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Smart Green Concrete: Innovation of Concrete Materials from Fly ash Waste and Lapindo Mud Integrated Smart E. crassipes Coir Geotextile to Realize Indonesia's Sustainable Infrastructure

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ABSTRACT
Pariaman City, situated near the Semangko fault and the Indo-Australian plate subduction zone, is highly prone to earthquakes and tsunamis. To address this, the Earthquake Buddy Application (EDY App) was developed as an innovative solution for disaster mitigation. EDY App utilizes Geographic Information Systems (GIS) to provide real-time earthquake vulnerability maps, early warnings, and evacuation route suggestions to Temporary Evacuation Sites (TES). It also offers education on earthquake preparedness and facilitates donations for relief efforts. The application's main contribution lies in its integration of comprehensive disaster management tools into one platform. By providing critical information during emergencies, the app empowers users to make informed decisions, which can reduce casualties in high-risk areas. The app also encourages community preparedness by offering accessible education on earthquake mitigation. EDY App is designed to create a disaster-resilient society in Pariaman, ensuring that residents are better equipped to respond to natural disasters through real-time alerts and evacuation support, ultimately enhancing local preparedness and reducing the potential impact of future earthquakes.

Introduction

Environmental issues such as global warming have become a major concern around the world. Increased carbon emissions, resulting in the depletion of the atmospheric ozone layer, consistently increase the Earth's temperature. In Indonesia, carbon emissions mainly come from various sectors, especially the infrastructure sector. This sector makes a significant contribution to the increase in carbon emissions from year to year. The majority of emissions from the construction sector come from construction materials used during construction. Some materials such as wood, iron, glass, concrete, and brick have carbon emissions ranging from 0 to 0.5 kg CO2. Concrete is one of the main materials in construction, which is a concern because of the high level of use even though the carbon emissions it produces are not as large as some other materials. This is reinforced by data from the Global Cement and Concrete Association (GCCA) which notes that about 14 billion m2 of concrete is produced every year. This large amount of concrete production is certainly in line with the high carbon emissions produced, both from the components and the manufacturing process (Chen et al., 2023).

Indonesia has intensified its efforts in carbon mitigation, particularly in the construction sector, in alignment with global climate initiatives like the Paris Agreement. The government's Nationally Determined Contribution (NDC) targets a reduction of carbon emissions by 29% by 2030, or up to 41% with international assistance. The construction industry, a significant contributor to national emissions, is a priority in these mitigation efforts. The *Green Building Code* mandates the use of energy-efficient designs and sustainable materials, encouraging the adoption of low-carbon alternatives such as fly ash, recycled steel, and sustainable wood.

Empirical data reflects progress in the sector. Carbon emissions from construction decreased by 7% between (2019) and 2022, largely due to green building practices and the increased use of low-emission materials like fly ash-based concrete. This material has been shown to reduce emissions by up to 30% compared to conventional Portland cement, contributing to Indonesia's broader goal of sustainable infrastructure development while addressing the ongoing challenges of climate change.

The problem of carbon emissions in buildings is most affected by the 10 components contained in concrete. Not only that, the emissions contained or produced by concrete are also divided into two aspects, namely raw materials and concrete production. Carbon emissions produced in the aspect of raw materials include the mining and transportation processes. Meanwhile, carbon emissions in concrete production consist of mixing, casting, transportation, compaction, and curing processes. Seeing the many components and processes needed to produce concrete, of course, a method of handling carbon emission waste generated from these components and processes is needed. Unfortunately, until now there has been no solution that really focuses on efforts to reduce carbon emissions produced in concrete production (Kamakaula, 2024).

In addition, Indonesia is a country with abundant fossil fuel reserves in the form of coal. Based on data from the Ministry of Energy and Mineral Resources, in (2021) Indonesia has coal reserves of 31.69 billion tons with 43% of the total reserves in the East Kalimantan region. Coal burning produces 5% solid pollutants in the form of ash (fly ash and bottom ash or FABA) with a composition of 80-90% fly ash and 10-20% bottom ash. Fly ash is a waste of coal combustion in the form of a very light powder and grayish in color. FABA contains 40-60% silica, 20-35% aluminum, 4-10% peroxide, 5-30% calcium oxide, and additives (magnesium oxide, titanium, phosphorus oxide, and carbon) in relatively small compositions. Based on the composition it contains, this waste can be used as a fine and lightweight aggregate in lightweight concrete (Samawi et al., 2024).

In addition, the Lapindo mud is a problem that has not been solved in Indonesia to date. The impact of the Sidoarjo hot mud involves losses in the health, environment, and economy, especially for residents in Porong. However, in the midst of its negative impact, Sidoarjo hot sludge has the potential to be used as a valuable resource, especially in terms of its composition. According to the Lapindo Mud Management Agency, the sludge source continues to release around 30,000 to 60,000 cubic meters of sludge every day. Lapindo mud has produced various basic materials that can be used as materials for making concrete, such as silica. Therefore, Lapindo mud can be used as a substitute for cement. Chemical analysis of Lapindo mud conducted by Lusino in 2017 showed that

SiO_2 compounds dominated in Sidoarjo mud, with an average percentage of 51.92%. In the second position there is Al_2O_3 as much as 25.07% and Fe_2O_3 as much as 8.53%, so that Lapindo sludge has the potential as a raw material for pozzolan and a substitute for concrete aggregate (Abi et al., 2015).

On the other hand, Indonesia, with its geographical location along the Pacific Ring of Fire, is one of the most vulnerable countries to earthquake disasters. The high frequency and potential for devastation from earthquakes in Indonesia pose a major challenge for engineers, urban planners, and governments in building earthquake-resistant infrastructure. One of the innovations that can overcome this problem is earthquake sensing-based concrete technology. This technology is designed to improve the ability of building structures to detect and respond to earthquakes in real-time, so that it can minimize damage and save lives. Concrete technology based on earthquake sensing in the form of Optical Frequency Domain Reflectometry (OFDR) is not only a technical solution, but also an important step towards safer and more sustainable development in Indonesia, given the constant threat of earthquake disasters faced by the country.

This research aims to analyze the manufacturing process, effectiveness, feasibility potential, and contribution of smart green concrete to aspects of the SDGs in Indonesia, including the stages of its implementation. This paper is also expected to provide innovative technical solutions that have a positive impact on society and the environment, with the hope that the application of smart green concrete technology can improve resilience, sustainability, and efficiency in the construction industry in Indonesia.

Materials and Methods

The data collection method used is the literature study method, which is research based on reliable sources which is then studied, studied, interpreted, and poured in written form. The data used is secondary data, both qualitative and quantitative, obtained from books, journals, articles, and the internet. To validate the results of the literature study, field tests and direct implementation of green concrete technologies must be conducted. Initially, materials such as fly ash, Lapindo mud, and water hyacinth fibers should be sourced locally and tested for chemical composition using XRF analysis. Following material preparation, small-scale prototypes of green concrete mixes, including geopolymer paste and alkali activators, will be produced in controlled environments to test compressive strength, durability, and wear resistance. Successful prototypes will then be applied in pilot projects at real-world construction sites in disaster-prone areas, incorporating Optical Frequency Domain Reflectometry (OFDR) technology to monitor structural integrity under stress. Long-term monitoring and data collection will assess the material's resilience and its environmental benefits, such as reduced carbon emissions. Feedback from local engineers and stakeholders will further refine the technology, ensuring its practical applicability and effectiveness in contributing to sustainable infrastructure development in Indonesia.

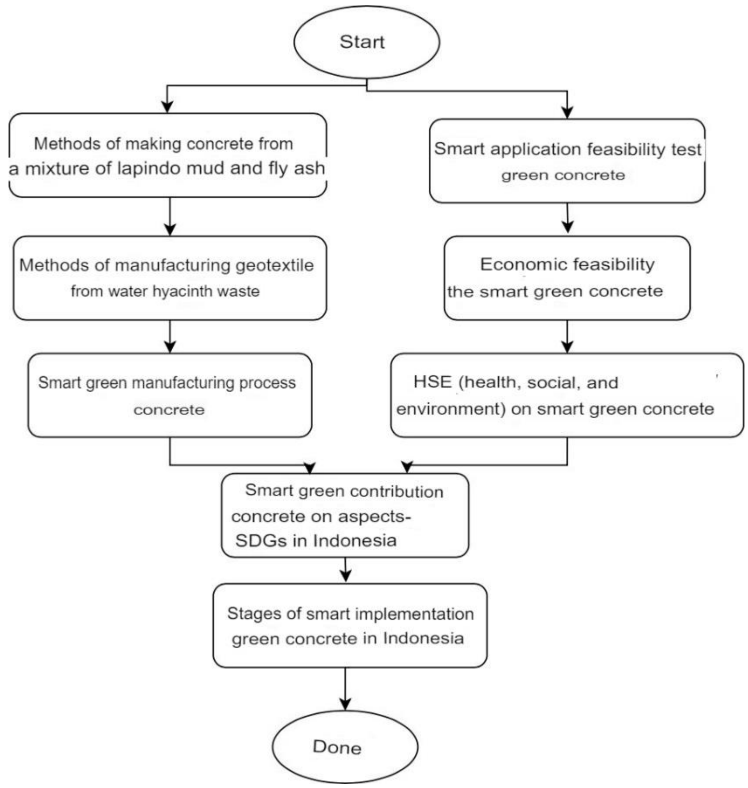

Figure 1. Research thinking framework

The analysis carried out was (1) Analyzing the method of making concrete from a mixture of lapindo mud and fly ash; (2) Analyze the method of making geotextiles from water hyacinth waste; (3) Analyze the process of making smart green concrete; (4) Analyzing the feasibility test of the implementation of smart green concrete; (5) Analyze the economic feasibility of smart green concrete; (6) Analyzing the feasibility of HSE (health, safety, and environment) on smart green concrete (7) Analyzing the contribution of smart green concrete to aspects of the SDGs in Indonesia; (8) Analyze the stages of smart green concrete implementation in Indonesia.

Results and Discussions

Making a concrete mixture from fly ash and lapindo mud

During the manufacturing process, material preparation was carried out by collecting Lapindo sludge from the Porong, Sidoarjo areas, as well as fly ash from various Steam Power Plants (PLTU) spread across Indonesia. Fine material analysis involves XRF and reactivity research. Lapindo sludge was analyzed using XRF tests to determine the composition of its content. The grouping categories are determined based on SiO_2, Al_2O_3, and Fe_2O_3 levels. If the content of SiO_2, Al_2O_3, and Fe_2O_3 exceeds 70%, it will be categorized as class F, while if it reaches or exceeds 50%, it will be categorized as class C. Lapindo mud is included in the class C category, because the amount of $SiO_2 + Al_2O_3 + Fe_2O_3$ which produces 66.72%. Meanwhile, fly ash based on its analysis, is included in the class F category with a total of $SiO_2 + Al_2O_3 + Fe_2O_3$ of 88.77%. Both Lapindo mud and fly ash can be used as materials to make up artificial aggregates based on geopolymer paste and cement paste because they have a high content of Si and Al (Rosanti & Winanti, 2016).

After preparing the materials, Lapindo mud and fly ash are heated in a furnace at 800°C for 15 hours to turn the compounds into reactive. After the heating stage, grinding is carried out to reduce the size of Lapindo mud particles and fly ash to make it easier to test concrete. The milling process uses a ball mill until the particle size reaches 75 µm by particel size distribution analysis using the Mastersizer 2000 tool. The manufacture of geopolymer paste aggregates involves the use of alkali as an activator, which is composed of Sodium Hydroxide (NaOH) and Na_2SiO_3. To achieve a molarity of 12 M in 1 liter of distilled water, 480 grams of solid NaOH is needed taking into account the relative atomic mass of NaOH which is 40 grams/mol. The activator alkaline mixture is then mixed with Lapindo sludge and fly ash in a ratio of 20% Lapindo sludge and 80% fly ash. Next, the mixture is poured into a 5 cm x 10 cm cylindrical mold (Rosanti & Winanti, 2016).

The compressive strength test results showed that the geopolymer paste with a ratio of 20% Lapindo mud and 80% fly ash reached the highest value of 33.00 MPa at the age of 28 days, with a wear of 25.08%. Meanwhile, cement paste with a ratio of 10% Lapindo mud, 30% fly ash, and 60% cement has a higher compressive strength value of 39.83 MPa, but its wear is higher by 30.60%. The maximum wear requirement to be used as a material based on ASTM C 131-03 is 50%, so that a concrete mixture with a ratio of 20% Lapindo mud and 80% fly ash, as well as 10% Lapindo mud, 30% fly ash, and 60% cement can be used as a paste-based material (Putri et al., 2022). The mixture of fly ash and lapindo sludge has a very high silica content of almost 50%. Silica has several significant roles as a building material in green concrete, especially in the context of its use in concrete. During the concrete hardening process, silica reacts with CO2 in the air and converts it into an insoluble calcium carbonate compound (CaCO3). This process is known as carbonation, and is a way in which CO2 can "lock" in a concrete structure, reducing the amount of CO2 released into the atmosphere (Pamaratana, 2023).

E. crassipes Geotextile

The manufacture of geotextiles from water hyacinth (Eichhornia crassipes) involves a series of important steps to ensure the strength and reliability of this material in concrete construction applications. The process begins with the harvesting of hyacinth plants that thrive in the waters, followed by the separation of the fibers from other plant parts such as leaves and roots. The separated fibers then undergo a retting process, which aims to remove the attached pectin and lignin substances, thereby improving the flexibility and strength of the fibers (Jirawattanasomkul et al., 2021). After the retting process is completed, the water hyacinth fibers are carefully cleaned and sorted to ensure their quality before entering the geotextile forming stage.

This geotextile is made through the cooking or thermal bonding technique, where separate fibers are thermally bonded together to form a strong, porous sheet or tissue structure. In addition, mechanical methods and the use of special textile machinery can also be used to ensure the consistency and strength of the resulting geotextile (Abral et al., 2014). The geotextile of water hyacinth is then integrated in a mixture of Lapindo mud concrete and fly ash as a reinforcing additive. This integration helps to improve the tensile strength and resistance to cracking of concrete, as well as improve mechanical properties and resistance to earthquakes (Jirawattanasomkul et al., 2021). Concrete with the addition of 6% hyacinth fiber has an average compressive strength value of 33.97 kg/cm2 at the age of 7 days and 48.53 kg/cm2 at the age of 28 days.

Figure 2. Geotextiles from water hyacinth

Earthquake and Deformation Sensing

Detection of deformation due to earthquakes in concrete structures plays an important role in alerting building occupants and accurately assessing the extent of damage that occurs (Hou et al., 2021). Various technologies have been developed for this purpose, such as fiber optic monitoring and Optical Frequency Domain Reflectometry (OFDR). The technology allows for real-time monitoring and can effectively evaluate the integrity of concrete structures. Fiber-optic sensing technologies such as OFDR can monitor deformation and detect earthquakes with high resolution. OFDR can provide a detailed explanation of the distributed strain on the concrete frame structure, directly measure the curvature of steel beams and deformation in the reinforcement cage, as well as assess structural damage (Zhang et al., 2022).

Distributed sensing technology using optical fibers has been used for decades to detect damage to infrastructure. OFDR is a type of fiber optic sensing technology that has high spatial resolution and can produce accurate data on damage in concrete frame structures. The information can be detected by the relevant station and then send a danger signal to the building occupants to immediately evacuate.

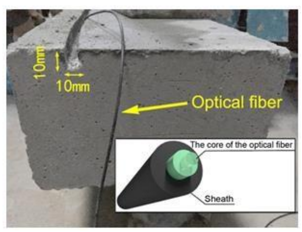

Figure 3. Planting of fiber optic cables on concrete (Hou et al., 2021)

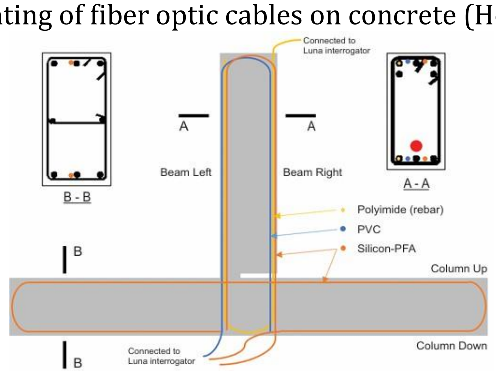

Figure 4. Cable layout at beam-column joints Zhang et al., (2022)

Fiber optic cables are embedded in steel and concrete reinforcement structures at each joint of the building's beams and columns. The layout of the cable arrangement is as shown in the image above. On the beams and columns there are two cables planted in the concrete, namely PVC and Silicon-PFA cables. The cable is installed horizontally between the column reinforcing steel and the beam. One other cable, that is, a polymide cable, is attached to the horizontal reinforcement on the beam. The cables are arranged to determine the effect of deformation that occurs on each cable. All fiber optic cables are set to a spatial resolution of 1.3 mm with a sampling rate of 6.25 Hz. The cables are connected to a monitoring station that can see the deformation conditions in concrete directly.

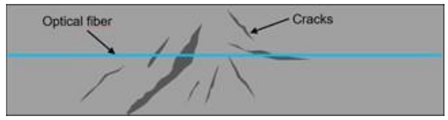

Figure 5. Cracks arising in concrete due to the earthquake Hou et al., (2021)

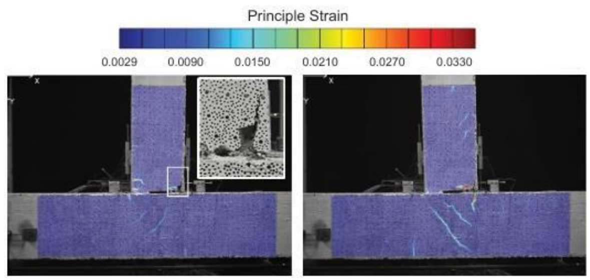

Figure 6. Cable tension at beam-column joints Zhang et al., (2022)

In the event of an earthquake, the attraction will arise on the deformation of the concrete and make the tension of the fiber optic cable increase. This is due to the difference in concrete structure before and after the earthquake occurred. Cracks like the one in the picture above make fiber optic cables become more attractive and tense, linear with the large dimensions of the cracks that occur. The distribution of tension spread throughout the concrete structure will indicate earthquake damage to the building. In the picture above, the tension of the optical cable on the concrete is uniform. As a result of the earthquake, there are areas where the cable tension becomes higher. The area shows the damage that occurs to the concrete structure in a building. Thus, the monitoring station can immediately send an alarm signal to the building occupants to immediately evacuate and take further disaster mitigation measures.

Implementation of smart green concrete in smart buildings

Concrete made from lapindo sludge waste and fly ash that has been added geotextiles, water hyacinths and integrated with soil deformation sensors, namely Optical Frequency Domain Reflectometry can be implemented in ordinary buildings and smart buildings (smart buildings)

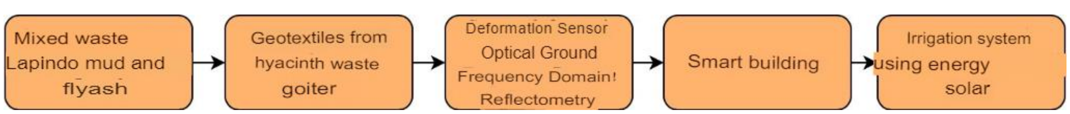

Figure 7. Implementation steps

Many urban high-rise buildings in several countries have a smart building concept that is equipped with gardens to improve air quality in the building area. Smart systems can be implemented in garden areas to improve work efficiency.

Gambar 8. Smart garden Torres et al. (2019)

One of the smart systems that can be applied is the automatic irrigation system. Automatic irrigation can be an efficient irrigation method for rooftop gardening that has several advantages such as reducing human effort to manage irrigation in the garden, applying accurate and precise amounts of water when needed to maintain the optimum soil moisture available at the roots to reduce the management time required on monitoring the water needs of plants and manual control of irrigation systems (Sangeetha et al., 2022).

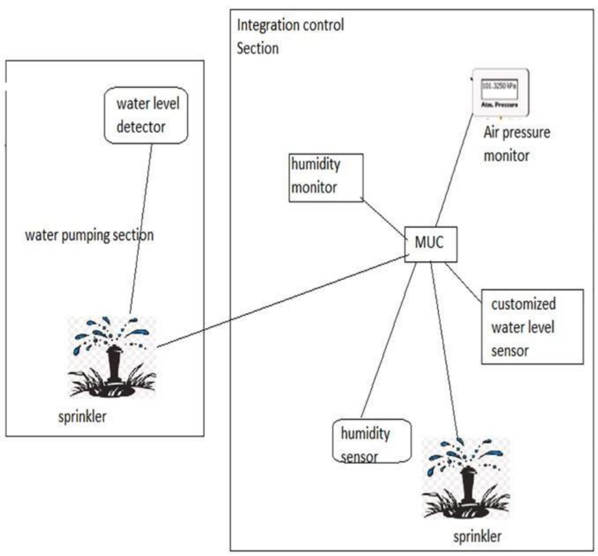

Figure 9. Integrated water management and monitoring management in smart buildings (Sangeetha et al., 2022)

The automatic irrigation structure is based on IoT technology to manage groundwater storage pumps in the garden and monitor the humidity, pressure, and temperature of the soil in the garden. During the first stage, operators continue to run software applications through the use of mobile portals that manage garden irrigation or through mobile devices . By using Internet access, each server sends data to the user (Sangeetha et al., 2022).

The water monitoring and irrigation unit consists of a water pump, sensors, irrigation sprinklers to collect water including an MCU that regulates the operation of the base. The power of the water pump from photovoltaic is used to pump water, which is then stored as a backup to ensure irrigation can be carried out as needed at any time in the event of a power outage (Sangeetha et al., 2022).

Potential feasibility of applying smart green concrete

Economic Analysis

To determine the sustainability of this innovation, an economic analysis was carried out consisting of calculations of the cost of process tools and utilities, profit before and after tax, depreciation, internal rate of return (IRR), and break-even point (BEP). The calculation of the cost of the equipment is adjusted on the assumption that the construction phase is planned to start in 2025. The price of each tool is obtained from references in the market according to studies on trusted websites and adjusted using the Chemical Engineering Plant Cost Index (CEPCI).

In calculating the Purchased Equipment Cost (PEC), the variable value of the Chemical Engineering Plant (CEP) Index in 2025 is required. The value of this CEP Index can be obtained by the regression equation from the graph above, which is y = 9.5267x–18,620 where y is the index and x is the year. From the results of the analysis, a PEC value of 336871.86 USD was obtained. If the total PEC and total installation costs are summed, a fixed capital value of 522,151.38 USD is obtained.

Table 1. Installation cost

Component	Ratio of PEC	Fees (USD)
Control system and instrumentation	5%	16843,59
Construction	30%	101061,56
Contingency	10%	33687,19
Engineering and supervision	5%	16843,59
Project management	5%	16843,59
Total		**185279,52**

From the calculation of assumptions, the entire product has a selling price of 8366 USD. Then, the calculation of profit before and after tax includes details of fixed capital, operational and maintenance costs, and the amount of tax. The amount of tax used is 25% of the profit before tax in accordance with Law No. 36 of 2008 concerning Income Tax. From the calculation results, an after-tax profit of 7,333,593.23 USD per year was obtained.

Table 2. Profiit calculation details

Details	Value (USD)	Information
Fixed capital	522.151,38	During the construction phase
Operational and therapy	261.075,69	Per year
Sales of product products	10.039.200	Per year
Advantages before tax	9.778.124,31	Per year
After Profit tax	**7.333.593,23**	**Per year**

Furthermore, the calculation of NPV and IRR includes details of cash flows and the present value of those cash flows in each year from the start of the project to the completion of the project. Cash flow and present value in the first to second year are negative because the first two years of the project are the investment and construction stages of the hot-mud concrete system. Cash flow and present value began to have a positive value in the 3rd year when the system started operating. The results of the calculation of NPV and IRR can be seen in **Table 5**.

Table 3. NPV and IRR calculation

Year	Information	Value (USD)	Present Value (USD)
1	Fixed capital	-208.860,55	-189.873,23
2	Fixed capital	-313.290,83	-258.918,04
3	Cash flow	7.333.593,23	5.509.837,14
4	Cash flow	7.333.593,23	5.008.942,85
5	Cash flow	7.333.593,23	4.553.584,41
15	Cash flow	7.333.593,23	1.755.603,91
16	Cash flow	7.333.593,23	1.596.003,56
17	Cash flow	7.333.593,23	1.450.912,32
18	Cash flow	7.333.593,23	1.319.011,20
19	Cash flow	7.333.593,23	1.199.101,09
20	Cash flow+SV	7.385.808,37	1.097.853,35
	Total (NPV)		49.266.259,66
	IRR		**15,85%**

Based on the analysis, it can be concluded that the system is economically feasible to implement. This is shown by a positive NPV, IRR greater than discounts, and a short payback period.

Table 4. Results of economic analysis

Parameter	Value
Fixed capital	522.151,38
Net Present Value (NPV)	49.266.259,66
Internal Rate of Return (IRR)	15,85%
Return period	3 years

This innovation supports the development of more sustainable infrastructure by utilizing industrial waste and available local materials. Strong and environmentally friendly infrastructure will increase Indonesia's overall economic competitiveness, attract foreign investment, and boost economic growth.

Analisis HSE (health, safety, and environment)

The health analysis in this project that needs to be considered is the mixing process and the use of materials such as fly ash, Lapindo mud, and water hyacinth fibers that can produce dust and particulates. The analysis should consider effective dust control and the use of personal protective equipment (PPE) to protect workers from potentially harmful exposure to the respiratory tract, while waste management from all production and construction processes must comply with applicable environmental regulations.

The safety aspect that needs to be considered is that when installing earthquake and deformation sensors in concrete requires special technical skills and a deep understanding of electronic systems, so it is necessary to ensure that workers are well-trained in the installation, testing, and operation of sensors to avoid electrical accidents and potentially adverse system failures. As for the construction stage with geotextile-reinforced concrete, it is necessary to pay attention to the potential for accidents such as falling from a height while working at height or being hit by a heavy object during the casting process. The use of fly ash waste, Lapindo sludge and water hyacinth as the main raw materials in concrete shows a commitment to recycling, reducing carbon emissions and reducing waste that pollutes the environment. Environmental analysis must still pay attention to the impact of the extraction and initial processing of materials on the quality of air, water, and soil around the collection site.

Social Analysis

Social analysis for smart green concrete, focusing on impact and interaction with local communities. Projects can have a positive economic impact through the creation of local jobs and increased economic activity, while paying attention to social welfare by improving access to public services such as health and education. It is necessary to pay attention to the potential for social conflicts related to land rights and the distribution of economic benefits, and to develop strategies to manage these conflicts with open dialogue and participatory approaches. By involving a wide range of stakeholders and paying attention to local education and training, this project can contribute positively to the local communities in the project area.

The contribution of smart green concrete to aspects of the SDGs in Indonesia
Role in SDGs number 9 (Industry, Innovation and Infrastructure)

By implementing smart green concrete , it has a positive impact on the industrial and infrastructure sectors. Data shows that the contribution of the construction sector to Indonesia's Gross Domestic Product (GDP) reached around 10% in 2021 by Central Statistics Agency, (2022). By utilizing industrial waste as the main material in concrete, the project not only helps to reduce waste but also supports the development of a circular economy and the reduction of carbon footprint in the construction industry. The use of geotextiles from water hyacinth in construction also has the potential to improve the efficiency of material use and reduce infrastructure costs, while creating new opportunities for local innovation. The integration of Optical Frequency Domain Reflectometry (OFDR) sensor technology in concrete not only improves structural safety but also encourages the adoption of advanced technologies in the construction sector, supporting the growth of innovation and technological advancement in Indonesia.

Role of SDGs number 11 (Sustainable Cities and Settlements)

Smart green concrete supports the transformation of cities towards better sustainability. Data shows that more than 60% of Indonesia's population will live in urban areas by 2030, emphasizing the need for strong and secure infrastructure (Central Statistics Agency, 2021). The use of industrial waste as the main material in concrete not only reduces waste and carbon emissions, but also reduces the pressure on natural resources in rapid urban development. The implementation of geotextiles from water hyacinth in construction projects can strengthen urban infrastructure against earthquakes, which is relevant considering that 43% of major cities in Indonesia are in earthquake-prone zones (World Bank, 2020). The integration of Optical Frequency Domain Reflectometry (OFDR) sensors not only improves building safety but also aids in urban spatial planning that is more adaptive to natural disaster risks.

Role of SDGs number 13 (Handling Climate Change)

Smart green concrete makes a direct contribution to reducing carbon emissions and increasing resilience to the impacts of climate change. Data shows that the construction and infrastructure sector in Indonesia was responsible for about 23% of total greenhouse gas emissions in 2020 (World Bank, 2021). By using industrial waste as the main material in concrete, this project helps reduce carbon emissions from the production of conventional building materials and coal burning at coal-fired power plants. The use of geotextiles from water hyacinths not only reduces the use of new raw materials but also helps in increasing the resilience of infrastructure to natural disasters that are increasingly frequent due to climate change. The integration of earthquake and deformation sensing technology in the form of Optical Frequency Domain Reflectometry (OFDR) in construction also contributes to reducing the risk to urban infrastructure against the impact of earthquakes that can be exacerbated by climate change.

Stages of smart green concrete implementation in Indonesia

Parties involved

The large-scale implementation of smart green concrete in Indonesia, various parties need to be involved in the success of this implementation. First, central and local governments have a key role to play in providing regulations, policies, and incentives that support the adoption of these technologies, including fiscal incentives for companies that use environmentally friendly materials and new technologies. The Ministry of Public Works and Public Housing (PUPR) in particular will play a role in regulating technical standards and the quality of construction materials used. Second, the industrial sector and construction companies need to be involved in the adoption of this technology through partnerships and collaboration in large-scale construction projects. These companies must invest in research and development (R&D) to optimize the use of waste feedstocks and earthquake sensor technology. Third, academics and research institutions can make a significant contribution through scientific research that supports technological innovation and ensures the effectiveness and safety of the materials used. Fourth, local communities and communities must also be involved in this process, especially in the aspect of education and awareness of the importance of sustainable development and disaster mitigation. Finally, non-governmental organizations (NGOs) and international agencies can play a role in providing technical and financial support and promoting best practices in sustainability and climate change mitigation.

Towards Golden Indonesia 2045, the implementation of smart green concrete technology requires clear and structured milestones. In the 2024-2025 period, the main focus will be on preparation and planning, including the establishment of cross-sectoral teams, the development of national roadmaps, the procurement of initial funds, and the establishment of regulations to support research and development. During 2026-2030, research and development will be carried out through pilot projects in strategic regions, evaluation of results, development of national standards, and preparation of incentive policies. In the 2031-2035 period, medium-scale implementation will begin with the application of technology to infrastructure projects such as school buildings, hospitals, and public housing, as well as increasing the capacity of local industries for the production of related materials. Policy and regulatory evaluations will continue to be carried out to ensure conformity and effectiveness. Furthermore, in 2036-2040, evaluations and expansions will be carried out in other fields. Finally, in the 2041-2045 period, further research and technological innovation will continue to be carried out to improve efficiency and reduce costs. International cooperation will be strengthened to share knowledge and experience. By following this milestone, Indonesia is expected to achieve the status of a country with environmentally friendly earthquake-resistant infrastructure and lead construction technology innovation in the Southeast Asian region by 2045.

The implementation of green concrete technology in Indonesia has demonstrated significant potential for both environmental and economic impacts. One notable case study is the application of fly ash-based green concrete in infrastructure projects in Sidoarjo, where Lapindo mud, previously considered a waste product, was repurposed as a key material. The project successfully reduced the use of conventional Portland cement, leading to a reported decrease of 30% in carbon emissions compared to traditional concrete mixes (Rosanti & Winanti, 2016). This approach not only mitigates the environmental impact of concrete production but also solves the problem of hazardous waste disposal.

Further field tests in the Jakarta metropolitan area applied green concrete to road construction, incorporating fly ash and water hyacinth geotextiles to improve durability and reduce the carbon footprint. These pilot projects, monitored over a period of 12 months, showed enhanced structural resilience, particularly in reducing cracks caused by seismic activity, which is prevalent in Indonesia due to its location on the Pacific Ring of Fire. Monitoring through embedded Optical Frequency Domain Reflectometry (OFDR) technology allowed real-time tracking of structural integrity, offering early warnings of potential deformations (Jirawattanasomkul et al., 2021).

In terms of economic benefits, a feasibility study conducted by the Ministry of Public Works and Public Housing (PUPR) indicated that green concrete applications in public infrastructure projects could lead to a cost reduction of 20-25%, primarily due to the lower costs associated with using recycled materials like fly ash and Lapindo mud (Samawi et al., 2024). These findings suggest that widespread adoption of green concrete in Indonesia could contribute to achieving the country's carbon mitigation targets while offering more sustainable infrastructure solutions. The technology's real impact lies in its ability to reduce both carbon emissions and construction costs while enhancing the resilience of buildings in earthquake-prone regions.

To accelerate the adoption of green concrete technology in Indonesia's construction sector, concrete implementation steps and supportive policies are essential. First, the government should establish mandatory regulations that require the use of low-carbon construction materials, such as fly ash and Lapindo mud, in all public infrastructure projects. This can be supported by providing tax incentives or subsidies for companies that incorporate green concrete technologies. Second, a nationwide certification system for sustainable building materials should be developed, ensuring that green concrete meets safety and environmental standards. Third, integrating training programs for construction workers and engineers on the proper use of green concrete technologies will ensure smooth adoption on-site. Additionally, pilot projects showcasing the benefits of green concrete, particularly in earthquake-prone regions, should be expanded to demonstrate its resilience and cost-effectiveness. The government could also promote partnerships between academic institutions, the private sector, and local communities to advance research and innovation in green construction materials. By implementing these steps, Indonesia can more rapidly reduce its carbon footprint in the construction industry while enhancing infrastructure sustainability.

Conclusion

In the midst of the increasing need for environmentally friendly and sustainable construction materials. Smart green concrete has superior mechanical properties and is able to withstand cracks due to earthquakes well. The use of smart green concrete can be an effective solution in increasing infrastructure resilience. Integration with earthquake sensors and Optical Frequency Domain Reflectometry deformation can detect cracks in concrete, so it can help reduce casualties. Concrete resulting from a mixture of Lapindo sludge waste, fly ash, and hyacinth geotextiles can be integrated in a smart building that is integrated with automatic irrigation based on solar energy in the garden to reduce the burden of air pollution around the building. The implementation of smart green concrete can increase the usability of Lapindo mud, fly ash, and water hyacinth which were previously detrimental and damaging to the environment, and at the same time reduce the carbon emission footprint. This advantage makes it relevant to the sustainable development goals that have been proclaimed by the Indonesia government. The application of smart green concrete in Indonesia has proven to be economically feasible. This is based on the results of economic analysis which shows a positive NPV, which is 49,266,259.66 USD and an IRR of 15.85% which is greater than the discount. In addition, the payback period is relatively fast, which is for 3 years. The system is also feasible in terms of HSE (health, safety, and environment) analysis by paying attention to various factors to avoid accidents. The system also has a positive impact on the social of the community. The implementation of smart green concrete can be a milestone for the transformation of Indonesia's construction industry towards a greener and more sustainable future.

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