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Project IGNITE 2024

Intelligence Green Material for Better Resilience

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Project title: **Intelligence Green Material for Better Resilience (IGNITE)**

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1. Context

Energy resources are the key factor in industrial activity, and integral to fostering economic prosperity. The conventional way to obtain energy is by combustion of energy resources such as fossil fuels, coal, or biomass and generating heat that can be used for many processes in production. Indonesia and Malaysia have similarities in their geographical feature, allowing for similar types of natural resources. Both countries have abundant coal reserves and biomass energy sources from large palm oil.

The innovations developed in Project IGNITE have significant cross-sectoral policy implications, particularly within the context of Malaysia's and Indonesia's policy environments. In Indonesia, the government's decision to delist coal ash from hazardous materials in 2021, *based on PP Nomor 22 Tahun 2021*, indicates a policy shift that could facilitate the utilization of coal fly ash (CFA) in construction. However, this decision also raises concerns about environmental and health impacts that need to be managed through stringent regulatory frameworks and enforcement.

In Malaysia, the emphasis on biomass energy from palm oil waste aligns with national policies aimed at promoting renewable energy. The Malaysian government has implemented the National Biomass Strategy 2020 to maximize the value of biomass resources, which supports the utilization of Palm Oil Fuel Ash (POFA) in geopolymer concrete. The alignment of Project IGNITE with these national strategies underscores the potential for policy support in scaling these innovations.

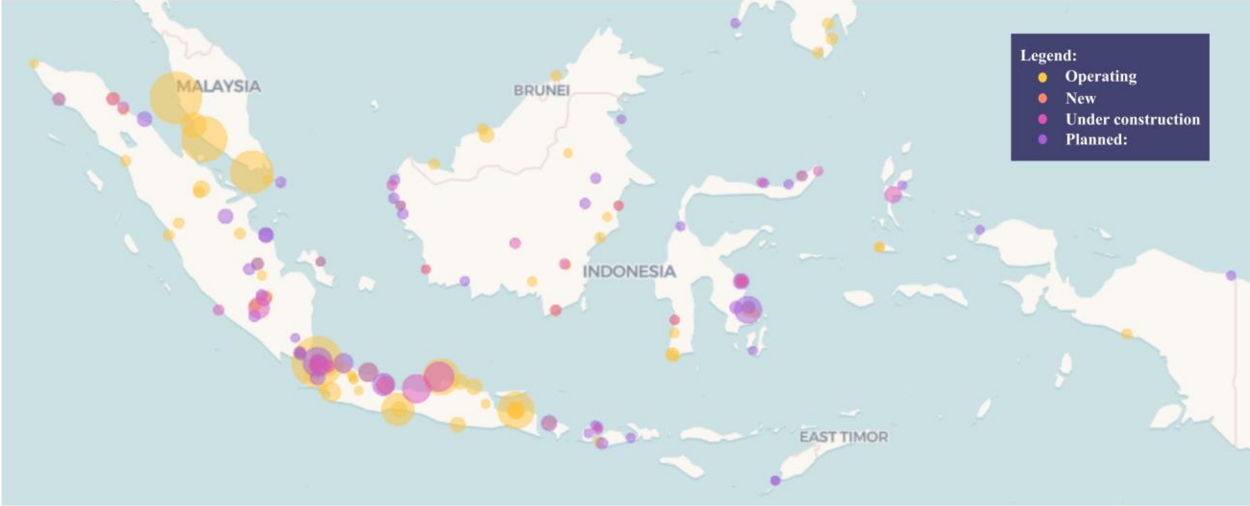


Figure 1 Map of coal power plant in Indonesia and Malaysia 2024 (Source: *https://www.carbon-brief.org/mapped-worlds-coal-power-plants/)*

In term of coal energy source, current state of coal consumption based on IEA report on 2020 shows that Indonesia and Malaysia are among the top coal producer and consumers within South-East Asian region registering 138, and 39 Mt/year coal consumption respectively [1], [2]. Coal consumption in this region is rapidly increasing, and by 2025, ASEAN is predicted to become the third-largest coal consumer in the world which mainly driven by Indonesia and Malaysia demands, surpassing the United States and the European Union. Coal is mostly used as an energy source to generate electricity for Southeast Asian region and the proportion of coal as the source of energy rapidly growing from 8.125% in 2000 into 25.8% of total energy consumption. As depicted in Figure 1, the numbers of coal power plant in both Indonesia and Malaysia is expected to rise in the coming years. This increase is strikingly different from the increase in renewable energy sources which only increased by 4.5% in the same period. This situation is predicted to continue since the governments are more pragmatic approach to the policy to fulfil country's energy demand with coal-energy source. The clear example of the government policy toward coal energy can be reflected in Indonesian government's controversial decision in 2021 to delist coal ash from their list of hazardous materials, after the material had been stay as a hazardous material for decades. This decision and many more example of policy tend to boost the coal consumption since coal energy is cheaper than other energy sources and abundantly available in Indonesia and Malaysia.

On the context of biomass energy, the palm oil industry in Indonesia and Malaysia generates energy primarily through the utilization of biomass, particularly palm kernel shells and empty fruit bunches, as well as by employing biogas captured from palm oil mill effluent. Currently, Indonesia and Malaysia are top producers of palm oil in the world. Despite this biomass energy resource is considered as renewable, burning this biomass to generate energy can give negative impact since the process resulting waste material known as palm oil fuel ash (POFA). POFA can give negative impact to environment since it can alter chemical and physical properties of soil which impacting vegetation and wildlife.

Fly ash waste management is a complex problem, with only less than 10% of fly ash waste generated being utilized by the cement and ready-mixed concrete industries. The remaining ash is disposed of in landfills, causing increased environmental concerns. The government has encouraged interdisciplinary research to develop cleaner technologies to reduce the environmental impact of combustion waste from industrial activity.

Currently, the state of technology proposes to reduce the environmental impact of combustion waste utilization by substituting cement with Coal Fly Ash (CFA) or POFA as a binding agent in geopolymer concrete. By utilizing CFA and POFA as an alternative and economical construction material, this solution will eliminate the environmental effect caused by these materials whilst also reducing the utilization of Portland cement.

Geopolymer concrete with rich calcium materials generally has higher early strength, better durability, and can cure at ambient temperatures. However, it may have reduced workability, shorter setting time, and increased carbonation risk. Furthermore, rapid setting time may be prone to cracking, reducing the durability of geopolymer products in long-term use. Introducing self-healing and self-sensing characteristics into geopolymer-based concrete products is a potential solution to this issue.

2. Objectives and Scope of Work

Thus, the development of self-healing and self-sensing geopolymer concrete for construction will give effect in three areas i.e. a significant reduction in the amount of carbon dioxide emitted by the cement manufacturing industry, increasing the utilization of carbon waste material for construction benefitting social economy of society and improving the monitoring and maintenance of the structure for more resilience infrastructure. Implementing self-healing and self-sensing geopolymer concrete can significantly reduce maintenance costs and extend the lifespan of infrastructure. This innovation can lead to economic savings estimated at 15-20% in maintenance and repair costs over the structure's lifetime. Additionally, the improved durability of infrastructure can reduce downtime and associated economic losses.

From a social perspective, the adoption of these technologies can create new job opportunities in the fields of smart materials and construction technology. Training and development programs will be essential to equip the workforce with the necessary skills, fostering local employment and enhancing economic stability in the regions.

The challenges to scaling this innovation include the initial cost of technology adoption, the need for specialized training, and potential resistance from traditional construction stakeholders. However, the long-term benefits of reduced environmental impact and improved infrastructure resilience present a strong case for investment.

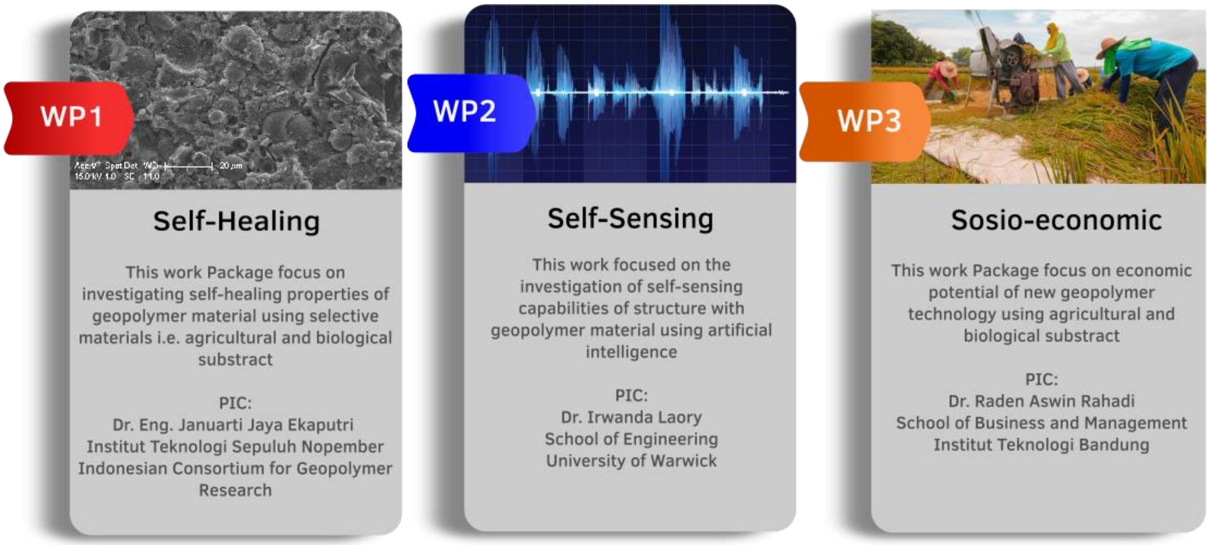


Figure 2 Work packages in Project IGNITE

Hence, the objectives are described as follows:

1. Work package 1(WP1) in IGNITE project aims to produce a non-cementitious geopolymer material which can increase the utilization of fly ash (i.e. coal-based fly ash and palm oil fuel ash) for construction material which will contribute for reducing environmental harm and leverage the effort to achieve sustainable cities and communities as targeted in point 11th and 13th of Sustainable Development Goals.
2. Work Package 2 (WP2) aims to identify self-sensing capabilities that appropriate in geopolymer-based concrete and useful for crack monitoring in concrete structure. The Structural Health Monitoring research team from University of Warwick which lead by Dr. Irwanda Laory will investigate smart material that can be injected into the concrete material to allow crack monitoring.

3. Work Package 3 (WP3) investigates the effect of geopolymer concrete technology to increase fly ash utilization and reducing carbon emission from Portland cement manufacture. Furthermore, it will identify further multiplier effect on social-economy aspect due to fly ash utilization.
4. General goals of the project is aimed to engage with industry, construction practitioner and and governmental official through outreach to brainstorming further development direction which in line with market demand and expectation as well as dissemination the current development from research in IGNITE project to the stakeholder.

Based on the objectives above, the scope of work is determined as follows:

- Exploring the characterization of fly ash from different power plant resource.
- Exploring the use of artificial aggregates for container of self-healing agent and technique to make it.
- Exploring the material for self-sensing on concrete
- Proof of concept to use the self-healing and self-sensing geopolymer concrete as a proxy to replace Portland Cement to reduce air pollution and fly ash problem.

3. Methodology

3.1 Evaluating smart geopolymer concrete: Self-healing and Self-Sensing factors

Fly ash is a key component in geopolymer concrete, offering several advantages over traditional Portland cement. It is abundant, cost-effective, and has excellent workability and physical properties. When used in geopolymer concrete, fly ash reduces CO2 emissions and costs, and provides superior performance, including better resistance to aggressive environments. This makes it an environmentally friendly and high-performing alternative to traditional concrete. Furthermore, the use of fly ash in geopolymer concrete minimizes waste production from thermal power plants, addressing both waste disposal and environmental concerns.

Geopolymer concrete benefits significantly from the inclusion of fly ash due to its unique properties that enhance both the performance and sustainability of the concrete. Fly ash, a by-product of coal combustion, is rich in aluminosilicates, which are essential for the repolymerization process (a process where small molecules creating larger molecules). When mixed with an alkaline activator, these materials form a strong, durable binder that gives geopolymer concrete its excellent mechanical properties, including high compressive strength and enhanced resistance to chemical attacks and environmental degradation.

However, before jumping into utilization of fly ash for geopolymer concrete with self-healing and self-sensing capabilities, we need to identify the characteristic of coal-based fly ash from each source in Indonesia and Palm Oil Fuel Ash (POFA) from Malaysia. Samples from various resource is collected for comparison.

As described in Figure 3, for the material characterization, extensive lab work is conducted using various testing and instrumentation, as shown in Figure 3. In the IGNITE project, the samples fly ash and POFA is analyzed by using Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD) and and X-Ray Fluorescent (XRF) to determine its chemical and physical characteristic as illustrated in Figure 3.

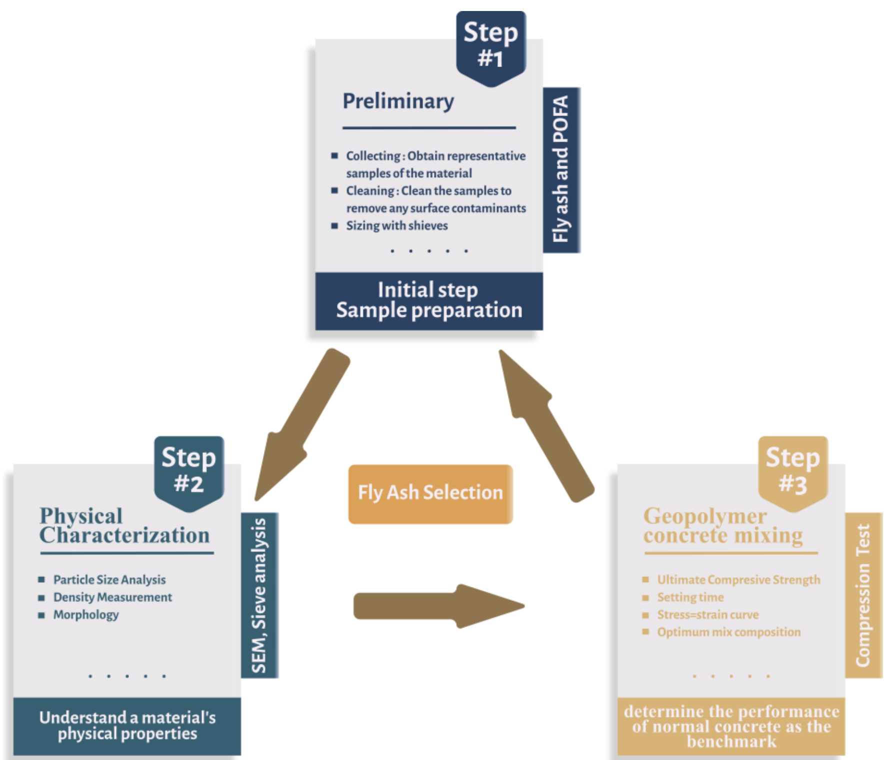


Figure 3 Flowchart for fly ash and POFA characterization.

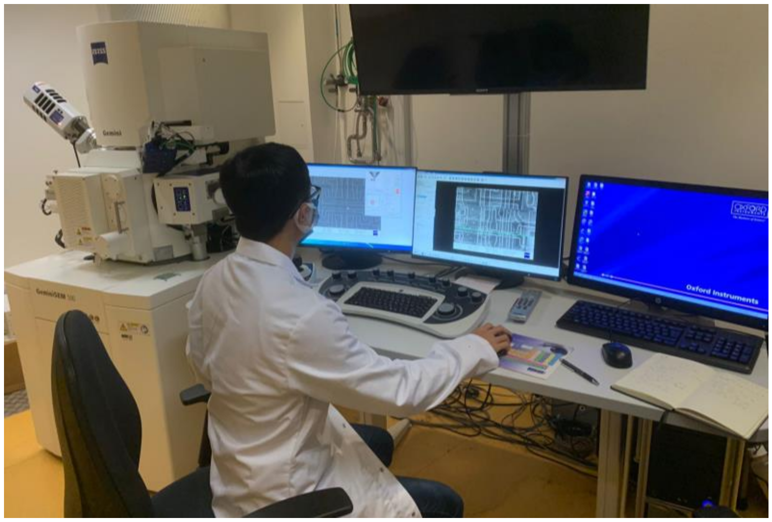


Figure 4 Physical characterization with SEM

There are three main types of used in coal power i.e. Pulverized Coal Combustion (PCC) boilers, Circulating Fluidized Bed (CFB) boilers, and Stoker boilers.

They offer excellent fuel flexibility, allowing them to burn various grades of coal. Nevertheless, PCC boilers must manage pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulates through extensive emissions control systems. These systems' low maintenance and high efficiency make them an ideal choice for utility-scale plants that aim to provide high power output and reliable performance.

Compared with PCC boilers, they emit fewer sulfur dioxide and nitrogen oxides, making them attractive for plants that must comply with environmental regulations. However, CFB boilers can be complex to operate and require sophisticated control systems for managing the fluidized bed and combustion process effectively.

Stoker boilers operate by mechanically feeding solid fuels (like coal) into the combustion chamber using a chain grate or reciprocating grate system. This design is more straightforward than PCC and CFB boilers, making them suitable for smaller-scale power plants or industrial applications. Stoker boilers offer fuel flexibility and to burn various solid fuels efficiently. However, they generally have lower thermal efficiency than PCC and CFB boilers. Modern stoker boilers incorporate emission control technologies to comply with environmental regulations, but their operational efficiency may still be lower than that of more advanced boiler types.

The combustion temperatures of PCC, CFBC and SC were in the ranges of 1000 - 1200°C, 800 - 900°C, and 650-700°C, respectively. Due to this difference, the fly ash produced from each type of boiler have difference characteristic. This difference will influence the performance of geopolymer concrete mixing with each type of fly ash. Hence, the fly ash characterization must identify fly ash from each of boiler type. For this project, the spread of coal power plant and type of its boiler can be summarized in Figure 3.

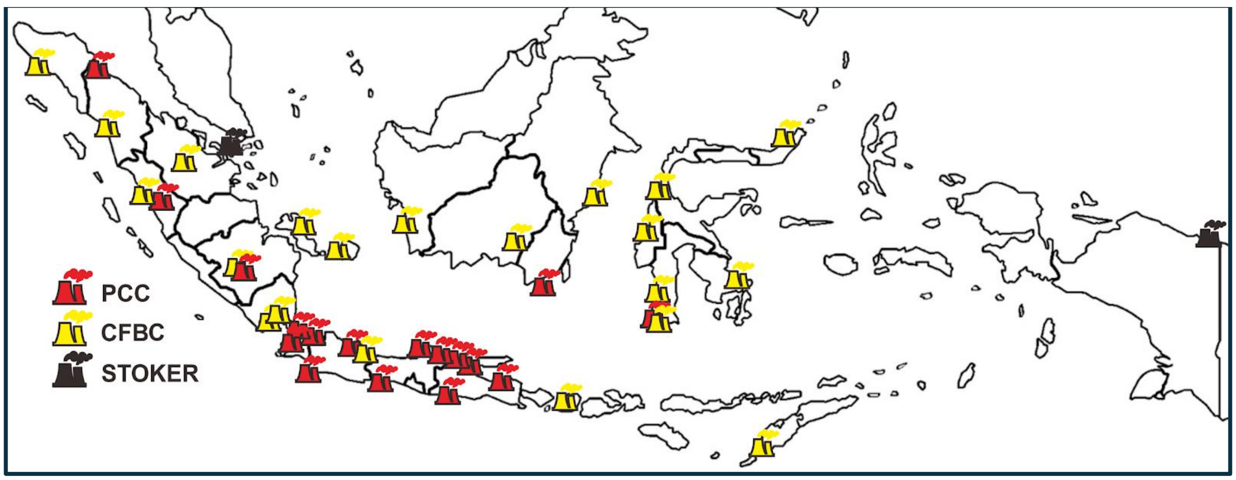


Figure 5 Location of power plant and its boiler type

After characterization of fly ash is completed, the selected fly ash is used to make geopolymer concrete. In this work, the mix design for making geopolymer concrete is calculated based on several contents i.e. Aluminosilicate Source(fly ash), Alkaline Activator Solution, fine and course aggregates.

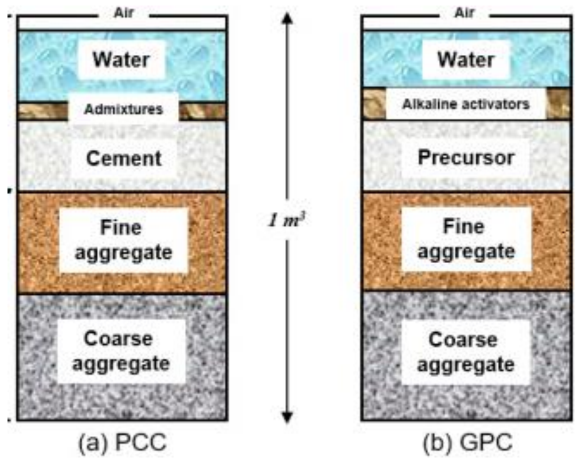


Figure 6 Comparison of component in Portland Cement concrete (PCC) and Geopolymer Concrete (GPC)

There are two factors that allowing normal concrete can be improved into smart concrete i.e. self-healing and self-sensing. Self-healing materials are designed to autonomously repair damage, such as cracks or scratches, either through intrinsic properties or embedded healing agents. This ability extends the lifespan of materials, reduces maintenance costs, and contributes to sustainability by lowering the need for replacements and raw materials. These materials are particularly valuable in industries where material integrity is crucial, such as construction, aerospace, and automotive, as well as in consumer products to improve durability and reduce environmental impact.

Self-sensing materials, on the other hand, can detect changes in their condition or environment, providing real-time data on factors like stress, strain, or temperature. This capability enhances safety through early damage detection and facilitates predictive maintenance by informing optimal maintenance schedules. Self-sensing materials are critical in applications requiring structural health monitoring, such as infrastructure and medical devices, and can also enhance manufacturing processes. Combining self-healing and self-sensing characteristics can create advanced materials that are both resilient and intelligent, leading to more durable and efficient systems across various industries.

To create concrete with self-healing characteristics, the process begins with the preparation and mixing of materials. First, artificial aggregate designed for self-healing is prepared and included in the mix, replacing a fraction of the traditional coarse aggregate. The mixing procedure carefully monitors the consistency of the fresh concrete to ensure optimal quality and appropriate setting time. Once mixed, the concrete is cast into samples and allowed to cure. The consistency of the concrete mix is crucial to ensure that the self-healing properties are effectively incorporated. After curing, the concrete samples are tested for their initial strength using a Universal Testing Machine (UTM), providing a baseline for comparison with results after self-healing.

After initial strength testing, artificial cracks are introduced into the concrete samples. The healing process is then monitored at ambient temperatures, focusing on the effects of moisture. This involves observing the cracks interacting with environmental moisture, which triggers the healing agent within the artificial aggregate. The healing agent undergoes a chemical reaction upon contact with water, producing a solid material that fills the cracks and bonds with the surrounding concrete, effectively restoring the structure's integrity. Key factors influencing healing acceleration include microbe preparation, curing conditions, crack size, and mineral addition. Throughout this phase, mechanical and physical tests are conducted to evaluate the effectiveness of the self-healing process, ensuring that the concrete regains its strength and durability over time.

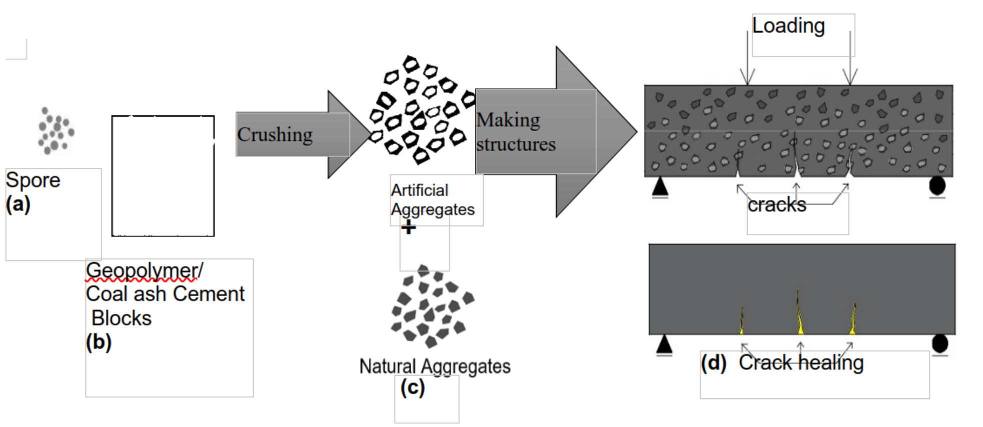


Figure 7 (a) Microbe spores containing food supplement; (b) Artificial aggregate is used for capsulation the spores; (c) Aggregates is mixed with natural aggregates in concrete; (d) When the crack occurs, the microbe acts as crack healer in the gap.

On the other hand, the self-sensing characteristic in geopolymer concrete which investigated in Project IGNITE is obtained by enhancing the unique electrical properties of fly ash with additional conductive agent such as graphite and milled carbon fiber. Self-sensing capability in concrete refers to the ability of concrete to detect and monitor its internal condition based on its respond to various environmental and mechanical conditions. The benefits of self-sensing, particularly in the context of Structural Health Monitoring (SHM) of civil infrastructure, is the ability to transform the structures into self-diagnostic systems. This enables automatic detection of faults or damage after critical events such as earthquakes, thereby enabling real-time diagnostic and prognostic data. Self-sensing technologies, such as smart concrete and smart bricks, provide measurable electrical output under mechanical loads, aiding in damage detection, localization and quantification.

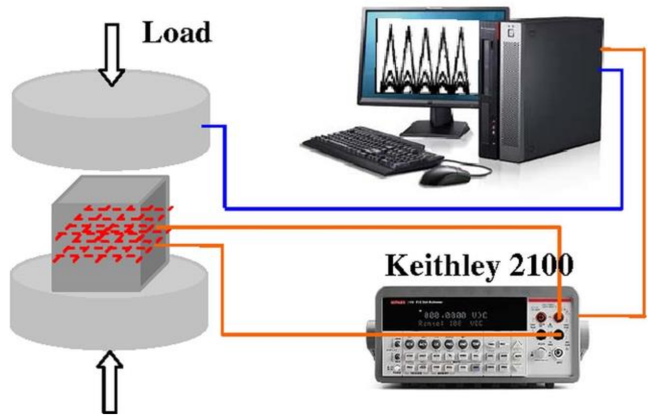


Figure 8 Self-sensing investigation method

Self-sensing in concrete has been vastly studied to provide a more effective and efficient solution for robust structural health monitoring systems in concrete structures. Self-sensing characteristic is divided into two main categories i.e. intrinsic self-sensing and non-intrinsic or extrinsically self-sensing concrete. Non-intrinsic self-sensing concrete is defined as the concrete's capability to monitor its own condition by involving external sensors to measure and monitor certain parameters that can represent the condition of structures. This approach employs embedded sensors in the concrete and measures the certain parameters based on external input to the concrete. There are many types of embedded sensors applied for non-intrinsic approaches such as stress, strain, crack, temperature, humidity, etc. On the other hand, the intrinsic self-sensing do not need external or embedded sensors/device to monitor its condition. Instead of inserting the sensors into the structure, this approach uses additional material/fillers to generate parameter which is related to damage monitoring. In Project IGNITE, we used the later approach for geopolymer concrete by investigating geopolymer-based sensor for crack detection.

3.2 Evaluating social-economy aspect of the impact of smart geopolymer-concrete

The IGNITE Project uses literature synthesis to evaluate the socio-economic implications of implementing smart geopolymer concrete derived from coal fly ash and palm oil fuel ash (POFA) in the building sector. We chose this methodology because it offers a comprehensive approach that allows us to systematically assess and analyze existing knowledge from various sources. Through the integration of peer-reviewed publications, industry reports, and reliable online databases, this project aims to understand the potential economic savings, environmental benefits, and social implications of the innovations introduced by Project IGNITE. The selection of this methodology ensures that the assessment is grounded in robust, well-established research and provides a holistic view of the impacts of fly ash and POFA utilization in construction.

The research methodology for this study is divided into three main phases: data collecting, data extraction, and data analysis. During the data collection phase, an extensive search is conducted across multiple databases, including Google Scholar, JSTOR, ScienceDirect, and industry-specific databases such as the American Concrete Institute (ACI) and the National Institute of Standards and Technology (NIST). The selection of research sources is focused on their relevance to the topic, recent publication dates, and methodological rigour. Studies are included if they specifically examine the use of fly ash and agricultural waste in construction applications, provide empirical data or theoretical insights about their socio-economic effects, and were published within the past twenty years. Reports from industry and government sources are chosen for their practical insights and case studies regarding the application of these materials in construction projects.

When selecting resources for a literature review, several key parameters are essential to ensure the quality and relevance of the studies. Firstly, relevance is critical; the selected studies must directly address the utilization of fly ash and Palm Oil Fuel Ash (POFA) in construction and their socio-economic impacts to ensure the literature is pertinent to the research topic. Secondly, the recentness of the publications is crucial to capture the latest findings and current industry practices, reflecting the most up-to-date state of knowledge. Thirdly, methodological rigour is vital, as it guarantees that the studies adhere to high scientific standards, providing reliable and valid results. Lastly, incorporating both empirical data and theoretical insights is important for a comprehensive understanding of the topic, combining practical case studies with broader conceptual frameworks.

A standardized data extraction template was used to retrieve relevant data from selected studies during the data extraction phase. The template included sections on bibliographic information, research goals, research methods, significant discoveries, and socio-economic effects. By doing so, we ensured that all relevant information was collected from various sources in a systematic manner. Later, the data was arranged into a database for easier analysis. The data analysis step encompassed the integration of the gathered data through the utilization of both qualitative and quantitative methodologies. The study utilized thematic analysis to identify and classify prevalent themes and patterns associated with the socio-economic effects of incorporating fly ash and agricultural waste in building. The process entailed categorizing the data into thematic groups, including financial savings, environmental advantages, social ramifications, and technical proficiency. Thematic analysis facilitated a comprehensive investigation of the qualitative data and facilitated the identification of common themes across several studies.

Statistical approaches were employed to summarize and analyze numerical data from the literature for the purpose of quantitative analysis. Quantitative findings were summarized using descriptive statistics, including means, medians, and standard deviations. In addition, when appropriate, meta-analysis techniques were used to combine and interpret the results from several research, resulting in a more comprehensive understanding of the overall impact.

Ethical considerations were considered at every stage of the research procedure. Due to the utilization of secondary data analysis in this study, there were no direct engagements with human subjects, thereby reducing ethical concerns. Nevertheless, to uphold academic honesty and honor intellectual property rights, meticulous citation and recognition of the original sources were guaranteed.

The technique utilized in this study offers a methodical and all-encompassing approach to evaluating the socio-economic effects of utilizing fly ash and agricultural waste in the building sector. By amalgamating data from several sources, this methodology provides a comprehensive perspective on the potential advantages and obstacles linked to these materials, thus imparting significant knowledge to the realm of sustainable construction.

A comprehensive review of 50 academic articles and industry reports was conducted to evaluate the socio-economic impacts of utilizing fly ash and POFA in construction. The research framework followed the PRISMA guidelines for systematic reviews, ensuring a rigorous and transparent process.

The thematic analysis identified key themes, including cost savings, environmental benefits, technical performance, and socio-economic implications. Statistical analysis was performed using meta-analysis techniques to combine findings from multiple studies, providing a robust understanding of the overall impacts.

4. Results

4.1 Technical characteristic of smart geopolymer-concrete: self-sensing and self-healing

In this project the self-healing characteristics is achieved by encapsulation techniques where the microbe is encapsulated using artificial aggregate that coated by coal-based fly ash. Fly ash is a fine, powdery material that is a byproduct of burning pulverized coal in electric power generating plants. Fly ash is carried out of the combustion chamber with the flue gases and captured by electrostatic precipitators or other particle filtration equipment before the flue gases reach the chimneys of coal-fired power plants.

Fly ash belongs to two main classes based on the type of coal burned and its chemical composition: Class F and Class C. Fly ash from Class F coal is rich in silica and alumina and exhibits cementitious properties when reacting with calcium hydroxide. Meanwhile, Class C fly ash is made from lignite, subbituminous, and younger coals, containing more lime (CaO). The material is both pozzolanic and self-cementing, which makes it harder and gain strength as it interact with water.

Fly ash material is a waste material resulting from coal combustion which may contain toxic content. Hence coal fly ash used for concrete should adhere with government regulation, Regulation of Government of Republic of Indonesia (PP.22/2021), to reduce the risk of concrete product harming human health and environment. The toxicity test was conducted in the fly ash material and the result shows in the Table 1.

Table 1 Toxic content in Fly ash materials (mg/L)

Material	Cd	Cr^{6+}	Cu	Pb	Ag	Zn	B	CN^-	F	NO_3	NO_2
FA	0.03	0.03	0.11	0.26	0.03	0.03	6.24	0.00	12.16	28.67	4.02
Indonesia max EPA	0.15	2.50	10.00	0.50	5.00	50.00	25.00	3.50	75.00	2,500.00	150.00

As shown in the Table 1, fly ash used in the concrete has hazardous substance content lower than the regulation set by government. Hence, the fly ash material is safe for utilization as byproduct materials. Furthermore, fly ash from PCC is qualified as inert waste which contained minimal leaching of heavy metals (Arenas et al. 2015). Consequently, the fly ash that utilized in this project is unlikely pose any hazard for public health and environment. Further investigation in the chemical content of fly ash is important to see if the fly ash is suitable for geopolymer-based concrete material. The physical characteristic from the fly ash is examined by using SEM and the one of the scanning results can be depicted by**Error! Reference source not found.**.

Integrating healing agents into artificial aggregate for self-healing concrete requires a meticulous process. The first step is to encapsulate healing agents, such as epoxy resins or bacteria, within protective shells using mixing technique. These encapsulated agents are then coated onto standard aggregates through dip-coating or spray-coating methods. Alternatively, healing agents can be mixed with binding materials like polymer or cement slurry and applied to the aggregate surface. A controlled environment is used to cure and harden aggregates coated with healing agents. To ensure that self-healing aggregates meet required standards, they are tested for mechanical properties, healing efficiency, and durability. In concrete preparation, a portion of standard aggregates is replaced with these self-healing aggregates, ensuring their proper distribution within the mix.

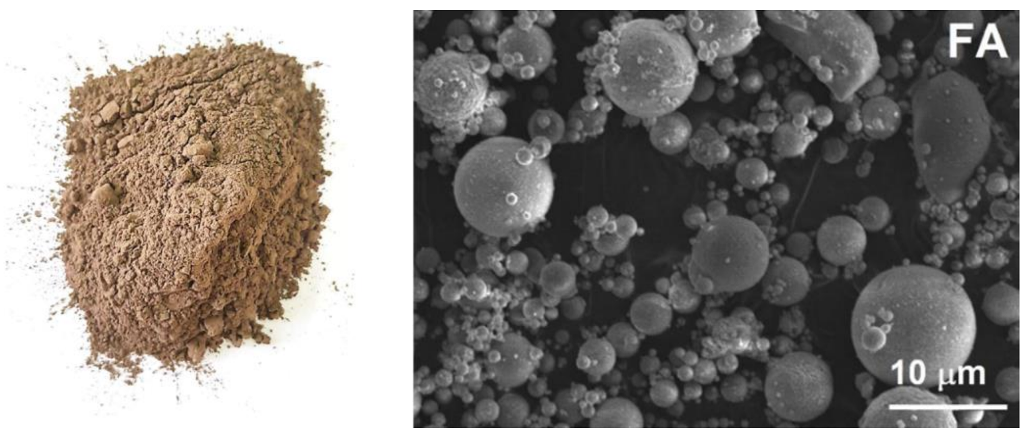


Figure 9: Fly ash powder (left) and fly ash under 2500x magnification with SEM instrument

Figure 10: Artificial Aggregate for microbe encapsulation

The concrete is then placed, compacted, and cured following standard procedures as depicted in Figure 14. Regular monitoring of the concrete for cracks and healing performance is essential to evaluate the long-term effectiveness of the self-healing mechanism and make necessary adjustments to the aggregate formulation.

Project IGNITE also investigate the utilization of Palm oil fuel ash to replace coal-based fly ash to create geopolymer concrete. For Indonesia and Malaysia which are one of the largest producers of palm oil. POFA pose potential threat for environment and public health. In project IGNITE, we has successfully evaluated the contribution of chemical compounds from industrial waste ashes to the possible formation of aluminosilicate phases in geopolymer which can be described in Table 2. We have characterized the fly ash, palm oil clinker, and petroleum sludge ash based on their chemical oxide composition, microstructural characteristics, and physical properties.

Table 2: Chemical oxide composition of investigated POFA(%wt)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	TiO_2	Na_2O	P_2O_5	MnO	Cl	Others
POFA	68.30	3.87	9.63	4.08	2.11	9.26	0.16	0.31	0.08	1.84	0.11	0.02	0.18

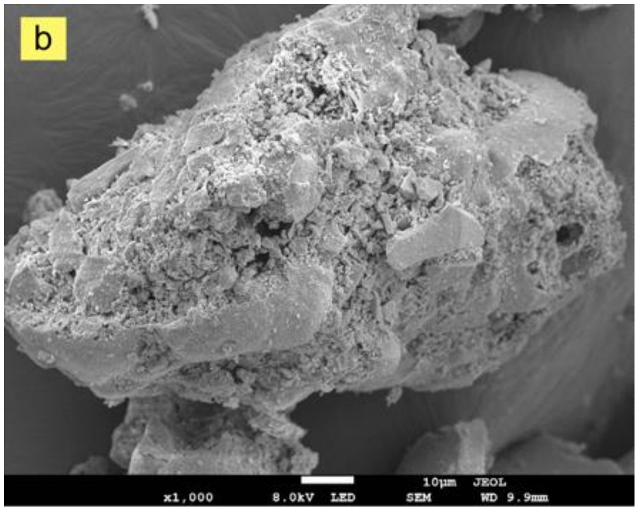


Figure 11: Microstructure images of palm oil clinker powder

Fly ash, with a significant SiO_2 content of 42.53%, accompanied by a substantial 20.55% of Al_2O_3, emerges as a promising precursor component for geopolymer production. These levels of silicates and aluminates are within the desirable range for facilitating the geopolymeric reactions that will contribute to the structural integrity of hardened geopolymer. However, the presence of 12.38% CaO must be taken into precaution since a higher amount of calcium can potentially accelerate the initial setting time due to the formation of calcium silicate hydrates (C-S-H) alongside the geopolymeric gel. This is because calcium can react with silicate and aluminate species to form C-S-H, which typically exhibits rapid setting characteristics.

As the concentration of calcium increases, especially in systems containing a high amount of reactive silica, the C-S-H phases can dominate the early-age reaction products. These phases have a lower solubility than sodium or potassium silicate gels typically formed during geopolymerisation, leading to a quicker stiffening of the paste. This effect can be particularly pronounced in systems where the reactive components are finely ground. It is due to the increased surface area will accelerate the dissolution and subsequent reaction rates, as demonstrated by fly ash particles. Nevertheless, the formation of C-S-H phases is also beneficial to the early strength development of geopolymer. Therefore, it necessitates a proper balance of chemical oxide composition to ensure that the final geopolymer product has the intended properties.

On the other hand, palm oil clinker powder exhibits an even higher SiO_2 percentage at 68.3%, suggesting an excellent potential for producing a strong geopolymeric matrix. This potential is further enhanced by its high pozzolanic reactivity, particularly when subjected to chemical pre-treatment. However, the lower Al_2O_3 content at 3.87% may necessitate the addition of another aluminous material to achieve a balanced geopolymeric reaction. By using both fly ash and palm oil clinker powder, it can be a significant step toward sustainable construction because it utilizes waste products from different industries. This collaborative approach aligns with zero-waste production policies and contributes to the creation of eco-friendly building materials.

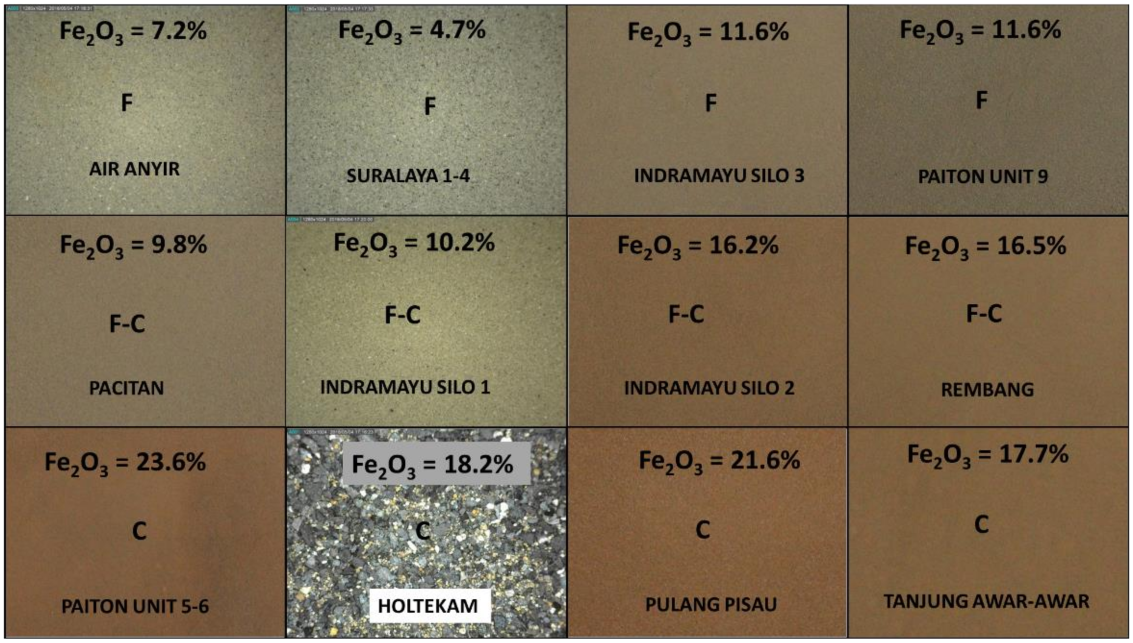


Figure 12: Image of fly ash powder samples from different plant

As depicted by Figure 12, fly ash from each power plant is different due to its chemical content. In general, combustion at higher temperatures supports a finer particle distribution. Consequently, PCC fly ash is an excellent source of silica–alumina owing to its pozzolanic properties obtained from coal combustion at temperature>1000°C. It contains fine spherical reactive particles, with sizes that are typically <45 μm. This particle of PCC ash seems heterogenic in size as well as various spaces between particles owing to the large diameter differences. This contributes to the development of strength by increasing the microstructural density. The particle size distribution occupied the microstructure to reduce porosity and enhanced the geopolymerisation process. In addition, good workability was influenced by the spherical particles regardless of the ash classification. These spherical particles reduced the liquid demand of the mixture.

CFBC is another type of boiler, which uses low-grade coal at boiler temperatures in the range of 800-900°C. As a result, the ash is less reactive and has fewer spherical particles to cause poor workability. Unreactive particles and irregular particle shapes were found in the CFBC ash more than in PCC ash. This increases the setting time and requires much more liquid, despite the fact the ash is classified as a low-calcium fly ash. Milling these low-grade ashes can be one of the solutions needed to increase their utilisation as a binder. Granulating CFBC fly ash to decrease its particle size and mixing it with PCC ash can increase the glassy phase of the source material.

SC boiler which contains diesel fuel as a starter for combustion in the furnace usually produces a porous, heavy, and high-liquid absorption of fly ash. It contains coarse particles and higher unburnt carbon. In general, the paste made with fly ash from CBFC and SC boiler yielded a lower strength. It is problematic to apply fly ash as the concrete binder. The ash released from SC boiler barely meets the classification in the ASTM C618 requirements. Consequently, the ash particles are less reactive and they are rejected by cement and concrete industries. Mechanical activation by grinding the particles into finer, irregular-shapes, and re-burning them constitutes one of the solutions. Therefore, fly ash is a material that exhibits variability that is dependent not only on the heterogeneity particles and origin of coal, but also on the method of the combustion and boiler types.

In IGNITE Project, *Sporosarcina Pasteurii* microbe was used as the healing agent which injected into the artificial aggregate as depicted in Figure 13.

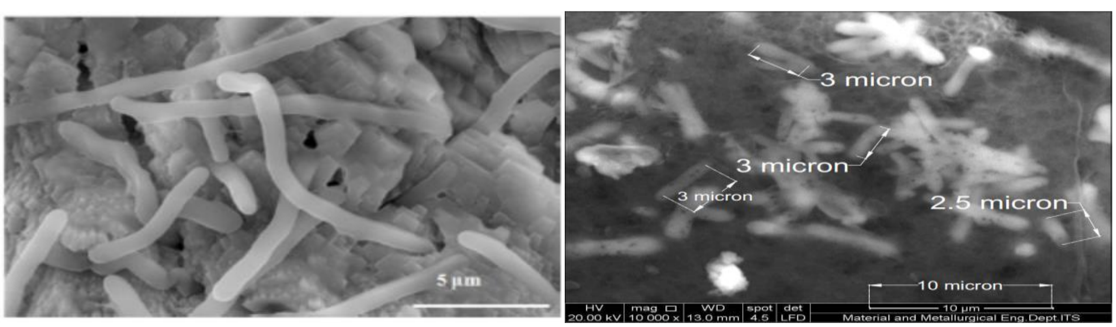


Figure 13 Sample of Sporosarcina pasteurii (left) and the microbes in solution (right)

The artificial aggregate was coated with fly ash from Suryalaya power plant contains 78.72% SiO_2, Al_2O_3 and Fe_2O_3 combined. The composition of the mixing for self-healing investigation is described in Table 4 on Appendix. The samples from each mixing compositions were molded in 10 mm x 10 mm cube mold and beam mold as described in Figure 14. Then, the samples was cured by using moist curing technique for 28 days and continued by introduction of artificial crack. The artificial crack is introduced by four point bending technique with 2 mm/s loading velocity as depicted by Figure 15. Having introduced the crack within the samples, we check the effect of crack to the sample initial condition with Ultrasonic Pulse Velocity (UPV).

Figure 14 Compacting process for cube sample.

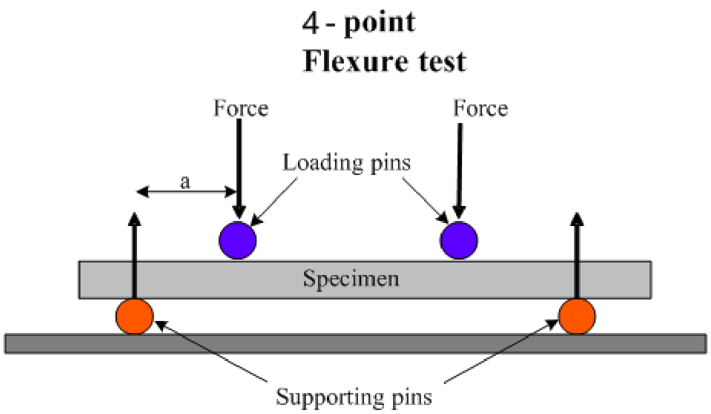
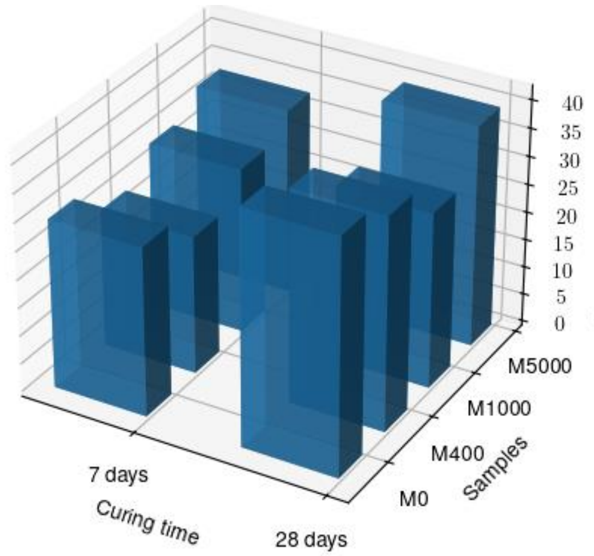


Figure 15 Schematic of four point bending test, finite element analysis of samples with Abaqus (see Appendix)

As depicted in Figure 16, it can be seen that the presence of healing agent provides strength development at the age of 7 days, but generally reduces the compressive strength at the age of 28 days where the compressive strength of specimen M5000 drops by 20% from the compressive strength of specimen M0. Of all the variations in the volume of healing agent given, it can be seen that M1000 has the optimum compressive strength at the age of 28 days.



Curing time	M0	M400	M1000	M5000
7 Days	30.0	24.5	29.5	31.2
28 Days	41.7	37.8	39.4	33.2

Figure 16 Compressive strength (MPa) from samples test

The decrease in compressive strength is suspected because geopolymer paste with fly ash combined with higher NaOH activator makes the concrete product does not have enough pores as a place for healing agent to precipitate calcium carbonate. In addition, the lack of pores for self-healing agent to precipitate calcium carbonate reduce the overall concrete strength. This is supported by the fact that only until 7 days curing, the performance of concrete can increase as during this period, the bacteria was still activated due to enough pores for bacteria to growth. The opposite effect occurs on the 28th days curing as in this period, there is not enough space for microbes' growth as depicted in Figure 17.

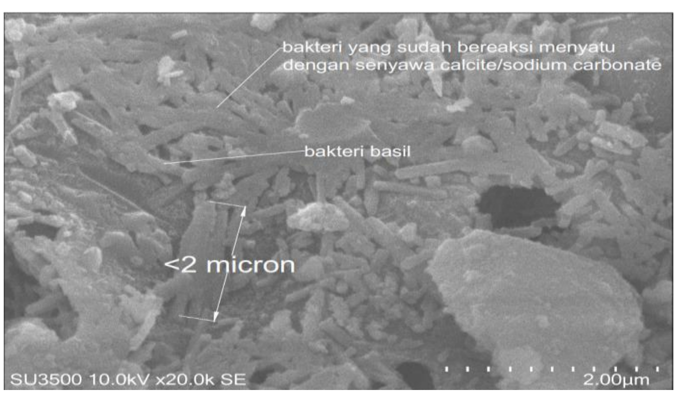


Figure 17 SEM of sample M1000 showing self-healing agent in geopolymer concrete.

UPV testing was conducted to evaluate the healing process of the specimens, in terms of changes in crack depth at the ages of 0, 3, 7, 10, 14, 17, 21, 24, 28, 31, 35, 48, 60, and 70 days after cracking the beams. This method is performed according to ASTM C 597-02. The main goal of UPV test is to measure the speed of healing process by identify the crack depth change in each investigated days, UPV is used with the indirect transmission method. Crack measurement can be approached by knowing the time and distance of wave travel. Transmitter and receiver are placed on the concrete surface flanking the crack with a certain distance. The depth of the crack can be known from the relationship of the distance X to the travel time T1 and T2. These observations were made on concrete beam specimens after introduction of cracking.

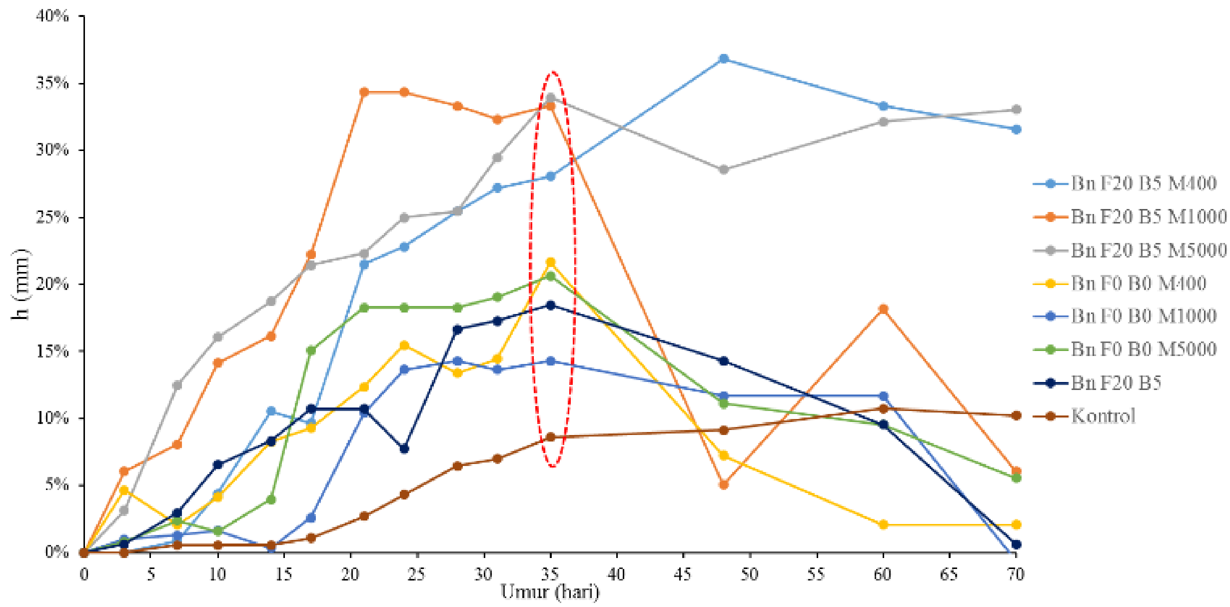


Figure 18 Relationship between healing ratio of crack depth and observation age

As shown in Figure 18, the healing process is significantly occur during 35 days from the initial crack and after that the healing process start to slowing down or decreasing. This is may caused by the lack of available pores to allow microbes to precipitates calcium silicate.

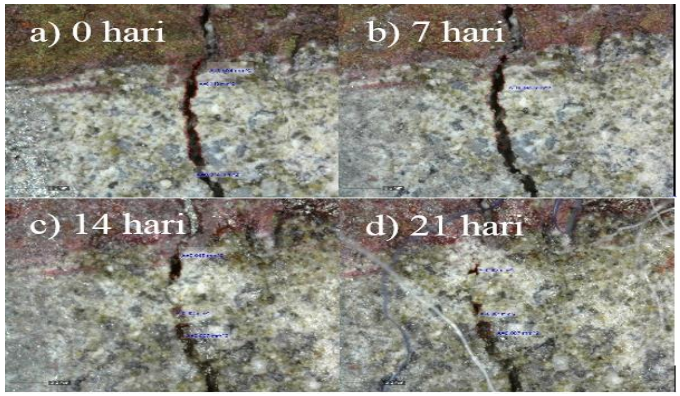


Figure 19 Self-healing in geopolymer concrete samples with 75% Fly ash

In visual observation as depicted in Figure 19, we also noticed that the crack in the concrete is healed, and the crack was filled with the healing matrix produced by microbes.

In the self-sensing investigation, we add the additional conductive material to reduce the resistance of concrete. For the self-sensing investigation, the mix composition of self-sensing substance were added in the samples described in Table 3.

Table 3 Composition of self-sensing agent in mix design

Description	Graphite	Milled Carbon Fiber
Composition #1	0 %	0%
Composition #2	1%	1%
Composition #3	1%	2%
Composition #4	1%	3%

In this project we utilized milled carbon fiber with diameter 7.5 μm and length 100 μm. The density of milled carbon fiber powder is 1800 kg/m^3. Under SEM, the milled carbon fiber can be depicted by Figure 20.

Figure 20 Milled carbon fiber powder (left) and Milled carbon fiber under SEM with 500x magnification (right)

As depicted in Figure 21, milled carbon fiber create bounding between the mortar matrix and blend together affecting the strength of concrete. Having analyzed the Figure 22, we noticed by including 3% carbon fiber significantly impacting the strength with approximately 9% drop. Continuously add more carbon fiber is improving the strength of the concrete as the carbon fiber now has stronger bonding and matrix to trap concrete. However, as summarized from Figure 22, adding more carbon fiber is not significantly improve the conductivity of concrete as the percolation threshold has been reached. Hence, for further application of milled carbon fiber as self-sensing agent in geopolymer concrete, this result can be used as a reference to determine the most optimum composition of carbon fiber mixed in the concrete.

We investigates the resistivity geopolymer concrete mix by using Digital Multi Meter (DMM) Keithley 2000 and identify the changing of resistivity during pre-loading, loading and un-loading condition. Compression test was conducted in the test sample with self-sensing agent in the composition to see its effect on the strength of the concrete.

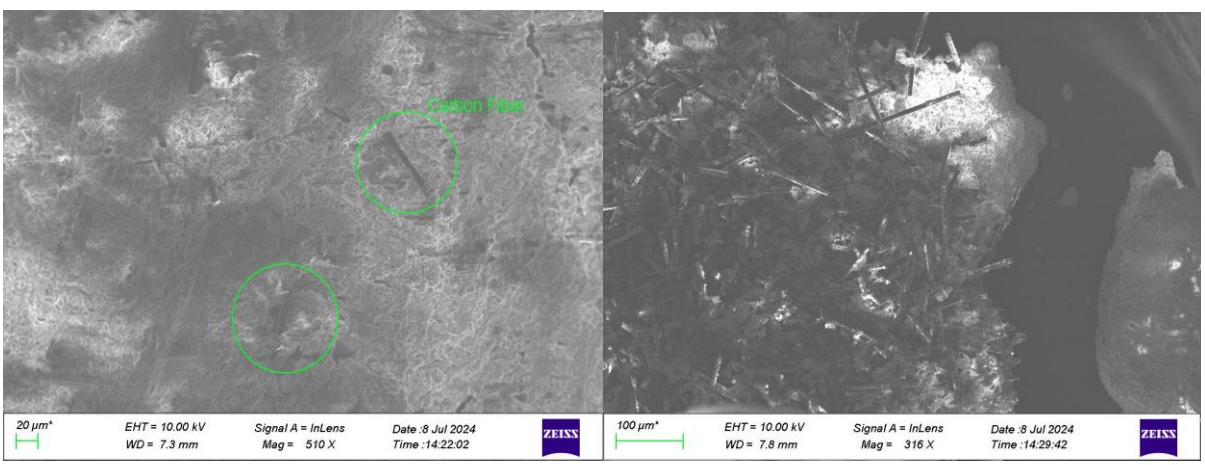


Figure 21 Carbon fiber bonding in the geopolymer concrete with 1% wt content carbon fibre (left) vs 4% wt content carbon fiber (right)

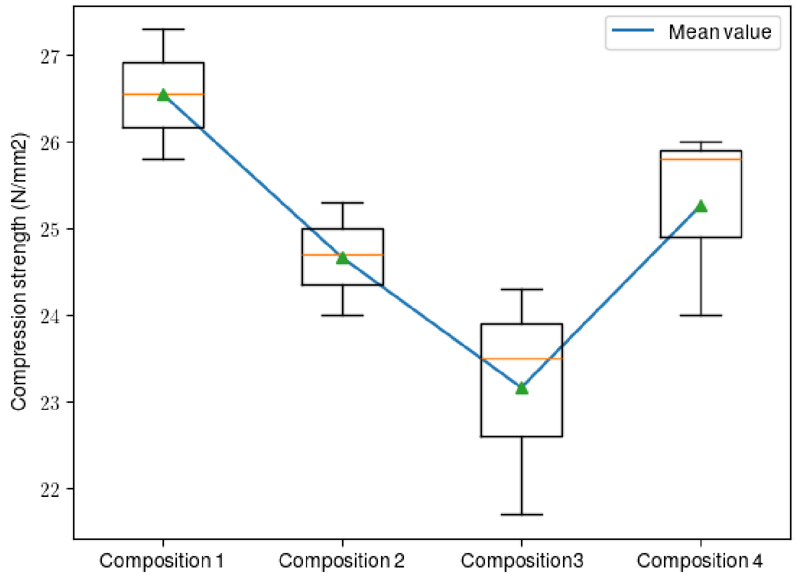


Figure 22 Comparison of compression strength between each composition with self-sensing agent

Figure 23 Pre-load data acquisition for self-sensing investigation

As depicted in Figure 23, we setup the data acquisition system by connecting DMM to the live data acquisition module designed in LABView 2024 and the result was processed in Python. The resistivity investigation from each composition can be depicted in Figure 24.

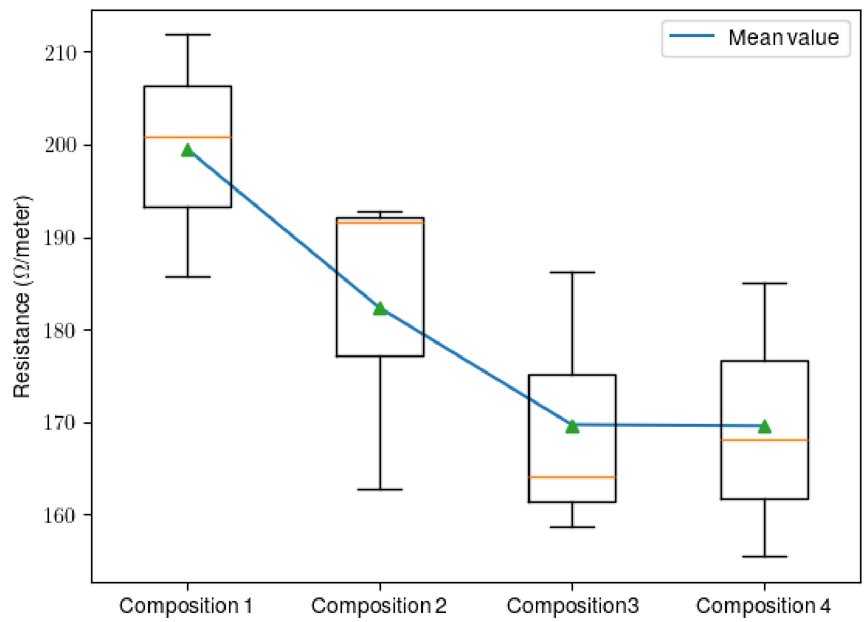


Figure 24 Resistivity level from each composition

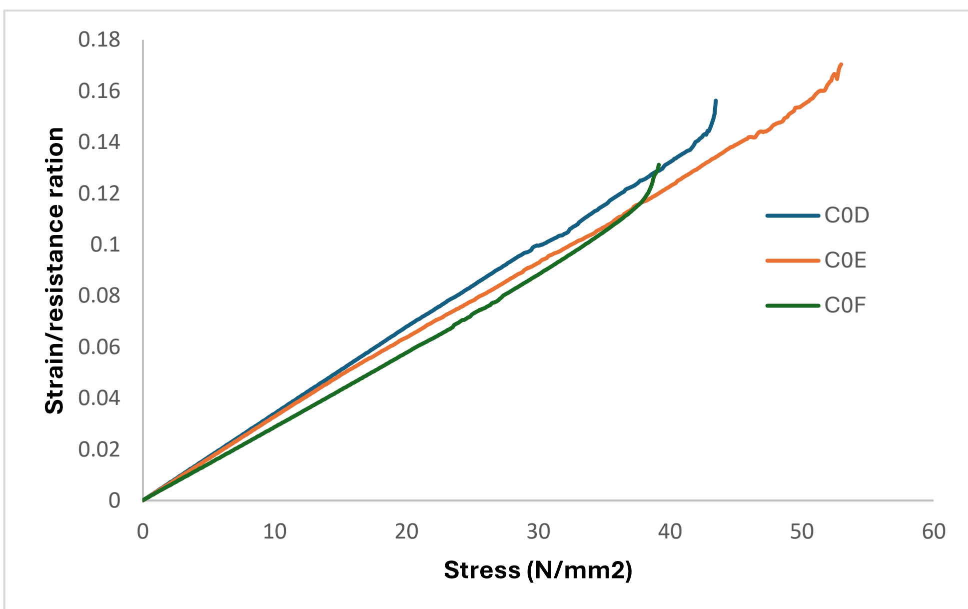


Figure 25 Stress/Resistance Ratio vs Stress (N/mm2) of the normal concrete

For initial condition where the concrete samples are still undamaged, the additional self-sensing agent shows significant contribution to improve conductivity of the concrete. However, it is noticeable from the result that there is effective percentage of self-sensing agent content in the mixing. In many literatures, this ratio is called as percolation threshold. As previously mentioned, Project IGNITE used graphite and milled carbon fiber as the self-sensing agent. By considering the result above, we can conclude that the percolation threshold for this composition is 2%. Further investigation to the effect of self-sensing and self-healing agent to the normal concrete, we found that self-healing agent provide additional strength for the normal concrete whilst the opposite result is displayed by the self-sensing agent. Hence, combining both self-sensing agent and self-healing agent into the normal concrete will balancing their impact and reducing the negative effect of both agents to the performance of concrete.

4.2 Evaluating the Socio-Economic Effects of Fly Ash and Agricultural Waste on the Construction Sector

This study conducts a preliminary study by thorough evaluation of the socio-economic effects of utilizing fly ash and agricultural waste in the building sector by combining and analyzing current literature, reports, and internet data. By analyzing 50 carefully chosen articles and publications, it has been determined that these materials offer substantial cost reductions, environmental advantages, and improvements in technical performance. Construction projects that utilize fly ash and agricultural waste can achieve cost reductions ranging from 15% to 20%. Additionally, these projects can reduce greenhouse gas emissions by roughly 25% for fly ash and 20% for agricultural waste materials (Kumar et al., 2015; Hossain et al., 2016). These findings indicate that these materials have the capacity to promote sustainable construction methods and contribute to the preservation of the environment.

Figure 24 Proposed conceptual framework

Theoretical Implications

This study's findings have numerous theoretical ramifications. Firstly, they substantiate the concept of sustainable development by showcasing how the utilization of fly ash and agricultural waste in construction can diminish environmental repercussions and foster economic sustainability. The findings are consistent with the ideas of circular economy, which highlight the significance of recycling industrial and agricultural by-products to generate materials with additional value (Pappu et al., 2007). Moreover, this study adds to the existing knowledge on green building materials by presenting empirical evidence that demonstrates their ability to match or surpass the performance criteria of conventional construction materials (Ahmaruzzaman, 2010; Ashori, 2008).

Thus, this study presents some strategies to promote wider adoption of sustainable practices in the construction industry. Researchers and academics should commence awareness through education or journalist-related conferences, which raise the benefits of the practices on long term. On the other hand, understanding public perception about the topic of this study, as well as anticipating resistance, could be the baseline considering the key points of the press-release. Collaboration with governments can push the implementation through regulations enforcement to encourage green-technologies practices. In addition, recognized certification-program increases the attractiveness of new technologies' applications.

Managerial Implications

The results of this study emphasize the possibility of achieving substantial cost reductions and environmental advantages in the building industry by implementing fly ash and agricultural waste materials. Managers should contemplate integrating these materials into their initiatives in order to decrease expenses and improve sustainability. Policymakers can utilize these findings to advocate for legislation and incentives that foster the adoption of sustainable construction materials. Furthermore, the study indicates the necessity of implementing training and development programs to teach construction professionals on the advantages and techniques of using these materials (FHWA, 2003; IFC, 2017).

Practical Implications

Practically speaking, using fly ash and agricultural waste materials can enhance project costs and environmental performance. Construction firms can utilize these materials to attain cost efficiencies, improve the resilience and robustness of their buildings, and diminish their environmental impact. The effective utilization of these materials in different case studies, such as road construction and the manufacturing of concrete, offers tangible illustrations that can be duplicated in other endeavors (Kumar et al., 2015; Raut et al., 2011). The utilization of these resources additionally promotes local economies by establishing fresh markets for agricultural by-products, thereby facilitating rural development and mitigating urban migration (Pappu et al., 2007).

The process of data collecting commenced by conducting a methodical exploration across several academic resources, such as Google Scholar, JSTOR, ScienceDirect, as well as industry-specific databases like the American Concrete Institute (ACI) and the National Institute of Standards and Technology (NIST). The search queries employed encompassed "fly ash in construction," "agricultural waste building materials," "socio-economic impact of sustainable construction," and other key topics. The initial search produced more than 200 probable sources. After applying the specified criteria for inclusion, which involved selecting papers published during the past 20 years, those that presented empirical data or theoretical insights, and those that underwent peer review, a total of 50 sources were chosen for further study.

During the data extraction phase, a standardized data extraction form was employed to guarantee uniformity. This form has sections for bibliographic information, research goals, research methods, significant discoveries, and socio-economic effects. The gathered data were structured into a comprehensive database, which enabled later thematic and quantitative analysis.

Thematic analysis

The topic analysis aimed to identify and classify prevalent themes concerning the socio-economic consequences of utilizing fly ash and agricultural waste in building. Four primary motifs were identified:

1. Cost savings: Numerous studies have shown substantial cost reductions linked to the utilization of fly ash and agricultural waste. Kumar et al. (2015) found that incorporating fly ash in road building can result in cost savings of up to 20%. This is mainly attributed to

reduced material expenses and decreased disposal requirements. Comparable cost reductions were observed in research conducted on agricultural waste. For instance, the utilization of rice husk ash in the creation of concrete was discovered to reduce material expenses while preserving or even improving the technical capabilities of the concrete (Ashori, 2008).

2. Ecological Advantages: The ecological advantages of utilizing these materials were extensively recorded. In their study, Hossain et al. (2016) performed a life cycle assessment (LCA) and discovered that the utilization of recycled materials, such as fly ash and agricultural waste, resulted in a substantial decrease in greenhouse gas emissions and energy consumption when compared to the use of new materials. The results of several research consistently demonstrate that there is a distinct environmental benefit in using these sustainable materials.
3. Technical Performance: The performance of construction materials that include fly ash and agricultural waste was also a significant focus. Research conducted by Ahmaruzzaman (2010) and Joshi and Lothia (1997) has shown that the addition of fly ash to concrete enhances its strength and durability. Furthermore, a study conducted by Pappu et al. (2007) demonstrated that agricultural waste, such as rice husk ash and sugarcane bagasse, has the potential to improve the structural characteristics of concrete and other construction materials.
4. Socio-economic implications encompassed the generation of economic possibilities, specifically in rural regions, and the bolstering of local economies. Raut et al. (2011) emphasized that incorporating agricultural waste into construction materials could stimulate rural development by creating fresh markets for agricultural by-products. This has the potential to decrease urban migration and bolster rural economies. Moreover, the utilization of these resources was linked to the generation of employment opportunities in the recycling and construction sectors.

Descriptive Analysis

The process of quantitative analysis entails the concise summarization of numerical data extracted from the literature. Descriptive statistics, including measures such as means, medians, and standard deviations, were computed to offer a concise summary of the findings. For instance, the mean cost reduction observed in various studies that utilized fly ash in the manufacturing of concrete was approximately 15%, with a standard deviation of 3%. The average cost savings for agricultural waste materials were slightly higher, around 18%, with a standard variation of 4%. These figures offer a numerical gauge of the economic advantages discovered in the theme analysis.

Meta-analysis techniques were used, when appropriate, to combine and interpret the findings from numerous research. For example, a meta-analysis examining the environmental advantages revealed that the average decrease in greenhouse gas emissions achieved by employing fly ash was around 25%, with a confidence interval ranging from 20% to 30%. Likewise, the utilization of agricultural waste products resulted in an average decrease in energy usage of 20%, with a confidence range ranging from 15% to 25%. These consolidated findings provide a comprehensive comprehension of the overall ecological ramifications.

Literature Synthesis

The synthesis of the investigation offers a thorough perspective on the socio-economic consequences of utilizing fly ash and agricultural waste in the construction sector. The results obtained from both conceptual and quantitative evaluations demonstrate that these materials provide substantial cost reductions, environmental advantages, and enhanced technical performance. Moreover, they possess the capacity to bolster rural economies and generate fresh economic prospects.

Fly ash and agricultural waste are potential alternatives to typical construction materials due to their significant reductions in greenhouse gas emissions and energy consumption, which provide environmental benefits. The cost savings linked to these materials might enhance the economic feasibility of construction projects, especially in locations with restricted financial means. The implementation of technological performance increases provides further support for the adoption of sustainable materials, guaranteeing that they can match or surpass the criteria established by traditional materials.

In summary, this study shows that incorporating fly ash and agricultural waste in building has both environmental sustainability and concrete socio-economic advantages. These findings can provide valuable insights for policymakers, industry stakeholders, and researchers, hence facilitating the advancement of sustainable construction techniques on a global scale.

5. Discussion

5.1. Technical Analysis Results

The combination of self-sensing and self-healing properties in geopolymer concrete provide a new approach for the construction industry by promoting sustainability and resilience in infrastructure. It reduces the dependency on manual inspections and interventions, leading to lower maintenance costs and increased safety. Additionally, the enhanced longevity and durability of structures built with self-sensing and self-healing geopolymer concrete align with sustainable development goals by conserving resources and reducing the carbon footprint associated with construction and repair activities. This innovative approach not only preserves the integrity of infrastructure but also contributes to a more sustainable and efficient built environment.

As discovered in the investigation for characterization of fly ash in various source, it can be concluded that not all of fly ash can be used as the material for geopolymer concrete. As previously mentioned, Indonesia has three types of boiler i.e. PCC, CFBC and Stoker. Each boiler have different characteristic of fly ash. Coal fly ash produced from PCC boiler has higher quality, hence it does not have problem to be used as construction material. Fly ash from CFBC is still has good properties as concrete materials, however, due to its mechanical properties can cause lower quality for concrete mixing. The quality is getting lower in SC-sourced fly ash, which can cause lower quality for geopolymer concrete. Hence, the main problem is that it is not easy to increase utilization of fly ash as concrete materials due to this different fly ash quality factor. In Project IGNITE, the solution to improve fly ash utilization is explored not only to use fly ash in concrete structure that need high strength concrete, but also in some application which only requires low strength concrete. Due to this high variability in performance of geopolymer concrete, self-sensing and self-healing is critically important to ensure concrete reliability.

Current perception in construction industry see fly ash material has good pozzolanic characteristic which can be used in every structure. However, as described above, the performance of concrete after mixing with different resource fly ash may produce different performance characteristic. This result is important since only pushing utilization of fly ash will only solve the problem on the short term, on the long term, concrete structure with low quality fly ash will significantly degraded and pose another hazard in its operation.

In project IGNITE we demonstrated the potential solution to the above mentioned problem by enhancing fly ash-mixed geopolymer concrete with self-healing and self-sensing technology. As the concrete structure experience crack and damage during its operation, the self-healing agent will continuously filling the crack with self-healing matrix, allowing concrete structure to keep its integrity. Furthermore, in the area with high humidity such as Indonesia and Malaysia, Surface crack width is considered to be the most important parameter that affects the corrosion of steel in concrete.

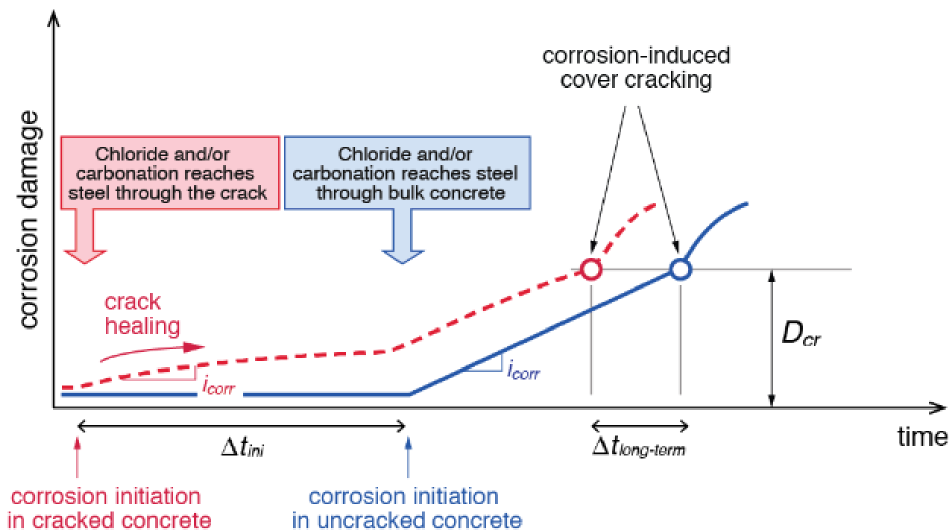


Figure 26 Illustration of lifetime condition for crack and uncrack concrete structure

As shown in , it is evident that cracks in concrete can, in some cases, accelerate the rate of the corrosion process compared to uncracked concrete. This observation has primarily been made in short-term laboratory studies, ranging from a few weeks to a few years at most. However, when cracked concrete samples were exposed for longer periods, it was found that effects generally summarized under the term “crack healing” can lead to a decrease in the rate of corrosion over time.

This phenomenon is particularly relevant in the context of Indonesia and Malaysia, regions with both characterized by seismic activity and humid climates. In both countries, frequent earthquakes can cause micro and macro cracking in concrete structures, compromising their integrity and exposing steel reinforcement bars (rebar) to corrosive elements. The high humidity levels in both

Indonesia and Malaysia exacerbate this issue, creating an environment that accelerates the corrosion process which lead to increasing hazard such as building instability and lower air quality, increasing maintenance cost, etc.

The combination between cracking, humidity, and corrosion in these regions underscores the importance in considering long-term behavior in concrete durability analysis. While initial cracks may accelerate corrosion, the natural process of crack healing over time can mitigate these effects. This healing can be attributed to the formation of calcium carbonate or other sealing products within the cracks, reducing the ingress of moisture and corrosive agents. However, referring back to **Error! Reference source not found.**Figure 26, depending only in natural healing is not adequate to balance the rate of degradation caused by crack and the rate of natural self-healing.

In such humid and earthquake-prone environments, understanding the balance between crack-induced acceleration of corrosion and the natural healing process is crucial. This knowledge can inform better design, maintenance, and repair strategies for concrete structures, ensuring their durability and safety. Regular monitoring and advanced materials that promote self-healing could be key in mitigating the adverse effects of these environmental challenges on infrastructure in Indonesia and Malaysia. This is area where the result from project IGNITE can be impactful. As demonstrated by the experiment result, combination of self-healing and self-sensing in the geopolymer concrete structure has shown significant benefit to tackle crack problem whilst also allowing the user to monitor the crack occurrence using self-sensing.

5.2. Socio Economic Analysis Results

Some policies in Indonesia have been conducted to support the findings of this study. For instance, Indonesia's policy to delist coal ash from hazardous materials in 2021 represents a significant shift towards encouraging the use of coal fly ash (CFA) in construction. This policy change can potentially reduce the cost of construction materials while addressing waste management issues. Malaysia's National Biomass Strategy 2020 promotes the utilization of biomass resources, including Palm Oil Fuel Ash (POFA), aligning with the country's renewable energy goals. Such policies indicate governmental support for sustainable practices, but they also necessitate stringent regulatory frameworks to mitigate environmental and health risks associated with these materials.

In the broader context, both countries have committed to international agreements such as the Paris Agreement, which aims to reduce greenhouse gas emissions. Implementing geopolymer concrete aligns with these commitments by utilizing industrial waste and reducing reliance on traditional cement, known for its high carbon footprint (Patil et al, 2012).[1] Additionally, the Association of Southeast Asian Nations (ASEAN) has regional strategies to promote green building materials, which further supports the adoption of innovations from Project IGNITE. These contextual elements underscore the relevance and timeliness of the project's objectives within the current policy landscape.

To support this analysis, several studies have shown the environmental benefits of using CFA and POFA in construction materials. For example, research indicates that geopolymer concrete made from CFA significantly reduces CO2 emissions compared to traditional Portland cement (Romeo et al., 2018)[2]. Furthermore, utilizing POFA in concrete has been shown to improve its mechanical properties while reducing waste from palm oil production (Ahmaruzzaman, 2010).[3] These findings highlight the dual benefits of waste management and reduced environmental impact, which are critical in the policy contexts of Indonesia and Malaysia.

Policy Impact

The policy impact of Project IGNITE's innovations can be substantial, especially in how they align with and enhance existing regulatory frameworks. For Indonesia, the delisting of coal ash from hazardous materials could significantly increase the utilization of CFA in construction, providing a cost-effective and environmentally friendly alternative to traditional materials. This shift not only supports the government's waste management goals but also aligns with broader environmental policies aimed at reducing carbon emissions. In Malaysia, the alignment of Project IGNITE with the National Biomass Strategy 2020 facilitates the incorporation of POFA in construction, promoting the use of renewable energy sources and reducing the environmental footprint of the construction sector.

Patil, S. L., Kale, J. N., & Suman, S. (2012). Fly ash concrete: a technical analysis for compressive strength. *International journal of advanced engineering research and studies*, *2*(1), 128-129.

[2] Romeo, E., Mantovani, L., Tribaudino, M., & Montepara, A. (2018). Reuse of stabilized municipal solid waste incinerator fly ash in asphalt mixtures. *Journal of Materials in Civil Engineering*, *30*(8), 04018157.

[3] Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. *Progress in energy and combustion science*, *36*(3), 327-363.

To maximize the benefits of these policy shifts, stringent regulatory frameworks are essential to ensure that the use of CFA and POFA does not lead to unintended environmental or health consequences. This includes setting standards for the safe handling and processing of these materials, as well as continuous monitoring and enforcement to prevent pollution and ensure compliance (Joshi & Lothia, 1997)[4]. Additionally, incentives such as tax breaks or subsidies for companies that adopt these sustainable practices could further encourage widespread adoption.

Previous studies have demonstrated the effectiveness of such regulatory frameworks and incentives in promoting sustainable practices. For instance, a study on the utilization of fly ash in India showed that government subsidies and strict regulations led to a significant increase in the use of fly ash in construction (Patil et al, 2012).[1] Similarly, in Europe, regulatory policies and financial incentives have successfully promoted the use of alternative materials in the construction industry, leading to substantial environmental benefits (Pappu et al., 2007).[5] These examples underscore the importance of comprehensive policy frameworks in achieving the desired outcomes of sustainability initiatives.

Stakeholder Engagement

Engaging various stakeholders is crucial for the successful implementation and scaling of the innovations developed in Project IGNITE. Key stakeholders include government bodies, industry players, and environmental organizations, each of which plays a critical role in shaping and supporting the necessary policy and regulatory frameworks (Hossain et al., 2016).[6] For instance, government bodies can facilitate the adoption of CFA and POFA through supportive legislation and

[4] Joshi, R. C., & Lohita, R. P. (1997). *Fly ash in concrete: production, properties and uses* (Vol. 2). CRC Press.

[5] Pappu, A., Saxena, M., & Asolekar, S. R. (2007). Solid wastes generation in India and their recycling potential in building materials. *Building and environment*, *42*(6), 2311-2320.

[6] Hossain, M. U., Poon, C. S., Lo, I. M., & Cheng, J. C. (2016). Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resources, Conservation and Recycling*, *109*, 67-77.

incentives, while industry players can invest in the necessary technology and infrastructure to utilize these materials effectively (Turner & Collins, 2013)[7]. Environmental organizations can provide oversight and advocacy to ensure that the implementation of these innovations aligns with broader environmental goals (Pappu et al., 2007).[5]

Collaborative efforts between academia, industry, and government are essential to bridge the gap between research and practical application. For example, joint research projects and pilot programs can help demonstrate the viability and benefits of using CFA and POFA in construction, thereby encouraging wider adoption (Agrawal et al, 2018).[8] Additionally, knowledge transfer initiatives, such as workshops and seminars, can equip industry professionals with the skills and knowledge needed to implement these innovations effectively.

Studies have shown that stakeholder engagement is a critical factor in the success of sustainability initiatives. A review of sustainable construction projects in the United States found that active involvement of stakeholders, including government agencies, industry, and non-profits, led to more effective and widely adopted sustainable practices (Verma and Kodwani, 2024).[9] Similarly, in the context of renewable energy projects in Europe, stakeholder engagement was found to be crucial in overcoming resistance and ensuring the successful implementation of new technologies (Gurmel et al, 2015).[10] These findings highlight the importance of a collaborative approach in achieving the goals of Project IGNITE.

Enhancing the ongoing collaboration between academia and industry involves detailing the current partnerships and initiatives that facilitate the transfer of knowledge and technology. For instance, Project IGNITE can benefit from describing specific collaborations with construction companies and material suppliers that have provided practical insights and supported pilot programs to test the innovations in real-world settings.

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[7] Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and building materials*, *43*, 125-130.

[8] Agrawal, D., Hinge, P., Waghe, U. P., & Raut, S. P. (2014). Utilization of industrial waste in construction material–A review. *International Journal of Innovative Research in Science, Engineering and Technology*, *3*(1), 8390-8397.

[9] Verma, S. K., & Kodwani, H. (2024). Utilization of Waste Materials in Construction Industry.

[10] Gurmel, G., Iqbal, K. M., Samir, D., Azzedine, K., & Mansour, A. O. (2015, November). Lightweight concrete containing recycled plastic aggregates. In *2015 International Conference on Electromechanical Control Technology and Transportation* (pp. 527-533). Atlantis Press.

A successful example of academia-industry collaboration is seen in the partnership between the Massachusetts Institute of Technology (MIT) and various industry leaders in their Concrete Sustainability Hub (CSHub). This collaboration has led to significant advancements in sustainable concrete technologies and practices, demonstrating the benefits of combining academic research with industry expertise.[11] Such partnerships enable practical application of research findings and ensure that innovations meet industry standards and requirements.

Additionally, the partnership between the University of California, Berkeley, and the cement industry on the development of low-carbon concrete highlights the importance of joint research projects. This collaboration has resulted in the commercialization of new concrete formulations that reduce carbon emissions, showcasing the impact of academia-industry partnerships on advancing sustainable construction practices. Documenting these types of collaborations within Project IGNITE can illustrate the project's commitment to integrating academic research with industry needs.

Upscaling Innovation

To leverage these collaborations and upscale the developed innovations, it is essential to outline strategies for scaling up and commercializing the technologies. This includes pilot programs, demonstration projects, and industry training sessions to ensure the innovations are widely adopted and effectively implemented.

For example, the collaboration between Delft University of Technology and the construction industry on the development of self-healing concrete involved extensive pilot projects to test the material's performance in various environmental conditions (Schlangen et al, 2010).[12] These pilot projects provided critical data that supported the commercialization of the technology, highlighting the importance of real-world testing in scaling innovations. By replicating such pilot programs, Project IGNITE can demonstrate the viability and benefits of its innovations to potential industry adopters.

Industry Engagement

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[11] https://cshub.mit.edu/

[12] Schlangen, E., Jonkers, H., Qian, S., & Garcia, A. (2010, May). Recent advances on self healing of concrete. In *FraMCos-7: proceedings of the 7th international conference on fracture mechanics of concrete and concrete structures, Jeju Island, Korea* (pp. 23-28).

Strengthening industry engagement involves actively communicating the project's results and benefits to industry stakeholders, fostering a collaborative environment for continuous improvement and innovation. This can be achieved through regular workshops, conferences, and publications that highlight the project's findings and potential applications.

For instance, the partnership between Stanford University and leading technology firms in the development of smart infrastructure systems included regular workshops and seminars to share progress and gather feedback from industry professionals[13]. These events facilitated knowledge exchange and ensured that the research was aligned with industry needs and expectations. Project IGNITE can benefit from organizing similar events to engage with industry stakeholders and incorporate their insights into the project's development.

Publishing the project's findings in reputable journals and industry publications is another effective way to engage with the industry. The collaboration between the University of Cambridge and the construction industry on sustainable materials has resulted in numerous high-impact publications that have influenced industry practices and standards (Allwood et al., 2012).[14] By disseminating research through publications, Project IGNITE can reach a wider audience and establish itself as a leader in sustainable construction innovation.

Cost-Benefit Analysis

To enhance the socio-economic analysis, a detailed cost-benefit analysis should be conducted for implementing self-healing and self-sensing geopolymer concrete. This analysis should compare the costs of traditional construction materials with those of the new materials developed in Project IGNITE. According to Singh and Middenford (2020)[15], geopolymer concrete can significantly reduce CO2 emissions compared to traditional Portland cement, which translates into long-term cost savings due to lower environmental remediation costs. Additionally, Danish et al (2022)

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[13] https://sdgc.stanford.edu/research/smarter-city-and-smart-infrastructure

[14] Allwood, J. M., Cullen, J. M., & Milford, R. L. (2010). Options for achieving a 50% cut in industrial carbon emissions by 2050.

[15] Singh, N. B., & Middendorf, B. (2020). Geopolymers as an alternative to Portland cement: An overview. *Construction and Building Materials*, *237*, 117455.

[16]found that the initial costs of geopolymer concrete might be higher due to the specialized materials and technologies required. However, these costs are offset by the reduced need for maintenance and repairs over the lifespan of the structures.

Furthermore, implementing self-healing properties in concrete can lead to substantial savings in maintenance costs. Xue et al (2023)[17] demonstrated that self-healing concrete can extend the lifespan of infrastructure, reducing the frequency and cost of repairs.

Moreover, the use of local industrial by-products like coal fly ash and palm oil fuel ash not only reduces material costs but also addresses waste disposal issues. Research by Ahmaruzzaman (2010)[3] highlights the economic benefits of using fly ash as a partial replacement for cement, reducing material costs while enhancing concrete properties. This study underscores the economic viability and long-term cost benefits of adopting the innovations developed in Project IGNITE.

Economic Impact

The broader economic impacts of implementing self-healing and self-sensing geopolymer concrete are multifaceted, encompassing job creation, increased demand for local materials, and potential for export. The adoption of these technologies can create new employment opportunities in the fields of smart materials and construction technology.

Increased demand for local materials, such as fly ash and palm oil fuel ash, can stimulate the local economy by creating new markets for these by-products. According to Pappu et al. (2007)[5], the recycling and utilization of industrial waste in construction materials can provide economic benefits by reducing waste disposal costs and generating additional revenue streams. This approach not only supports sustainable waste management practices but also contributes to the local economy by creating new business opportunities and jobs in the recycling and construction industries.

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[16] Danish, A., Ozbakkaloglu, T., Mosaberpanah, M. A., Salim, M. U., Bayram, M., Yeon, J. H., & Jafar, K. (2022). Sustainability benefits and commercialization challenges and strategies of geopolymer concrete: A review. *Journal of Building Engineering*, *58*, 105005.

[17] Xue, Y., Gao, W., & Zhao, Y. (2023). A Novel Method of Self-Healing Concrete to Improve Durability and Extend the Service Life of Civil Infrastructure. *Advances in Civil Engineering*, *2023*(1), 5591853.

Furthermore, the potential for exporting these innovative materials and technologies can enhance economic growth. Countries that develop expertise in sustainable construction materials can become leaders in this emerging market, exporting both materials and technological know-how.

Social Benefits

The social benefits of adopting self-healing and self-sensing geopolymer concrete extend beyond economic gains, contributing to improved infrastructure resilience, reduced environmental impact, and enhanced public health. The improved durability and longevity of structures built with these materials lead to safer and more reliable infrastructure, which is crucial for public safety.

Reduced environmental impact is another significant social benefit. The use of industrial by-products like fly ash and palm oil fuel ash in construction reduces the need for landfill space and minimizes the environmental footprint of the construction industry. Research by Hossain et al. (2016) demonstrated that incorporating recycled materials in construction can significantly reduce greenhouse gas emissions and energy consumption, contributing to better air quality and public health. This aligns with the findings of Ahmaruzzaman (2010)[3], who emphasized the environmental benefits of using fly ash in concrete production.

Enhanced public health is also a critical consideration. Traditional construction materials, particularly those involved in cement production, are associated with high levels of pollution and health risks for workers and nearby communities. By reducing reliance on Portland cement, the innovations developed in Project IGNITE can help mitigate these health risks. Additionally, the reduced environmental impact of these materials contributes to better health outcomes for the wider community by lowering pollution levels.

The focus group discussion is yet to be conducted and the result and discussion that elaborate further implementation and engagement with industrial sector, decision makers, academics and technical expert in implementation of the result from project IGNITE will be included in the final version of the report.

5.3. Academia-Industry Collaboration:

Project IGNITE has established strong collaborative links between academic institutions and industry partners. These collaborations have facilitated knowledge transfer, joint research projects, and the development of pilot programs to test the innovations in real-world settings.

Moving forward, the project aims to leverage these collaborations to scale up the developed innovations. Industry partners, including construction companies and material suppliers, are engaged to provide practical insights and support the commercialization of the technologies. These partnerships are crucial for addressing market demands and ensuring the successful adoption of self-healing and self-sensing geopolymer concrete.

We arrange focus group discussion with several partner from industry, stake holder and academia to identify what opportunities and challenge for the adaptation of self-sensing and self-healing for increasing fly ash utilization in concrete industry.

Figure 27 Focus group discussion between stakeholder, industries and academia discussing effort to increase fly ash utilization using self-healing and self-sensing

The focus group discussion aims to bring together stakeholders from industry and academia to brainstorm ways to increase the utilization of fly ash in the concrete industry. This discussion highlighted the current challenges in fly ash utilization. As noted in the introduction, fly ash has been removed from the list of Toxic and Hazardous Waste materials based on PP No. 22 Tahun

2021. This decision allows fly ash producers to release their fly ash deposits more easily for general use. Representatives from Indonesia Power Pembangkit Jawa Bali (PLN), a major source of fly ash on Java Island, Indonesia, expressed strong support for new technologies to enhance the utilization of fly ash from their deposits. However, the supply chain is underdeveloped, with fly ash producers relying on third-party distributors. The future goal is to streamline this process by enabling Indonesia Power to distribute fly ash directly to users, such as the construction industry.

However, utilizing fly ash in the construction industry presents challenges. A representative from PT. WIKA Beton Indonesia, one of the largest concrete product manufacturers in Indonesia, stated that they currently use 15% fly ash in their products and aim to increase this to 30%. Achieving this target will require further research and development, ideally in collaboration with academia. Regulatory standards for fly ash content in construction materials are not yet established. Researchers from institutions like Institut Teknologi Sepuluh Nopember (ITS) and Universitas Islam Riau (UIR) noted that the development of concrete material standards incorporating higher fly ash content has not yet garnered significant attention. Moreover, higher fly ash content in concrete can result in defects due to varying fly ash quality. To address these concerns, researchers agreed that advanced techniques such as self-healing and self-sensing should be incorporated into high fly ash content concrete to enhance reliability.

The Green Building Council Indonesia (GBCI) also supports the IGNITE project for its potential to reduce the environmental impact of the construction industry by using waste materials. GBCI encourages the use of Coal Fly Ash (CFA) and Palm Oil Fuel Ash (POFA) in concrete materials and advocates for the consideration of reusing construction materials to support the Indonesian Government's circular economy roadmap for 2025-2045 (Figure 28). By focusing on these areas, the IGNITE project can not only promote sustainable practices but also contribute to a more resilient and efficient construction industry. The integration of these innovative approaches is essential for advancing the use of fly ash in concrete while maintaining high standards of quality and performance.

Figure 28 Presentation and discussion of the result from project IGNITE to audience from industry, academia and stake holder

Having concluded the focus group discussion between all audience and stakeholders, we can draw the following conclusion:

1. The construction industry is expected to have more access to fly ash from the fly ash producer, allowing for higher utilization rates.
2. There is a pressing demand for a higher level of discussion between decision-makers and stakeholders to make regulations for concrete standards using higher fly ash content, including geopolymer concrete. Project IGNITE can be a stepping stone to attract more attention from decision maker such as local government and government body such as Badan Standar Negara (BSN) to implement the result from Project IGNITE in the building code in Indonesia and Malaysia.
3. Self-sensing and self-healing technology in concrete is one way to increase concrete reliability, which in turn can improve the utilization of fly ash.
4. Self-sensing and self-healing technology in concrete can play a vital role in allowing concrete to incorporate material reuse and achieve higher performance in a circular economy.

Figure 29 Industrial visit to PT WIKA Beton Indonesia to discuss possibility for future implementation of research from IGNITE Project in their product

Figure 30 Discussion with PT. WIKA Beton Indonesia which is an Industrial partner that will in the future use higher content Fly ash concrete product

Figure 31 Current production of concrete product in PT. WIKA Beton Surabaya which incorporate 15% fly ash

6. Challenge and Limitations

In technical aspect, replacing Ordinary Portland Cement with geopolymer concrete is still a significant challenge as the OPC industry has been well-established and the supply chain of OPC for concrete production has been around for decades. During the IGNITE project, procurement of of Geopolymer Concrete material is still challenging as it is not easily accessible for normal users. Hence, the lesson learn can be taken from the IGNITE project is to take gradually steps in substituting the percentage of OPC in concrete material with Geopolymer Concrete material and incorporating self-healing and self-sensing capabilities in the combined product to ensure its reliable performance.

This study applied standards and code within the region of research. Aiming to minimize the risk of bias, all the final data presented are transparent, inclusive to negative results, and comprehensive. Although this study is thorough, it is important to recognize that there are certain limitations. The use of secondary data restricts the opportunity to perform primary data analysis and may add biases that are inherent in the original study. Furthermore, the examined literature may not comprehensively encompass the global variations in the availability and utilization of fly ash and agricultural waste materials. Furthermore, the study specifically examines the advantages of these materials, but it is important to note that there may exist some obstacles and restrictions that were not thoroughly discussed in the literature review.

7. Sustainability of the project

As an initial collaborative study, all the findings have been analyzed and found potentially promising. Even though some hurdles and challenges are ahead the path to implementing in construction industry, scaling up the studies is the only option. Other than optimizing the content of waste in the presented advanced material, we committed in characterizing its mechanical properties. It is important in aiming to apply in more construction projects with more industry partners.

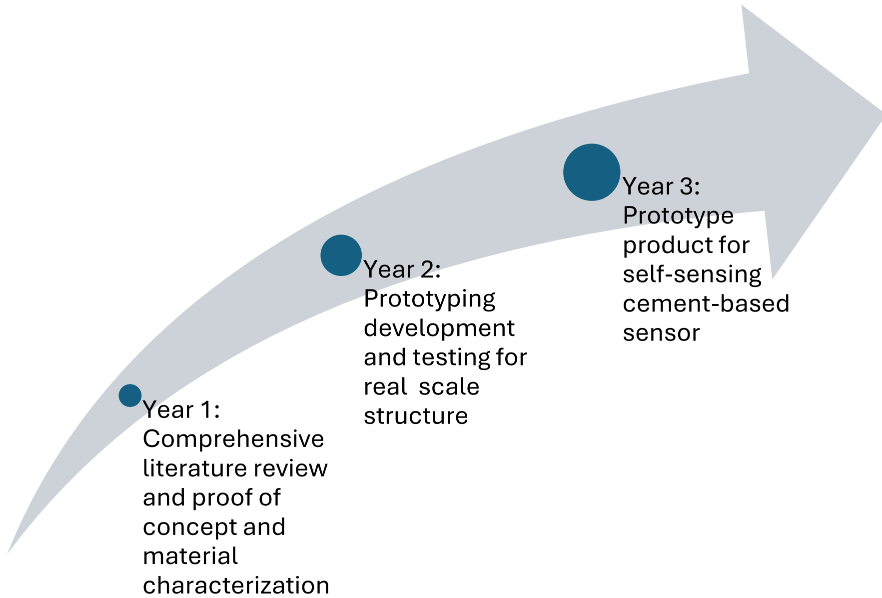
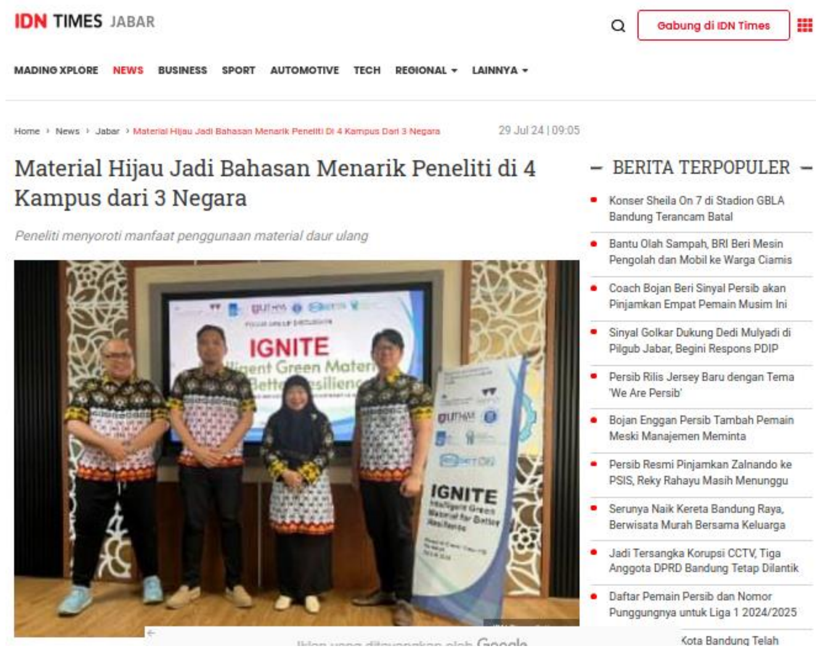


Figure 32 Milestone of the future development

Assessment of durability, strength, and environmental impact will validate the long-term benefits while monitoring its performance over an extended period. As previously mentioned, the research team has long experience and research history in self-sensing and self-healing geopolymer concrete. Hence, IGNITE project is a part of grand plan of research activity which will not only stop after the end of RIDA funding. We have planned some strategies ensuring the sustainability of this project as well as mapped potential resources of fund aiming deliverables of our studies such as Engineering and Physical Sciences Research Council (EPSRC) and Hibah DIKTI. Hence, the milestone as shown in Figure 32 is planned. The result for first year milestone shows that the self-sensing and self-healing geopolymer concrete has great potential to improve sustainability of concrete industry. However, in term of socio-economy impact, we need further investigation with field survey to determine the best business model for smart concrete. With regards to Figure 32, our next work will try to achieve milestones for the second years which include prototyping and determining social-economic model with field dataset.

Furthermore, as shown in Figure 33, to gain more attention from wider audience and potential collaborators, we promote the IGNITE project in national media, introducing potential benefit from IGNITE project to support government program. In the focus group discussion (Section 5.3), PLN, an Indonesian government-owned corporation, expressed their commitment to support and supply us with fly ash should we have further funding to continue the project.

Figure 33 Promotion in national newspaper (Republika Jabar) to improve public awareness and possibility for potential collaboration with wider audience (https://rejabar.republika.co.id/berita/shdmgg512/peneliti-empat-perguruan-tinggi-dari-tiga-negara-gelar-diskusi-bahas-material-hijau)



IDN TIMES JABAR

Gabung di IDN Times

MADING XPLORE NEWS BUSINESS SPORT AUTOMOTIVE TECH REGIONAL LAINNYA

Home › News › Jabar › Material Hijau Jadi Bahasan Menarik Peneliti Di 4 Kampus Dari 3 Negara

29 Jul 24 | 09:05

Material Hijau Jadi Bahasan Menarik Peneliti di 4 Kampus dari 3 Negara

Peneliti menyoroti manfaat penggunaan material daur ulang

– BERITA TERPOPULER –

- Konser Sheila On 7 di Stadion GBLA Bandung Terancam Batal
- Bantu Olah Sampah, BRI Beri Mesin Pengolah dan Mobil ke Warga Ciamis
- Coach Bojan Beri Sinyal Persib akan Pinjamkan Empat Pemain Musim Ini
- Sinyal Golkar Dukung Dedi Mulyadi di Pilgub Jabar, Begini Respons PDIP
- Persib Rilis Jersey Baru dengan Tema 'We Are Persib'
- Bojan Enggan Persib Tambah Pemain Meski Manajemen Meminta
- Persib Resmi Pinjamkan Zalnando ke PSIS, Reky Rahayu Masih Menunggu
- Serunya Naik Kereta Bandung Raya, Berwisata Murah Bersama Keluarga
- Jadi Tersangka Korupsi CCTV, Tiga Anggota DPRD Bandung Tetap Dilantik
- Daftar Pemain Persib dan Nomor Punggungnya untuk Liga 1 2024/2025

Figure 34 Promotion in national newspaper (IDN Times) to improve public awareness and possibility for potential collaboration with wider audience (*https://jabar.idntimes.com/news/jabar/yogi-pasha/material-hijau-jadi-bahasan-menarik-peneliti-di-4-kampus-dari-3-negara*)

The result from project IGNITE is also disseminated for academia in the form of journal publications which can be listed as follows:

1. EKAPUTRI, J. J., RUITAN, X. D. E. A., PETRUS, H. T. B. M., ANDA, M., PURBAWINASTA, L. H., LAORY, I., SETIAMARGA, D. H. E., CHIJIWA, N. & FUJIYAMA, C. 2024. Utilization of high-volume fly ash in pervious concrete mixtures for mangrove conservation. Resources, Conservation & Recycling Advances, 21, 200204. Doi: https://doi.org/10.1016/j.rcradv.2024.200204

2. LAORY, I., EKAPUTRI, J. J., KUSBIANTORO, A., RAHADI, R. A., SETIAMARGA, D. H. E., ADHA, A. & AFGANI, K. F. 2024. Evaluating the Socio-Economic Effects of Fly Ash and Agricultural Waste on the Construction Sector. Journal Integration of Management Studies, 2, 196-20. Doi: https://doi.org/10.58229/jims.v2i2.232

3. HANANI ISMAIL, A., KUSBIANTORO, A., TAJUNNISA, Y., JAYA EKAPUTRI, J. & LAORY, I. 2024. A review of aluminosilicate sources from inorganic waste for geopolymer production: Sustainable approach for hydrocarbon waste disposal. Cleaner Materials, 13, 100259. Doi: https://doi.org/10.1016/j.clema.2024.100259

8. Conclusions

The urgent need to increase the utilization of fly ash is driven by the necessity to mitigate its negative impact on human health and the environment. This need is particularly pressing in Indonesia and Malaysia, two of the main producers of fly ash and Palm Oil Fuel Ash (POFA). The development of geopolymer concrete as an alternative to Portland Cement offers a promising solution to enhance fly ash utilization. However, several factors have hindered the widespread adoption of fly ash in the construction industry. One of the biggest challenges in geopolymer concrete production is the high uncertainty in its performance due to the variability in fly ash content which can lead to cracking and low durability.

Project IGNITE addresses these issues by investigating the characteristics of various types of fly ash. Our research has revealed that different coal power plants produce fly ash with distinct properties. We concluded that the best fly ash for construction ranks as follows: fly ash from Pulverized Coal Combustion (PCC), Circulating Fluidized Bed Combustion (CFBC), and Stoker Combustion (SC) from best to worst fly ash quality respectively. This classification helps in selecting the most suitable fly ash for high-performance geopolymer concrete.

To further enhance the durability and monitoring capabilities of geopolymer concrete, we proposed incorporating smart characteristics, specifically self-sensing and self-healing properties. This can be achieved by adding artificial aggregates as self-healing agents and mixing conductive materials such as graphite and milled carbon powder as self-sensing agents. Our experiments demonstrated that these enhancements significantly improve the reliability of geopolymer concrete by enabling it to detect cracks and repair itself, thereby preventing further deterioration.

In addition to the technical aspects, we also investigated the socio-economic impact of increasing the utilization of fly ash and POFA. Using a literature synthesis method, we evaluated the implications of the rising demand for fly ash in smart geopolymer concrete. Our findings highlighted four key benefits: increased cost efficiency, improved performance, ecological advantages, and enhanced social welfare. Despite the promising results from Project IGNITE, further research is needed to quantitatively measure these benefits to ensure the project's sustainability.

Recommendations:

- Policy Support: Encourage policymakers in Indonesia and Malaysia to develop supportive policies and regulations that promote the use of fly ash and POFA in construction. This includes providing incentives for companies that adopt these sustainable materials.
- Industry Collaboration: Strengthen collaboration between academia and industry to facilitate the adoption of self-healing and self-sensing geopolymer concrete. Joint research projects, pilot programs, and knowledge transfer initiatives can help bridge the gap between research and practical application.
- Training and Development: Implement training programs for construction professionals to equip them with the necessary skills to work with new smart materials. This will ensure a smooth transition from traditional construction methods to more sustainable practices.
- Further Research: Conduct additional research to explore the long-term performance of self-healing and self-sensing geopolymer concrete under different environmental conditions. This will provide more comprehensive data to support its widespread adoption.

Conclusion: Increasing the utilization of fly ash through the development of geopolymer concrete not only addresses environmental and health concerns but also offers significant technical and socio-economic benefits. Project IGNITE's findings underscore the potential of this innovative approach, paving the way for more sustainable and resilient construction practices. Further investigation will solidify these benefits, making Project IGNITE a cornerstone for sustainable research and development in the construction industry.

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Xue, Y., Gao, W., & Zhao, Y. (2023). A Novel Method of Self-Healing Concrete to Improve Durability and Extend the Service Life of Civil Infrastructure. *Advances in Civil Engineering*, *2023*(1), 5591853.

Appendix

Table 4 Composition of geopolymer mortar samples

Paste cylinder (Sp)	**Fly Ash** 75% weight	**Alkali** 25**%** weight (Na_2SiO_3 : NaOH 8M = 2:1)	**Healing Agent (ml/m^3)**
M 0	√	√	-
M 400	√	√	400
M 1000	√	√	1000
M 5000	√	√	5000

Table 5 Result from compression test of samples with self-sensing agent

	ID	Test type	A	{rho}	F{lo m}	{sigma}{lo m}
Nr			mm^2	g/cm^3	kN	N/mm^2
1	C0A - 10.6.24	Compression tests	10000	2.07	273.3	27.3
2	C0B - 10.6.24	Compression tests	10000	-	-	-
3	C0C - 10.6.24	Compression tests	10000	2.08	258	25.8
4	C1A - 10.6.24	Compression tests	10000	2.11	252.7	25.3
5	C1B - 10.6.24	Compression tests	10000	2.01	247	24.7
6	C1C - 10.6.24	Compression tests	10000	2.03	240.1	24
7	C2A - 10.6.24	Compression tests	10000	2.05	243.1	24.3
8	C2B - 10.6.24	Compression tests	10000	2.02	216.8	21.7
9	C2C- 10.6.24	Compression tests	10000	2.02	234.7	23.5
10	C3A- 10.6.24	Compression tests	10000	2.01	240	24
11	C3B- 10.6.24	Compression tests	10000	2.03	260.3	26
12	C3C- 10.6.24	Compression tests	10000	2.03	258.3	25.8
13	C4A- 10.6.24	Compression tests	10000	2.05	258.2	25.8
14	C4B- 10.6.24	Compression tests	10000	2.08	263.3	26.3
15	C4C- 10.6.24	Compression tests	10000	2.06	256.5	25.6
16	C0D- 10.6.24	Compression tests	10000	2.13	254	25.4
17	C0E- 10.6.24	Compression tests	10000	2.16	309.7	31
18	C0F- 10.6.24	Compression tests	10000	2.13	229.2	22.9
19	C1D- 10.6.24	Compression tests	10000	2.05	238.2	23.8
20	C1E- 10.6.24	Compression tests	10000	2.1	262.3	26.2
21	C1F- 10.6.24	Compression tests	10000	2.1	251.1	25.1
22	C2D- 10.6.24	Compression tests	10000	2.09	230.4	23
24	C2E- 10.6.24	Compression tests	10000	2.04	238.7	23.9
25	C2F- 10.6.24	Compression tests	10000	2.04	241.9	24.2

26	C3D- 10.6.24	Compression tests	10000	2.02	265.8	26.6
27	C3E- 10.6.24	Compression tests	10000	2.05	264.8	26.5
28	C3F- 10.6.24	Compression tests	10000	2.09	270.9	27.1
29	C4D- 10.6.24	Compression tests	10000	2.09	259.5	25.9
30	C4E- 10.6.24	Compression tests	10000	2.12	249.1	24.9
31	C4F- 10.6.24	Compression tests	10000	2.08	252.2	25.2

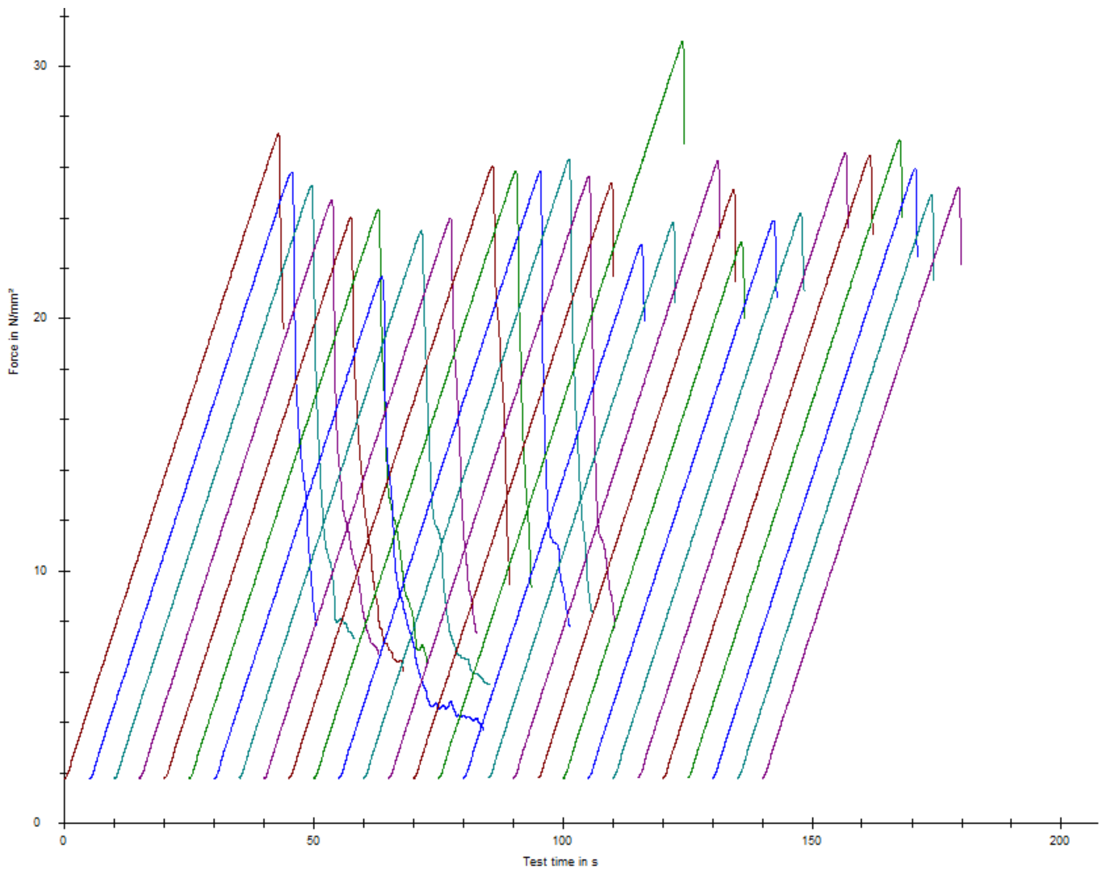

Figure 27 Record of loading from Tony Technic Compression Test Equipment

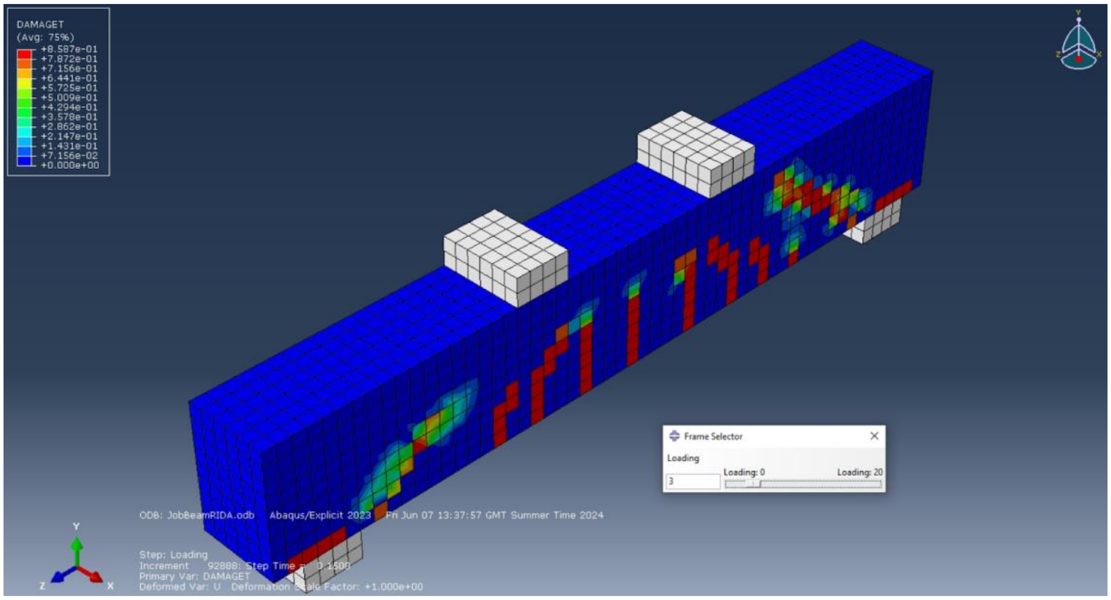

Figure 28 Tension controlled damage of beam under bending test

Finite Element Command input in Abaqus

```
**
** PARTS
**
*Part, name=Beam
*Element, type=C3D8R
** Section: Section-Beam
*Solid Section, elset=Set-1, material="Concrete fc 25 MPa"
,
*Part, name=RebarCompr
*Element, type=T3D2
** Section: Section-dia10
*Solid Section, elset=Set-1, material=Steel_450
78.5,
*Part, name=RebarTens
*Element, type=T3D2
** Section: Section-dia10
*Solid Section, elset=Set-1, material=Steel_450
78.5,
*Part, name=Stirrups
*Element, type=T3D2
** Section: Section-dia8
*Solid Section, elset=Set-1, material=Steel_450
50.24,
*Part, name=Support
*Element, type=C3D8R
```

```
** Section: Section-Support
*Solid Section, elset=Set-1, material=Steel_450
,
**
** MATERIALS
**
*Material, name="Concrete fc 25 MPa"
*Density
 2.3e-09,
*Elastic
 15427.3, 0.18
*Concrete Damaged Plasticity
35.,      0.1,     1.16,    0.667, 0.007985
*Concrete Compression Hardening
    12.5,        0.
 14.7794,  1.5e-05
 16.8972,    4e-05
 18.8151,  7.9e-05
 20.4997, 0.000132
 21.9254, 0.000202
 23.0769,  0.00029
 23.9494, 0.000396
 24.5492,  0.00052
 24.8918, 0.000661
     25., 0.000816
 24.9016, 0.000985
 24.6269, 0.001166
 24.2065, 0.001356
*Concrete Tension Stiffening
       3.,        0.
  1.66435, 0.000281
  1.17915, 0.000507
 0.923358, 0.000718
  0.76383, 0.000923
 0.654173, 0.001124
 0.573836, 0.001324
 0.512265, 0.001522
 0.463463,  0.00172
 0.423761, 0.001917
*Concrete Compression Damage
       0.,        0.
       0.,  1.5e-05
       0.,    4e-05
       0.,  7.9e-05
       0., 0.000132
```

```
      0., 0.000202
      0.,  0.00029
      0., 0.000396
      0.,  0.00052
      0., 0.000661
      0., 0.000816
 0.003936, 0.000985
 0.014926, 0.001166
  0.03174, 0.001356
*Concrete Tension Damage
      0.,       0.
 0.445215, 0.000281
 0.606951, 0.000507
 0.692214, 0.000718
  0.74539, 0.000923
 0.781942, 0.001124
 0.808721, 0.001324
 0.829245, 0.001522
 0.845512,  0.00172
 0.858746, 0.001917
*Material, name=Steel_450
*Density
 7.8e-09,
*Elastic
210000., 0.3
*Plastic
450.,0.
**
** BOUNDARY CONDITIONS
**
** Name: BC-1 Type: Symmetry/Antisymmetry/Encastre
*Boundary
Set-3, PINNED
** ----------------------------------------------------------------
**
** STEP: Loading
**
*Step, name=Loading, nlgeom=YES
*Dynamic, Explicit
, 1.
*Bulk Viscosity
0.06, 1.2
**
** BOUNDARY CONDITIONS
**
```

```
** Name: BC-2 Type: Displacement/Rotation
*Boundary, amplitude=Amp-1s
Set-4, 2, 2, -10.
**
** OUTPUT REQUESTS
**
*Restart, write, number interval=1, time marks=NO
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
A, RF, U, V
*Element Output, directions=YES
DAMAGEC, DAMAGET, EVF, LE, PE, PEEQ, PEEQVAVG, PEVAVG, S, SVAVG
*Contact Output
CSTRESS,
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
```