorption remains a critical indicator in assessing aggregate and concrete quality. The relationship between material composition, production method, curing temperature, and microstructure strongly determines absorption values and compressive strength. Therefore, further research is necessary to optimize composition and production methods in order to produce artificial aggregates with low water absorption and optimal mechanical performance.

3. Research Method

Based on the General Specification of Highways 2010 rev 3 there are seven types of tests for coarse aggregates. The material used must pass sieve No. 200. Next, find out the artificial aggregate requirements for each test. The test specimens are made according to the needs and left at the required curing temperature. Variations in curing/treatment temperature are carried out in four variants, namely room temperature, 80oC, and 60oC using an oven machine. Then, tests are carried out on artificial aggregates, this test is limited to 2 tests, namely abrasion and specific gravity and water absorption. Because there is no applicable standard for both the manufacture and testing of artificial aggregate specific gravity, the standards used in this study are adjusted to the technical requirements listed in the General Specification of Highways 2010 rev 3 and abrasion testing (SNI 2417: 2008). This research plan is prepared through a flow chart presented in Figure 1.

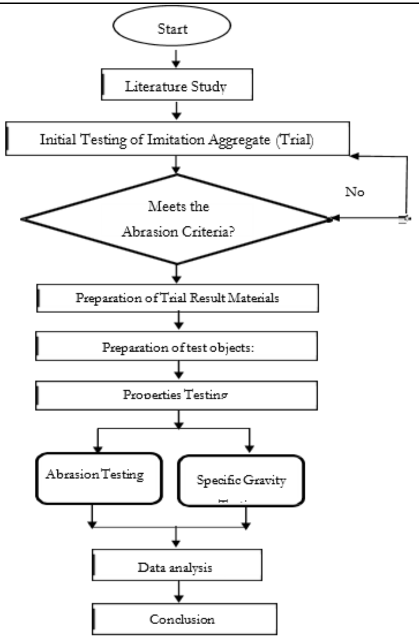

Figure 1. Research Flowchart

4. Results and Discussion

Several stages in the research are (1) testing the characteristics of the material on coarse aggregate in the form of specific gravity and water absorption testing then testing with a Loss Angeles machine to determine the wear value, (2) determining the workability of the mixture of material compositions, namely fly ash against geopolymer and fly ash against the addition of cement and additive mixtures (3) making samples for abrasion testing with a Loss Angeles machine with a retained sieve of ½ and ¾ at a ratio of 30:70%, 40:60%, 50:50%, 60:40%, 70:30% as well as testing the specific gravity and water absorption in the form of a circle with a retained sieve of ½ and ¾ at a ratio of 50:50%, 60:40%, 70:30% (4) curing was carried out on all test objects which was carried out for 24 hours at a temperature of 60oC

Research Test Objects

The research specimens were designed with several composition variations to evaluate the mechanical and physical characteristics of the artificial coarse aggregates. These variations were prepared to determine the optimal mixture proportion capable of producing aggregates with adequate strength and durability. The primary parameters evaluated in this study were abrasion resistance, specific gravity, and water absorption. Each specimen represented a different ratio of fly ash to cement in order to observe the influence of material composition on aggregate performance. This systematic variation allowed for a comprehensive comparison between mixtures.

The preparation of the specimens began with the mixing of fly ash, cement, water, and additive materials according to the predetermined composition ratios. The materials were blended until a homogeneous mixture was achieved to ensure uniform particle formation. After mixing, the material was shaped manually into aggregate-sized particles corresponding to coarse aggregate grading requirements. The formed aggregates were then left to stabilize before undergoing the curing process. Careful handling during this stage was necessary to prevent premature cracking or deformation.

Curing was conducted at a controlled temperature of 60°C for 24 hours after specimen production. This curing condition was selected based on preliminary trials indicating that it provided better aggregate performance compared to room temperature or higher oven temperatures. The purpose of curing was to maintain internal moisture and allow optimal hydration of cement and pozzolanic reactions of fly ash. Adequate curing ensured stronger bonding within the aggregate structure. As a result, the aggregates achieved improved density and mechanical integrity.

After the curing process was completed, the specimens were subjected to abrasion testing to evaluate their resistance to mechanical wear. In addition, specific gravity and water absorption tests were carried out to determine density and porosity characteristics. These tests are essential indicators of aggregate quality, particularly for pavement and concrete applications. Lower abrasion values and controlled absorption levels indicate better durability performance. Therefore, the testing phase provided critical data for assessing the feasibility of the artificial aggregates.

The variations of the research specimens are summarized in Table 1, which presents the composition ratios used in the abrasion and physical property tests. Each variation was carefully labeled and tested under identical conditions to ensure consistency and reliability of results. The comparison among specimens enabled the identification of the most effective mixture proportion. Through this experimental design, the study aimed to establish a technically acceptable artificial aggregate composition. Ultimately, the specimen variations formed the basis for performance evaluation and further analysis.

Table 1. Comparisons Used in Abrasion Testing

No	Types of Comparison	Materials used in abrasion testing		
1	70 : 30	70% fly ash	30% cement	
2	60 : 40	60% fly ash	40% cement	
3	50 : 50	50% fly ash	50% cement	26% Sika and distilled water
4	40 : 60	40% fly ash	60% cement	
5	30 : 70	30% fly ash	70% cement	

Fly Ash Class F

The basic materials used in this study have previously passed material testing with the XRD method known in the SEM-EDX testing method, namely in the form of fly ash content testing carried out at PT. Sucofindo Lampung. The results obtained show that the fly ash content is a type of fly ash classified as type F fly ash. In this study, the pozzolanic properties of fly-ash were studied.

Figure 2. (a) Third Experiment m8 r2 with curing oven temperature 80^{o}
(b) test specimen after curing system oven temperature 60o Celsius for 24 hours

The primary material used in this research was fly ash, which had previously undergone material characterization testing to determine its chemical and mineralogical composition. The analysis was conducted using X-Ray Diffraction (XRD) to identify crystalline phases present in the material. In addition, microstructural and elemental composition analyses were performed using Scanning Electron Microscopy coupled with Energy Dispersive X-ray spectroscopy (SEM-EDX). These tests provided detailed information regarding the oxide composition and particle morphology of the fly ash. Comprehensive characterization was necessary to ensure the suitability of the material for artificial aggregate production.

The laboratory testing was carried out at PT. Sucofindo Lampung, an accredited material testing institution. The results indicated that the fly ash used in this study belongs to Class F fly ash. Class F fly ash is characterized by low calcium oxide (CaO) content and high silica (SiO_2) and alumina (Al_2O_3) composition. This classification confirms that the material exhibits strong pozzolanic properties rather than self-cementing behavior. Therefore, an additional binder such as cement or chemical activator is required to enhance its binding capacity.

The pozzolanic nature of Class F fly ash plays an important role in the formation of artificial aggregates. Pozzolanic materials react with calcium hydroxide in the presence of water to form additional calcium silicate hydrate (C–S–H) gel, which contributes to strength development. In this research, the pozzolanic reaction was expected to improve the internal bonding of aggregate particles. The reaction process helps reduce porosity and enhance structural integrity. Consequently, understanding the chemical properties of fly ash was essential before proceeding to specimen production.

Figure 2(a) illustrates the third trial specimen (m8 r2) subjected to curing at an oven temperature of 80°C. At this temperature, rapid moisture loss was observed, which potentially affected the surface quality of the aggregate particles. Some specimens exhibited minor cracking due to accelerated drying conditions. This indicated that excessively high curing temperatures might negatively impact aggregate integrity. Therefore, curing temperature required careful optimization.

Figure 2(b) shows the specimen after undergoing a curing process at 60°C for 24 hours. Compared to the 80°C treatment, the 60°C curing condition produced aggregates with more stable and uniform physical characteristics. The surface appeared denser with fewer visible cracks or defects. This suggests that moderate curing temperatures provide a more controlled hydration and pozzolanic reaction process. As a result, curing at 60°C for 24 hours was considered the most suitable condition for producing high-quality artificial coarse aggregates in this study.

Imitation Coarse Aggregate Made from Fly Ash and Geopolymer

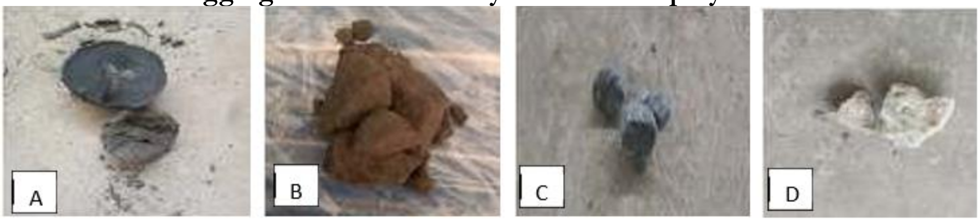

Figure 3. (a) testing using naphtha (b) testing using mixed concrete and (c) testing using sika. (d) natural stone fragments

The development of artificial coarse aggregates in this study involved the use of fly ash combined with different binding materials, including geopolymer-based mixtures and chemical additives. The objective was to evaluate which binder provided the best mechanical performance and physical stability. Several trial mixtures were prepared using naphtha-based materials, conventional concrete mix binders, and Sika additives. Each mixture was molded into coarse aggregate particles and subjected to identical curing conditions. The curing process was conducted at an oven temperature of 60°C to ensure consistent comparison among specimens.

Figure 3(a) shows the test results of aggregates produced using a naphtha-based binder. Under the 60°C curing condition, these aggregates exhibited structural weakness and were prone to breakage. When subjected to impact or simple drop tests, the particles fractured easily into smaller fragments. This indicated insufficient bonding strength between fly ash particles. The internal cohesion formed by the naphtha-based material was not adequate to withstand mechanical stress.

Figure 3(b) illustrates the aggregates produced using a conventional concrete mix binder. Although the particles initially appeared more compact than the naphtha-based specimens, they still showed weaknesses. During drop testing, partial fragmentation and surface disintegration were observed. In some cases, the aggregates experienced slight softening or crumbling upon impact. This behavior suggested that the bonding mechanism was not fully optimized under the selected curing condition.

In contrast, Figure 3(c) presents the aggregates manufactured using Sika as an additive binder. These specimens demonstrated significantly improved integrity and resistance to breakage. When compared to natural crushed stone shown in Figure 3(d), the fracture pattern of the Sika-based aggregates closely resembled that of conventional aggregates. The particles exhibited sharper, more stable fracture surfaces and did not easily crumble upon impact. This indicates stronger internal bonding and better mechanical performance.

Based on the comparative trial results, it can be concluded that the Sika-based mixture provided the most favorable performance among the tested binders. The combination of fly ash and Sika additive, followed by curing at 60°C for 24 hours, produced aggregates with superior durability and structural stability. The optimized curing condition allowed adequate hydration and bonding reactions to occur without excessive moisture loss. Therefore, the Sika-based composition was selected as the most suitable formulation for producing artificial coarse aggregates in this research.

Abrasion Testing SNI 2417:2008

This study aims to prove that the following mixture design will be used in making imitation coarse aggregate from trial results using a Los Angeles machine, as shown in table 4.5 which shows a list of test objects and their mixture composition.

Figure 4. Test Object

Abrasion testing in this research was conducted to evaluate the mechanical durability of artificial coarse aggregates in accordance with SNI 2417:2008. The primary objective was to verify whether the selected mixture designs from the preliminary trials were suitable for producing artificial aggregates with adequate resistance to wear. The Los Angeles abrasion machine was used to simulate mechanical impact and friction conditions similar to those experienced in pavement applications. The list of test specimens and their respective mixture compositions are presented in Table 4.5. Figure 4 illustrates the prepared specimens prior to testing.

The testing procedure followed the abrasion requirements specified in the General Specifications of Bina Marga 2010 Revision 3, which state that the maximum allowable abrasion value must be below 40%. During the test, the aggregate samples were placed inside the rotating drum along with steel balls and rotated for a specified number of revolutions. After completion, the material was removed and sieved. The percentage of material passing through sieve No. 12 (1.70 mm) was calculated to determine the abrasion loss. This value represents the aggregate's resistance to mechanical degradation.

Based on the preliminary trials using naphtha, conventional concrete mix, and Sika as binding materials, significant differences in abrasion performance were observed. The naphtha-based aggregates showed high material loss due to weak bonding strength. Similarly, the concrete mix specimens did not achieve optimal abrasion resistance. In contrast, the Sika-based mixture demonstrated superior performance and produced abrasion values closer to the required standard. Among the tested compositions, the 50:50 ratio showed the most promising result.

The abrasion test result for the 50% fly ash and 50% binder (Sika-based) composition yielded a value of 24.45%. This value is well below the maximum limit of 40% specified in the Bina Marga 2010 Revision 3 requirements. The relatively low abrasion percentage indicates strong internal bonding and adequate resistance to mechanical wear. These findings confirm that the selected mixture proportion meets national technical standards for aggregate durability. Therefore, the Sika-based artificial aggregate can be considered mechanically acceptable.

Based on these results, further property evaluations such as specific gravity and water absorption testing were conducted for the planned mixture variations. The satisfactory abrasion performance justified proceeding with additional physical characterization tests. The systematic evaluation ensured that the selected artificial aggregate composition not only met abrasion standards but also complied with other technical performance criteria. This comprehensive testing approach strengthens the validity of the research findings.

Specific Gravity and Absorption Testing (SNI 1969 – 2008)

Figure 5. (a) Aggregate Absorption Process (b) Aggregate Result Weighing (c) Aggregate Result

The specific gravity and absorption tests were conducted by preparing materials such as a water-filled tub, a cup, a scale, and a sieve to place the test specimens in during immersion. The required test specimens were in a ratio of 70%:30% A and B, 60%:40% A and B, and 50%:50% A and B. The calculation table above shows that the specific gravity of the artificial aggregate (on an oven-dry basis) ranges from 1.428 to 1.260, thus meeting Hutama Karya's 3% specification. Meanwhile, the water absorption rate ranges from 2.597 to 1.676, which is relatively high but still meets the 2010 General Bina Marga Specifications, Rev. 3, which requires a maximum of 3%. The high water absorption rate of this artificial aggregate indicates that the voids in the artificial aggregate are relatively good. This is indeed a good form of imitation aggregate, where the aggregate/granules produced do not have many large voids.

Aggregate Wear/Abrasion Test Results (SNI SNI 2417:2008)

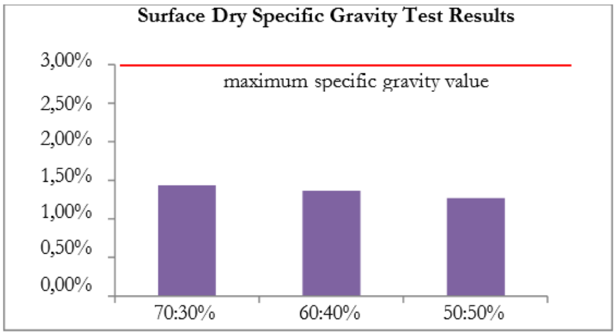

Figure 6. Results of Surface Dry Specific Gravity Testing Graph

Surface Saturated Dry (SSD) specific gravity is necessary because normally used concrete only partially permeates the water-permeable pores. Figure 4.18 shows that using a 60°C oven temperature does not significantly affect the SSD specific gravity. The SSD specific gravity remains within the range of 1.3. This test was conducted with three material ratios: 70:30%, 60:40%, and 50:50%. Therefore, these results are still below the maximum specific gravity value according to Bina Marga 2010 rev 3, which is a maximum of 3%. Figure 16 shows that the Apparent Specific Gravity Test results for aggregates cured at 600°C have the highest apparent specific gravity value, at 1.45, at a ratio of 70:30%. Figure 17 shows that increasing the ratio or the amount of fly ash used will increase the absorption value of the artificial aggregate.

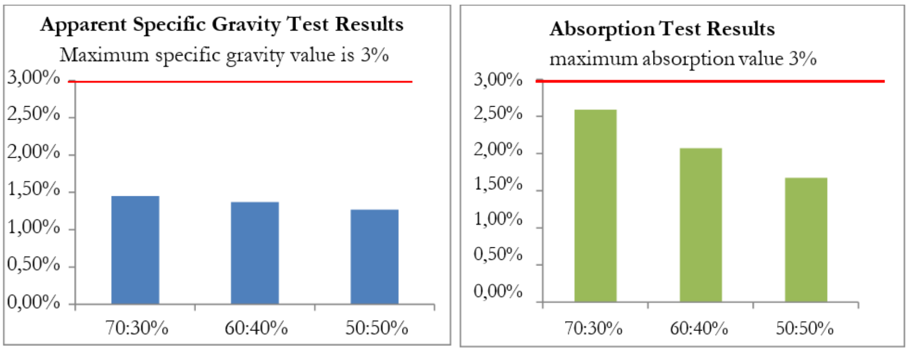

Figure 7. Apparent Specific Gravity Test Results and Absorption Test Graph Results

Crushed Stone Natural Aggregate Price

Table 2. Price of Crushed Stone Natural Aggregate

No	Type of Material	Unit	Unit price	Information
1	Crushed stone 0.5 - 1 cm / Screening	M^3	340.600	The specific gravity of natural aggregate is 1,800 kg/m3
2	Crushed stone 1 - 2 cm	M^3	404.600	

The price data presented in this study were obtained from the unit price analysis of construction materials in Bandar Lampung in 2021. These prices represent the market value of natural crushed stone commonly used as coarse aggregate in construction projects. The specific gravity of natural coarse aggregate was referenced from publicly available technical sources using the keyword “specific gravity of coarse aggregate.” The average bulk density considered in this calculation was 1,800 kg/m^3. This value was used as the basis for converting the price per cubic meter into price per kilogram.

To determine the price per kilogram of natural crushed stone with a size of 0.5–1 cm (screening), the unit price per cubic meter was divided by the bulk density. The recorded price was Rp. 340,600 per m^3. By dividing this value by 1,800 kg, the unit cost becomes Rp. 189.22 per kg. This calculation provides a more practical comparison basis with artificial aggregate prices, which are typically analyzed in weight units. Converting to kilogram units ensures consistency in cost evaluation.

Similarly, for crushed stone with a size of 1–2 cm, the recorded market price was Rp. 404,600 per m^3. Using the same bulk density assumption of 1,800 kg/m^3, the cost per kilogram is calculated by dividing Rp. 404,600 by 1,800 kg. The result is Rp. 224.78 per kg. This method standardizes the comparison between different aggregate sizes. It also allows for a more transparent economic analysis.

The conversion from cubic meter pricing to kilogram pricing is essential because artificial aggregate production costs are generally calculated based on material weight proportions. Since artificial aggregates in this research are formulated using fly ash, cement, and additives measured in kilograms, cost comparison must follow the same unit basis. This approach ensures fairness and accuracy in evaluating economic feasibility. Without uniform units, cost analysis may lead to misleading conclusions.

Overall, the calculated prices of Rp. 189.22 per kg for 0.5–1 cm crushed stone and Rp. 224.78 per kg for 1–2 cm crushed stone serve as reference values for comparing natural and artificial aggregates. These values highlight the economic benchmark that artificial aggregates must meet to become competitive alternatives. The cost comparison provides important insight into the financial viability of replacing natural aggregates with fly ash-based artificial aggregates in construction applications.

Comparison of Costs of Artificial Coarse Aggregates and Natural Aggregates

This cost comparison between artificial aggregate and natural crushed stone aggregate was conducted to determine the price disparity between the two. This is crucial given the significant effort required to ensure that artificial aggregate is widely accepted.

Table 3. Price of Crushed Stone Natural Aggregate

No	Aggregate Size	Artificial aggregates	Natural aggregate	Difference
1	Crushed stone 0.5 - 1 cm / Screening	Rp 911.38	Rp. 189.22	Rp. 722.16
2	Crushed stone 1 - 2 cm	Rp 911.38	Rp. 224.78	Rp. 686.60

The cost comparison between artificial coarse aggregates and natural crushed stone aggregates was conducted to determine the price disparity between the two materials. This analysis is essential because economic feasibility plays a crucial role in the acceptance of artificial aggregates in the construction industry. Even if technical performance meets required standards, cost competitiveness remains a determining factor for large-scale implementation. Therefore, a direct price comparison per kilogram was carried out. The results are summarized in Table 3.

Based on Table 3, the production cost of artificial aggregate is Rp. 911.38 per kg for both size variations. In contrast, the price of natural crushed stone sized 0.5–1 cm (screening) is Rp. 189.22 per kg. This results in a price difference of Rp. 722.16 per kg. Similarly, for crushed stone sized 1–2 cm, the natural aggregate price is Rp. 224.78 per kg, resulting in a difference of Rp. 686.60 per kg compared to artificial aggregate. These values clearly indicate a significant cost gap.

The large price disparity shows that artificial aggregates are currently less economical than natural aggregates. The production process of artificial aggregates involves additional materials such as cement and chemical additives, as well as energy consumption for curing. These factors contribute to higher manufacturing costs. In contrast, natural aggregates require relatively simple extraction and crushing processes. As a result, natural aggregates remain more affordable in the current market.

Due to this substantial price difference, artificial aggregates cannot yet fully replace natural aggregates as the primary material in concrete production. Although technically feasible, the economic burden may discourage contractors and developers from adopting artificial alternatives. Cost efficiency is especially important in large-scale infrastructure projects where material quantities are significant. Therefore, further optimization in production methods and material sourcing is necessary to reduce costs.

In conclusion, while artificial aggregates made from fly ash offer environmental benefits and acceptable technical performance, they are not yet economically competitive. The price differences of Rp. 722.16 and Rp. 686.60 per kg indicate that artificial aggregates remain more expensive than natural crushed stone. Consequently, despite the abundant availability of fly ash in Indonesia, artificial aggregates cannot currently be considered a fully viable solution for replacing natural aggregates. Future research should focus on improving cost efficiency to enhance practical applicability.

5. Comparison

This study demonstrates that artificial coarse aggregates made from Type F fly ash, as identified through testing at PT. Sucofindo, exhibit competitive performance compared to previous studies on coal combustion waste–based artificial aggregates. When compared with the study by Putri et al. (2018), which employed a pan granulator method and alkali activators, this research offers a simpler approach by utilizing cement and Sika additive as binding materials, without requiring a complex alkali activation system. This simplification enhances the practicality of the production process. As a result, the method proposed in this study is more applicable for medium-scale implementation.

In terms of abrasion value, the results indicate that the mixture containing 70% fly ash and 30% cement achieved a wear value below 40%, complying with the General Specifications of Bina Marga 2010 Revision 3 and SNI 2417:2008. In certain compositions, the abrasion value reached 24.45%, which is technically superior to several previous studies that reported values close to the maximum allowable limit. This finding suggests that the use of Sika additive combined with oven curing at 60°C for 24 hours significantly enhances the abrasion resistance of the artificial aggregate. Therefore, the curing method and additive selection play a critical role in improving mechanical durability.

Compared to the study conducted by Sudrajat (2016), which utilized sodium silicate and sodium hydroxide as geopolymer activators, this research provides advantages in terms of field applicability. Although geopolymer systems can produce high-density aggregates, they require stricter chemical control and more complex preparation procedures. This study proves that a conventional cement-based approach can still produce aggregates that meet technical specifications. Hence, the proposed method offers a more straightforward alternative without compromising performance standards.

Regarding water absorption, the artificial aggregates in this study exhibited absorption values ranging from 1.676% to 2.597%, remaining below the maximum limit of 3% specified in SNI 1969:2008. When compared to the study by Ediantonius Lubis et al. (2015), which reported absorption values up to 23.25% for bottom ash–based aggregates, the aggregates produced in this research demonstrate a much denser and more controlled pore structure. Lower absorption values indicate better durability and resistance to environmental exposure. This confirms the effectiveness of the selected composition and curing method.

When compared with the research by Domagała (2020), which utilized sintered fly ash aggregates at high temperatures, the method in this study is more energy-efficient, as it only requires oven curing at 60°C for 24 hours. While sintering produces highly dense microstructures, it demands significant energy consumption and higher production costs. In contrast, the present study offers a more economical and energy-saving alternative. This makes it more feasible for implementation in developing regions or medium-scale industries.

In terms of compositional variation, this study systematically examined five different fly ash–cement ratios, ranging from 30:70 to 70:30. This provides a more comprehensive analysis compared to previous studies that often focused on one or two optimal mixtures. The results show that increasing fly ash content tends to increase water absorption values. Therefore, achieving an optimal balance between fly ash and cement is essential to maintain both mechanical performance and durability.

From the specific gravity perspective, the artificial aggregates produced in this research have oven-dry specific gravity values ranging from 1.260 to 1.428, classifying them as lightweight to medium-weight aggregates. In comparison, natural crushed stone typically has a density of approximately 1,800 kg/m^3. The lower density of artificial aggregates offers potential benefits in reducing structural self-weight, particularly for applications requiring lightweight concrete. This characteristic may provide additional advantages in certain construction scenarios.

However, from an economic standpoint, the study reveals that artificial aggregates remain more expensive than natural aggregates in the Bandar Lampung region. The significant price disparity indicates that natural aggregates are still more commercially competitive. Unlike several international studies that achieved cost efficiency through mass production, this research remains at the laboratory scale, where production costs are not yet optimized. Consequently, further development is required to improve economic feasibility.

The main contribution of this study compared to state-of-the-art research lies in the integration of technical evaluation (abrasion, specific gravity, and water absorption) with direct cost analysis. Many previous studies focused primarily on mechanical properties without addressing economic viability. By incorporating a comparative cost analysis, this research provides a more realistic assessment of practical implementation. This comprehensive approach strengthens the relevance of the findings for industry stakeholders.

Overall, compared to previous studies on fly ash–based artificial aggregates, this research contributes a simpler production method, lower curing energy requirements, and evidence that a composition of 70% fly ash and 30% cement with Sika additive meets national technical specifications. Although further cost optimization is necessary, the technical results reinforce the potential of fly ash as a viable alternative material. This study supports efforts to reduce natural aggregate exploitation and mitigate the environmental impact of coal combustion waste in Indonesia.

6. Conclusion

From this research based on trial and error conducted imitation coarse aggregate made from fly ash can be made into imitation coarse aggregate by adding Sika additive in the mixing process. This can be proven by the results of the tests that have been done in chapter 4 and it was found that imitation coarse aggregate cured at 60o oven temperature performed better than room temperature or 80o oven temperature as seen from the proportional test that meets SNI. So in the use of a good material composition is to use a ratio of 70% fly ash and 30% cement with the need for 26% additive material, namely Sika, which is proven in property tests, namely abrasion tests and specific gravity and absorption in accordance with the SNI for each test. Then based on cost calculations, the price of artificial aggregate is economical. With a price disparity of Rp. 722.16 and Rp. 686.60, artificial aggregate can be the only choice as a substitute for concrete material. And thus, this artificial aggregate is one solution that can be developed further to reduce the environmental impact due to the abundant volume of fly ash in Indonesia. So the suggestion from the results of this study is that this study has produced that the basic material of fly ash can be used as an imitation coarse aggregate and for further research can be done making concrete using fly ash-based coarse aggregate. and in the process of making imitation coarse aggregate is done manually, in further research so that the manual manufacturing method becomes automated can be done using imitation coarse aggregate molding tools. And In this study has also produced that the basic material of fly ash can be used as an imitation coarse aggregate with an additional composition, namely sika additive material so that for further research can be done making asphalt designs that originally used natural aggregates replaced by the use of fly ash-based coarse aggregates.

Author Contributions: Conceptualization: Rajiman and Ronny Hasudungan Purba; Methodology: Rajiman; Software: Inggit Anugriyya Netriza; Validation: Rajiman, Ronny Hasudungan Purba and Inggit Anugriyya Netriza; Formal analysis: Rajiman; Investigation: Rajiman; Resources: Ronny Hasudungan Purba; Data curation: Inggit Anugriyya Netriza; Writing original draft preparation: Rajiman; Writing review and editing: Ronny Hasudungan Purba; Visualization: Inggit Anugriyya Netriza; Supervision: Ronny Hasudungan Purba; Project administration: Rajiman; Funding acquisition: Ronny Hasudungan Purba.

Funding: This research received no external funding.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request. No publicly archived datasets were generated during the current study. All experimental data were obtained from laboratory testing conducted at the Faculty of Engineering, Universitas Bandar Lampung, and are stored in institutional records.

Acknowledgments: The authors would like to express their sincere gratitude to the Faculty of Engineering, Universitas Bandar Lampung, for providing laboratory facilities and technical support throughout the experimental process. Appreciation is also extended to the laboratory staff for their assistance during material preparation and testing. The authors acknowledge the material support provided in the form of fly ash samples and construction additives used in this research. Additionally, the authors declare that AI-based writing assistance tools were used solely to support language refinement and manuscript structuring, while all scientific analysis, experimental results, and interpretations remain entirely the responsibility of the authors.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

Adi, E. P. (2016). *Pemanfaatan metakaolin sebagai bahan dasar alternatif pembuatan agregat ringan buatan*.

American Concrete Institute. (1993). *Manual of concrete practice* (Part 1, 226.3R-3). American Concrete Institute.

Arifi, E. (2020). Evaluation of fly ash as supplementary cementitious material to the mechanical properties of recycled aggregate pervious concrete.

ASTM International. (2018). *ASTM C618: Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*. ASTM International.

Domagała, L. (2020). Durability of structural lightweight concrete with sintered fly ash aggregate.

Frankovič, A., Bokan Bosiljkov, V., & Ducman, V. (2015). Lightweight aggregates made from fly ash using the cold-bond process and their use in lightweight concrete.

George, G. K., & Revathi, P. (2020). Production and utilisation of artificial coarse aggregate in concrete.

Junaid, M. T., Khennane, A., & Kayali, O. (2015). Performance of fly ash-based geopolymer concrete made using non-pelletized fly ash aggregates after exposure to high temperatures.

Kayathri, K., Vigneshkumar, C., Rani, M., Gohila, K., & Karthik, K. (2014). Effect of copper slag, fly ash and granite powder as a partial replacement in fine aggregate.

Palomo, A., Grutzeck, M. W., & Blanco, M. T. (1999). Alkali-activated fly ashes: A cement for the future. *Cement and Concrete Research, 29*(8), 1323–1329. https://doi.org/10.1016/S0008-8846(98)00243-9

Putri, I. R. B., Hariyadi, H., Karyawan, I. D. M. A., & Ahyudanari, E. (2018). Pengaruh variasi penambahan agregat buatan terhadap kadar aspal optimum untuk perkerasan aspal lapis aus.

Shahane, H. A., & Patel, S. (2021). Influence of curing method on characteristics of environment-friendly angular shaped cold-bonded fly ash aggregates.

Silvia Sukirman. (1999). *Perkerasan lentur jalan raya*. Nova.

SNI 1969:2008. (2008). *Cara uji berat jenis dan penyerapan air agregat kasar*. Badan Standardisasi Nasional.

SNI 2417:2008. (2008). *Cara uji keausan agregat dengan mesin Los Angeles*. Badan Standardisasi Nasional.

Srinivasan, K., Mutharasi, M., Vaishnavi, R., Mohan, S., & Logeswaran, V. (2016). An experimental study on manufacture of artificial aggregates incorporating fly ash, rice husk ash and iron ore dust.

Sudrajat. (2016). Penilaian agregat buatan berbahan dasar fly ash untuk bahan perkerasan jalan di berbagai variasi suhu perawatan.

Sunil, R., Panicker, L., Parvathy, M., Vijayan, R., Athira, K. K. P., & Ramaswamy. (2021). Preparation and properties of alkali-activated coarse aggregates using fly ash and slag.

Wardani. (2008). Klasifikasi dan komposisi fly ash.