УДК 691

КОНСТРУКТИВНЫЕ СВОЙСТВА УСТОЙЧИВЫХ МАТЕРИАЛОВ ДЛЯ СТРОИТЕЛЬСТВА В ЮГО-ВОСТОЧНОЙ АЗИИ

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Аннотация. Строительная отрасль в Юго-Восточной Азии стремительно растет, способствуя ухудшению состояния окружающей среды из-за высокого потребления энергии и выбросов CO_2. Цель этой статьи — изучить, как устойчивые материалы, такие как переработанная сталь, бамбук и экологически чистый бетон, могут играть свою роль в строительстве, и какие преимущества и недостатки это может иметь. Эти материалы частично изучались другими исследователями на предмет конструктивных свойств, экологических преимуществ и экономичности. Однако, несмотря на проблемы, включая более высокие первоначальные затраты и доступность материалов, это исследование привлечет внимание к тому факту, что устойчивые материалы могут сделать: это не только снижение воздействия строительного сектора на окружающую среду, но и повышение долгосрочной энергоэффективности. Эта статья сыграет значительную роль в использовании этих материалов в реальной практике. Продвижение устойчивых методов строительства может смягчить воздействие на окружающую среду, одновременно поддерживая городское развитие в Юго-Восточной Азии. Результаты этого исследования позволят получить представление об устойчивых материалах. Также статья привлечет больше внимания со стороны экспертов и исследователей для проведения дальнейших исследований по этой теме.

Ключевые слова: устойчивые материалы, Юго-Восточная Азия, переработанная сталь, бамбук, экологически чистый бетон, летучая зола, воздействие на окружающую среду

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CONSTRUCTIVE PROPERTIES OF SUSTAINABLE BUILDING MATERIALS IN CONSTRUCTION FOR SOUTHEAST ASIA

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Abstract. The construction industry in Southeast Asia is growing rapidly, contributing to environmental degradation due to high energy use and CO_2 emissions. The aim of this article, is to explore how sustainable materials like recycled steel, bamboo, and eco-friendly concrete could play their roles in the construction and what benefits and drawbacks would it appeared to be. These materials were studied partially by other researchers for the structural performances, environmental advantages, and economic. However, despite challenges, including higher initial costs and material availability, this study will draw the attention to the fact that sustainable materials can do: it is not just to reduce the environmental impact of the construction sector but also promote long term energy efficiency. This paper would play significant role for the usage of these materials in the real practice. Promoting sustainable building practices can mitigate the environmental impact while supporting urban development in Southeast Asia. The results of this research, will bring the insights over the sustainable materials, as well as, this paper would bring more attention from experts and researchers to conduct further research on this topic.

Keywords: sustainable materials, Southeast Asia, recycled steel, bamboo, eco-friendly concrete, fly ash, environmental impact

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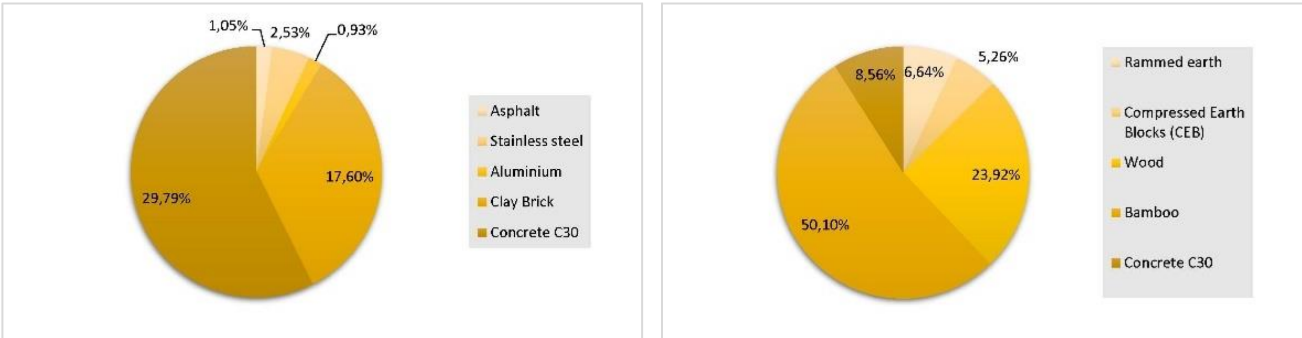
ВВЕДЕНИЕ

Southeast Asia, with its rapidly growing urban population and economic development, is experiencing a construction uprise, for instance, Singapore, Thailand, Vietnam, Cambodia, …etc. However, this growth comes at the cost of environmental degradation, as the construction industry is one of the largest sources of carbon emissions and resource consumption in the region. According to recent studies, the sector accounts for approximately 39% of the world's energy use and produces 25-40% of global carbon emissions [1]. The carbon footprints of sustainable materials (62.25 kg CO_2 eq per square meter) are substantially lower than those of traditional materials (171.93 kg CO_2 eq per square meter) [2]. Southeast Asia is a region which well known for their cultural building which were built by woods and bamboos, etc.

Рис. 1. Бамбуковый мост в Green School, Бали[1]
Fig. 1. A bamboo bridge at Green School, Bali

Рис. 2. Проект гостиницы в Сиануквиле, Камбоджа[2]
Fig. 2. A hotel project in Sihanoukville, Cambodia

Sustainable materials, such as bamboo, recycled steel, and eco-friendly concrete, are now being promoted as environmentally friendly alternatives which could provide the region's growing demand for infrastructure while reducing its carbon foot print [3, 4]. Consistent certification systems, integrated building operation management, ongoing technological advancements, and appropriate policy adjustments are all necessary criteria for sustainable construction [2]. The increasing demand for sustainable construction practices, driven both environmental and economic concerns, has led to a search for alternative building materials that reduce the carbon footprint, and enhance energy efficiency (Fig.3).



a) b)

Рис. 3. Вклад % кг CO_2-экв. на материал: а – традиционные материалы; б – устойчивые материалы [2]
Fig. 3. Contribution % of kg CO_2 eq. per material: a – traditional materials; b – sustainable materials

Bamboo, which is abundant in the region offers a sustainable solution due to its rapid growth and strength in tropical climates. Studies have shown that bamboo can replace traditional material in low- to mid-rise buildings, offering comparable strength while dramatically reducing environmental costs [5]. The development and application of green building materials has called for the promotion of sustainable construction in recent years, and bamboo is generally regarded as a characteristic form of green material [6]. The term "vegetal steel" refers to this alternative and renewable building material because of its great strength and low weight [7]. Bamboo

[1] The Jakarta Post [Электронный ресурс]. – URL: https://www.thejakartapost.com/travel/2018/07/22/seven-modern-buildings-to-visit-in-southeast-asia.html (дата обращения: 15.11.2024)
[2] VTN Architects [Электронный ресурс]. – URL: https://vtnarchitects.net/cambodia-hotel-pe261.html (дата обращения: 17.11.2024)

fibers develop along the culms' longitudinal axis, which makes sense that bamboo's axial strength is significantly greater in the fiber direction than it is in the lateral direction [8]. Another advantage of bamboo as a material is its ability to resist dynamic impacts, such as earthquakes, since it does no undergo destruction through brittle cracking, as in concrete [9-10]. With a high moisture content, bamboo's mechanical qualities: tension, compression, and shear, while its behavior at failure becomes more ductile [11]. It has socioeconomic advantages, as it is affordable and long-lasting [12]. Bamboo can be utilized in organically curved constructions and can prove to be a good substitute for current building materials [13]. The essential mechanical characteristics of bamboo are summarized and shown in (Table. 1) [14-19].

Таблица 1. Механические свойства бамбука [14-19]
Table 1. Ranged of mechanical properties of bamboo

№	Mechanical property	Range
1	Tensile strength (MPa)	70-210
2	Compressive strength (MPa)	20-65
3	Elastic modulus (MPa)	2500-17500

Short waste reinforcing bar (rebar) is produced when new reinforcing bar is cut and bent, during the construction of buildings and other infrastructure. 3-5% of the original rebar may be wasted as a result of such operations, and in certain cases, up to 10% [20]. Commercial structures typically utilize 0.119 tons of rebar per m^3 of concrete, whereas residential buildings typically use about 0.077 tons [21]. Steel production is energy-intensive, but recycling steel significantly reduces its environmental impact by minimizing the need for virgin raw materials and reducing energy consumption by up to 75% [22]. One notable approach that adheres to sustainable construction norms is the use of recycled steel fibers that are taken from used tires using techniques like shredding, pyrolysis, or cryogenics. By reusing waste materials, this creative access reduces environmental impact and conserves important resources, which is in line with the principles of sustainable construction. This strategy has a lot of promise; it is projected that the European Union alone could harvest half a billion tons of steel fibers from worn tires each year [23]. When used as reinforcement in hybrid designs that incorporate steel rebar and fibers, recycled steel fibers have shown promising results [24]. Waste rebar could be remanufactured into steel by-product for items like nails (Fig.4). By preventing rebar waste and reducing the need to manufacture new steel nails, these nails can be conducting in the building industry to support a circular economy, which will lower construction costs and environmental impacts [25-27]. Recycled steel provides the same structural properties as new steel while significantly reducing energy consumption [28].

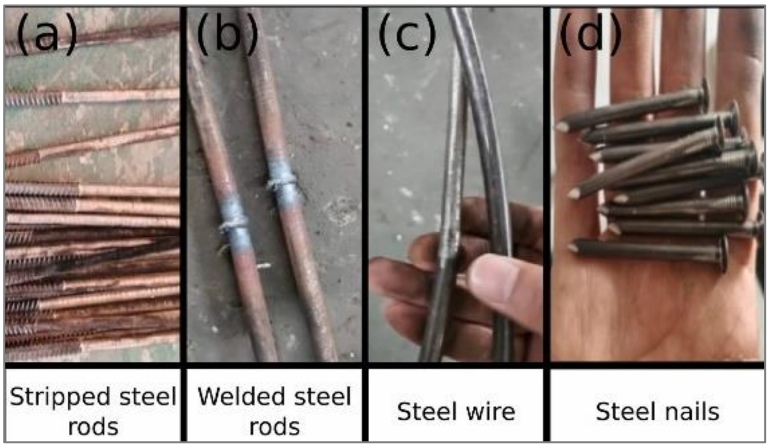


Рис. 4. Фотографии отходов арматуры после различных этапов процесса восстановления: а – зачищенные стальные стержни после зачистки ребер; б – сваренные стальные стержни после сварки встык; в – стальная проволока после уменьшения диаметра; г – конечный продукт в виде стального гвоздя [20]
Fig. 4. Photographs of the waste rebar after various steps in the remanufacturing process: a – stripped steel rods after stripping of the ribs; b – welded steel rods after butt welding; c – steel wire after diameter reduction; d – final steel nail product

One of the most widely used materials is concrete, which is consumed worldwide second only to water. It is seen as a crucial element in the modern construction sector. Due to its high energy requirements and emissions of greenhouse gases, primarily carbon dioxide (CO_2). Portland cement, which is a key ingredient in the manufacturing of concrete, presents a risk to the environment [29-32]. Regards to earlier studies, 4 GJ of energy are used and about 0.9 tons of CO_2 are released into the environment during the manufacturing of one ton of Portland cement [33-35]. Furthermore, the cement-making process releases a number of hazardous gases, including as SO_2, NOX, CO, and dust, which seriously pollutes the environment [36-37]. Joseph Davidovits developed geopolymer in the 1970s as a sustainable substitute for regular concrete made of Portland cement and emits roughly one-sixth of the CO_2 generated by traditional cement [38-40]. Materials rich in aluminosilicates, including fly ash, slag, metakaolin, and rice husk ash activated by an alkaline solution, are used to create geopolymer [29, 41]. Regards to [41], the specimen of fly ash compressive test is shown in (Fig.5). In addition to its advantageous mechanical qualities and other important characteristics, such as its superior resistance to chemical attack, thermal stability, and reduced greenhouse gas emissions, it is a sustainable substitute for conventional cement-based concrete. However, geopolymer concrete frequently has high brittleness and low ductility, which presents problems in structural applications where toughness and ductility are extremely important [42-44].

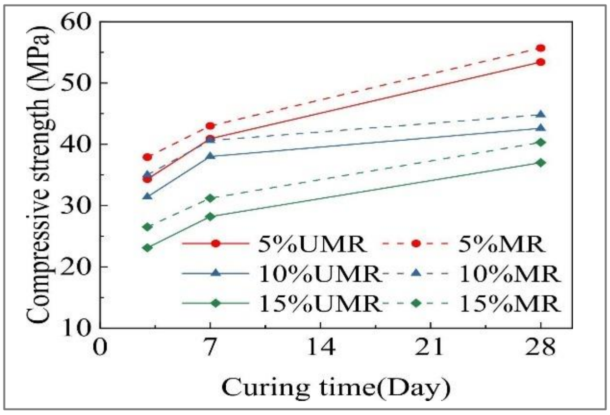


Рис. 5. Образец летучей золы (Span-40) с измененными результатами прочности на сжатие [41]
Fig. 5. The Specimen of fly ash (Span-40) modified compressive strength results

This article explores the use of sustainable materials such as bamboo, recycled steel and eco-friendly concrete in Southeast Asia, by examining the environmental and economic feasibility of these materials, as well as, the study will contribute to the growing body of research and support the transition to greener construction practices, focusing on their potential benefits and challenges within the regional context.

To accomplish the aim, the following tasks have been set:

– to adopt the benefit of its usage using Lifecyle Assessment (LCA)
– to analyze the cost benefit of using recycled steel, bamboo and fly ash concrete for Southeast Asia

THE STUDY MATERIALS

There are three sustainable building materials which are chosen for this study: bamboo, recycled steel and eco-friendly concrete (fly ash); which is playing a crucial material in the Asia regions like China, Indonesia, Cambodia, Vietnam, and Thailand. The bamboo used in the study, are chosen from the literature review and were harvested in Southeast Asia regions, while the recycled steels was sourced from the demolition projections across the region, however those steels, will be put under well treatment from the factory, as the result, the products will be returning with the strength and durability as new steels. Particularly, not just the quality of the recycled steels may as good as the new steels to 100%, even though, the tensile reduce up to 10-20% of its original capacity, but still, this material is the best for considering of its usage for the sustainability materials [45]. For the eco-friendly concrete was prepared using flying ash as a partial replacement for Portland cement. In this case, the flying ash concrete, is referred to the concrete that made from the fly ash cement which were produced from the recycling of the municipal waste [46]. Additionally, concrete produced using supplementary cementitious materials like fly ash, were produced especially considering of reducing the carbon footprint of traditional concrete [47-48].

METHODOLOGY

For methodology of this study, Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA), are used for analyzing and making assumption and consideration for the chosen materials. Life cycle assessment, will help this study for holding the insights of the environmental impacts throughout their entire lifecycle. The entire lifecycle of materials, means that it will be put under study from the start of its usage to demolition stage. Otherwise, cost-benefit analysis, is assisting to account on the cost of the sustainable materials, comparing to the traditional materials, which would possibly be replaced by the chosen materials for this study. Moreover, the cost in this research will be studied in the initial period and during its lifecycle period of usages.

The research methodology for this paper, is shown as illustrate in (Fig.6).

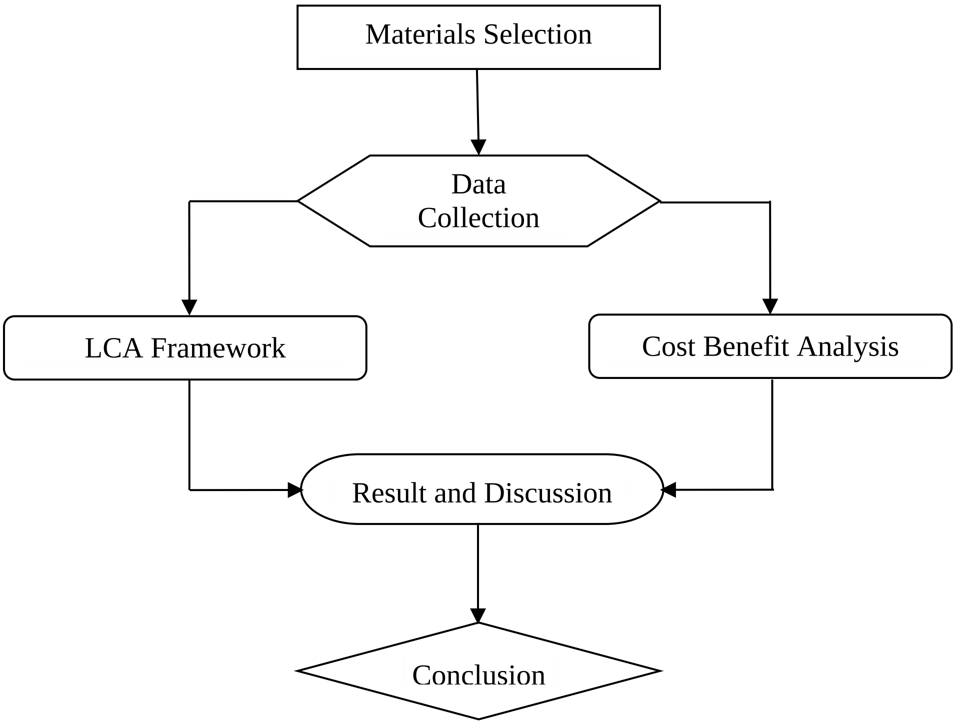


Рис. 6. Схема методики исследования
Fig. 6. Scheme of the research methodology

For the overall environmental impact of each material, is evaluated in accordance to the ISO 14040 standard for LCA, which are calculated using (1). In the particular, the main objective of this calculation is to evaluate the environmental performance of recycled steel, bamboo and eco-friendly concrete. The parameters used in Life Cycle Assessment (LCA) for each sustainable material present in (Table. 2).

$$I = \sum_{i=1}^{n} \left(E_i . CF_i \right), \quad (1)$$

where:
I - the total impact.
E_i - the energy input or emissions in the lifecycle phase *i*.
CF_i - the characterization factor (CO_2 equivalent per unit of energy or material).

Таблица 2. Входные параметры LCA для каждого материала [49-52]
Table 2. LCA input parameters for each material

№	Parameter	Recycled Steel	Bamboo	Eco-Friendly Concrete
1	Energy Consumption (MJ)	10.70	5.40	8.90
2	Carbon Emissions (kg CO2)	2.50	1.10	1.80
3	Water Usage (m^3)	1.20	0.80	0.90
4	Resource Depletion (kg)	0.02	0.03	0.05
5	Lifespan (years)	50	30	40

To analyze and evaluate the economic feasibility of these sustainable materials, a Cost-Benefit Analysis (CBA) is performed. The CBA compares the lifecycle costs of recycled steels, bamboo and eco-friendly concrete with traditional materials like new steels and Portland cement-based concrete. The cost structure includes; initial costs, maintenance costs, and end-of-life costs. The CBA also plays as a role for the factor in the potential for carbon credits, which can be sold based on the CO_2, savings achieved by using sustainable materials

The Cost-Benefit Analysis of each material is calculated by using the formula (2):

$$NPV = \sum_{t=0}^{n} \left(\frac{B_t - C_t}{(1-r)^t} \right), \quad (2)$$

where:

NPV- the net present value of using the material.

B_t - the benefit of energy saving and reduced CO_2 emissions in year t.

C_t - the cost of materials and maintenance in year t.

r - the discount rate.

t - the time period or building lifecycle.

RESULTS

The findings from this study demonstrate that the integration of sustainable building materials; recycled steel, bamboo and eco-friendly concrete; provides significant environmental, economic, and technical benefits when applied in the construction industry, particularly in Southeast Asia. The Life Cycle Assessment (LCA) results reveal that these materials offer substantial reductions in CO_2 emissions compared to their traditional counterparts. Recycled steel shows a 40% decrease in emissions compared to the new steels, while bamboo and eco-friendly concrete also demonstrate a remarkable reduction in carbon footprint. The result has shown that with bamboo, the carbon emission is almost neutral compares to another materials (Fig.7).

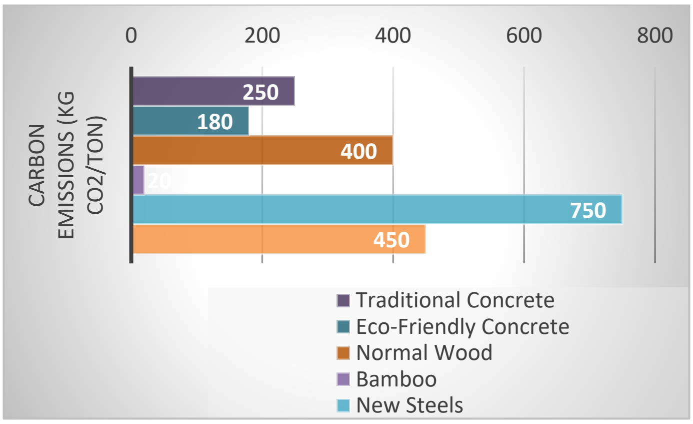
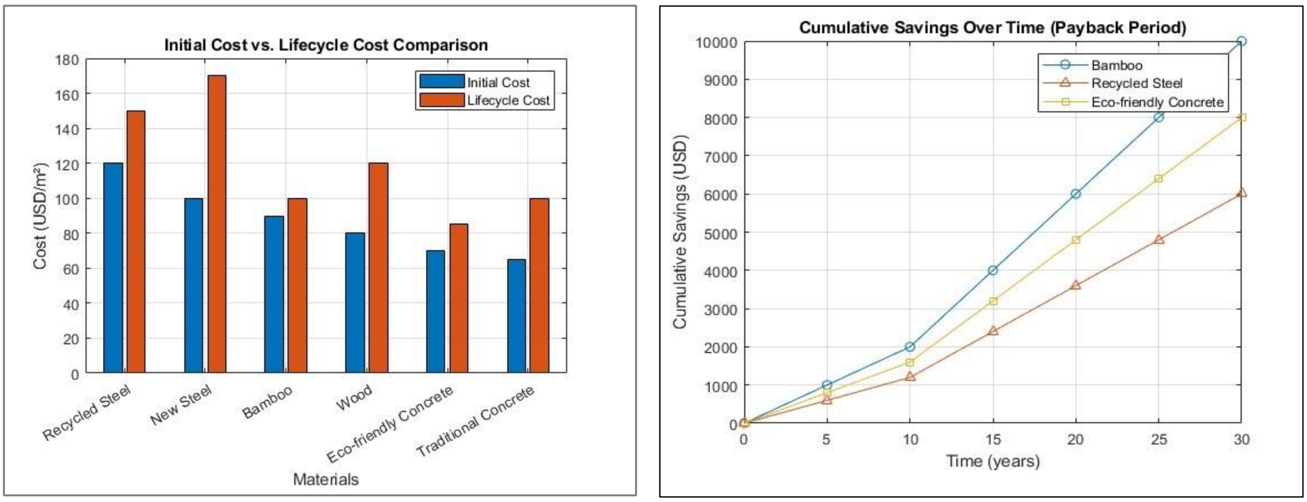


Рис. 7. Выбросы углерода для устойчивых и традиционных материалов
Fig. 7. Carbon Emissions for Sustainable & Traditional Materials

Within the result of the cost-benefit analysis, demonstrate that despite higher initial costs, the lifecycle cost of the sustainable materials chosen for this study, is noticeably lower. Recycled steel, bamboo, and eco-friendly concrete reduce lifecycle costs by 15-20%, 10-12% and 20% respectively, as a result of reduced energy consumption and lower maintenance needs. The sensitivity analysis further reinforces the long-term economic viability of these materials, even when accounting for variations in discount rates. Energy efficiency is a critical advantage of using bamboo and eco-friendly concrete, as both materials show substantial improvements in thermal performance, leading to significant reductions in energy consumption for climate control. Over 50 years building lifecycle, bamboo and eco-friendly concrete reduce energy use by 30% and 20%, respectively, compared to traditional materials. Furthermore, the material strength analysis demonstrates that recycled steel offers superior tensile strength, 20% higher than traditional steel, while eco-friendly concrete provides similar compressive strength to traditional concrete but with enhanced crack resistance. Bamboo's tensile strength is comparable to normal wood, making it a suitable alternative for certain structural applications.



a) b)

Рис. 8. Анализ затрат и выгод (CBA): а – начальная стоимость сравнивается со стоимостью жизненного цикла; б – накопленная экономия с течением времени

Fig. 8. The Cost-Benefit Analysis (CBA): a – Initial cost compares to Lifecycle Cost; b – Cumulative Saving Over Time

The results confirm that adopting sustainable building materials in construction projects can effectively address environmental concerns, improve energy efficiency, and reduce long-term costs without compromising structural performance. These findings strongly support the use of recycled steel, bamboo, and eco-friendly concrete as viable alternatives to traditional construction materials in Southeast Asia’s growing construction sector. As shown in (Fig.9), with the period of 50 years, recycled steel tends to work with a well performance with a 15% reduction in strength only, while bamboo shows a much decline in durability, with up to 60% in 20 years and possibly up 100% in 50 years period. This is largely due to susceptibility to moisture, pests and biodegradation. But for the short term use up to 10 years, bamboo is well known for its good tensile strength and affordable price, which is best for temporary structures. However, the eco-friendly concrete performs in an opposite way of the both materials above, which means that it can resist well to exposing in the environment, including moisture and chemical reaction, and would decrease its durability to 20% only.

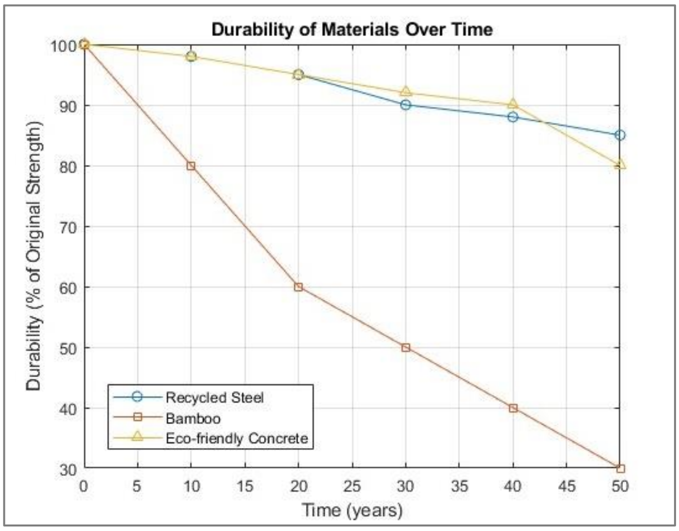


Рис. 9. Долговечность материалов с течением времени

Fig. 9. The Durability of Materials Over Time

DISCUSSION AND RECCOMENDATION

Recycled steel offers substantial environmental benefits by reducing energy consumption during production, and its widespread adoption can significantly lower the carbon footprint of construction in urban projects. Moreover, it maintains high structural integrity, making it suitable for both residential and commercial applications. Bamboo stands out as an ideal material for low-rise structures, especially in rural areas, due to its abundance and low carbon footprint. However, its use in urban settings and functions is limited due to durability concerns in humid climates and the need for advanced treatment processes. Fly ash concrete provides a sustainable alternative to conventional concrete, reducing the carbon footprint associated with cement production. Its increased durability and moisture resistance make it well-suited for tropical climates, as seen in Malaysia, Cambodia and Vietnam. However, its adoption faces challenges due to inconsistent availability of fly ash and regulatory hurdles in some Southeast Asia country, for instance, Cambodia and Thailand. The findings from the results also confirm that sustainable building materials can significantly reduce the environmental impact of the construction industry in Southeast Asia. The materials, which were chosen for this article play its role significantly to offer substantial CO_2 reductions, though the exact benefits vary depending on the material's source and application. Following the above results, the selected materials; recycled steel, bamboo, and econ-friendly concrete (fly ash concrete) reveals distinct trends in performance over time. Hence, the assumption is showed and arrange into a table for easy to understand and will be convenient for researchers and experts to put under consideration for their further studies over the topic about these materials to serve in the sustainability subject (Table. 3).

Таблица 3. Экономическая эффективность и долговечность устойчивых материалов
Table 3. Cost Efficiency and Durability of Sustainable Materials

№	Material	Early Cost	Long-term Cost Saving	Durability
1	Recycled Steel	Moderate	High	High
2	Bamboo	Low	Moderate	Requires treatment
3	Eco-Friendly Concrete (Fly Ash)	Moderate	High	High

CONCLUSION

1. Southeast Asia is the region that could start the further step of reducing the environmental footprint of the construction industry. According to the results obtained above, we could state that some materials: recycled steels, bamboo, and eco-friendly concrete could be used as sustainable materials to replace some traditional materials. These materials are not just reducing the carbon footprint, at the same time offer numerous environment and economic benefits as well, including enhanced energy efficiency and long-term savings.
2. Challenges such as higher initial costs, material availability, and the region's climate must be addressed. Government, industries and researchers must collaborate for the further studies and to promote the development of infrastructure and policies that facilitate the adoption of sustainable materials, ensuring that Southeast Asia's construction industry contributes to a more sustainable future. Recycled steel, bamboo, and fly ash concretes are promising alternatives to traditional materials, offering significant environmental and cost benefits.
3. Bamboo is well-suited for rural, low-structure due to its negative carbon footprint and availability, while recycled steel is ideal for urban projects, reducing energy consumption and waste. Fly ash concrete offers improved durability and reduced emissions, particularly in tropical climates. Overall, sustainable building materials can play a vital role in reducing the environmental impact of construction while supporting the region's growth.

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