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Interlocking Earthen Masonry Units for Sustainable Residential Building Construction

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Abstract: In addressing the goal for sustainability in the construction industry, the very materials used for construction and the methods utilized to implement said materials must be analyzed. Specifically, some traditional residential construction materials consist of wood, steel, and concrete. Because these materials vary in their levels of sustainability, there is a need to develop and explore new or other materials that can be used for residential construction. The primary purpose of this paper is to provide a review of interlocking earthen masonry units (IEMU) as an alternative option for residential building construction. This is in an effort to explore the variables impacting their existing and potential applications as sustainable materials and a method for residential building construction. IEMU's are then examined under the triple bottom line (TBL) sustainability framework which includes analyzing the environmental, economic, and social sustainability of IEMU's. The findings of this review may lead to further progression in the development of a framework for evaluating U.S. stakeholder adoption of IEMU's and potential implementation in U.S. residential construction.

Keywords: Earthen masonry, interlocking, residential building, sustainable construction, sustainable materials.

1. INTRODUCTION

Due to the COVID-19 pandemic, the skilled labor shortage in the United States construction industry has proven to be an issue. Among the construction firms surveyed by the Associated General Contractors of America (AGC), 61% said their projects are experiencing delays due to workforce shortages [1]. In addition, the overall construction material prices have increased by 19.4% in the past three years [2]. The effects of building construction on carbon emissions may also prove to be consequential. In 2019, the construction and building industry accounted for 29% of energy-related greenhouse gas emissions in the U.S. of which residential construction was responsible for about 17% [3]. Because of the general rise of greenhouse gas emissions, the effects of global warming, have been exacerbated [4] indicating the need to highlight the embodied environmental impact of construction materials to properly combat the negative effects.

Due to labor deficiencies, increased cost, and the effects of climate change, non-traditional construction methods and materials may be worthy of examination. In residential construction, the traditional construction materials used are wood, steel, and concrete. Within the scope of masonry construction, another option exists in the form of interlocking earthen masonry units (IEMU) which present potential benefits regarding the aforementioned issues in construction.

Interlocking earthen masonry units (IEMU's) are cement stabilized soil blocks that allow for dry stacked construction. Typically, each brick is constructively designed to "lock" itself to another brick of the same design with little to no mortar involved. The interlocking mechanism is achieved using a shear-key and lock configuration. The shape of the shear key will vary based on the design and another lock is typically provided on the other side of the brick. Load transfer is achieved by shear transfer and gravity. In summary, IEMU's rely on the interlocking mechanism to provide resistance to applied loads without surface bonding cement [5].

Despite potential for labor efficiency and a reduced amount of pollution during the fabrication process, there has been an evident lack of stakeholder adoption of IEMU's into U.S. construction methods [6, 7] In spite of the reported increasing use of IEMU's worldwide for residential construction (specifically in rural areas), the U.S has primarily remained steadfast in its use of timber [8, 9]. Despite some of the associated challenges/impacts with timber construction such as deforestation and the rising cost of wood, alternatives have failed to take hold in common residential construction practices across America [10, 11]. Although the idea of IEMU's and similar technologies have been around for centuries, modern research in this field is still relatively new [12]. A potential obstacle is the lack of regulation associated with IEMU's. Outside the states of New Mexico and California, earth material construction is not prominent in building codes across the U.S. [13]. This article seeks to review IEMU's within the industry of residential construction. In particular, IEMU's will be analyzed in their application as a sustainable construction material and a sustainable construction method. This article will also use the triple bottom line (TBL) sustainability framework as a benchmark for further analysis. This is done in order to properly measure its viability as a sustainable alternative in residential construction.

2. RESEARCH METHOD

An exploratory research design was implemented to identify and examine relevant concepts about interlocking earthen masonry units (IEMU's) and their viability for sustainable residential construction. The methods adopted in achieving the objectives of this research are divided into two parts, as illustrated in Figure 1. The first part involved a contextual review of IEMU's and their aptitude regarding the goal of sustainability. This was divided into two separate categories. The first category involved evaluating IEMU's as sustainable construction materials. The second category involved evaluating IEMU's for sustainable construction. Google Scholar was probed to search for articles on studies related to earthen building materials and methods, interlocking masonry, residential construction, and sustainable construction and materials. Over 70 articles were reviewed out of which 43 were selected and included in the review analysis.

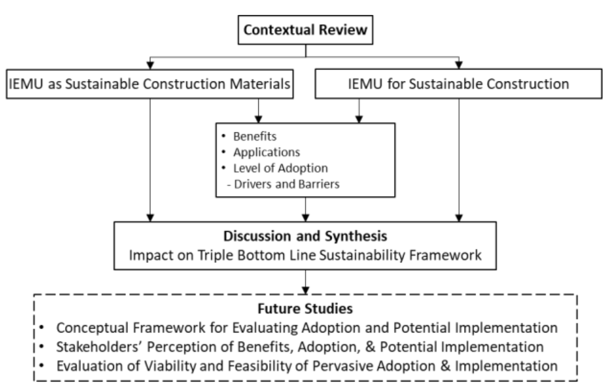

Figure 1. Research Process Overview

Once the various articles were selected and annotated, a review was conducted after which IEMU's were then contextualized and examined under the TBL sustainability framework. This framework addresses sustainability under 3 different factors: environmental, economic, and social. The review culminated in a proposal for future studies to fill the gap in knowledge geared toward developing a conceptual framework for implementation, surveying stakeholders' perceptions, and evaluating the feasibility of implementing IEMU's in U.S. for residential building construction.

3. APPLICATIONS AND BENEFITS OF IEMU'S FOR SUSTAINABLE CONSTRUCTION

Interlocking earthen masonry units (IEMU's) offer a variety of benefits regarding sustainable residential building construction. These benefits can be examined in two broad categories: IEMU's as sustainable construction materials and sustainable construction. Sustainable construction materials can be defined as materials used throughout our consumer and industrial economy that can be produced in required volumes without depleting non-renewable resources and without disrupting the established steady-state equilibrium of the environment and key natural resource systems. Sustainable construction can be defined as construction methods that facilitate economic sustainability regarding cost-effectiveness, efficient project delivery, quality assurance, material performance, and availability. Both categories seek to review the viability of IEMU's as a sustainable alternative for residential construction.

3.1. IEMU's as Sustainable Construction Materials

Two factors were examined regarding IEMU's as sustainable construction materials. The first factor is the availability of the material. For a material to be considered readily available in terms of sustainability, the material must have the ability to be produced in required volumes to meet economic demand without depleting or minimizing the depletion of any non-renewable resources. The second factor is the ability for the material to be fabricated without disrupting the established steady-state equilibrium of the natural environment and key resource systems. The construction sector can be categorized as one of the largest global materials consumers, and the building sector has the most significant single energy use worldwide [14]. In another study, the United Nations Environmental Program claimed that buildings worldwide are responsible for 40% of global greenhouse gas (such as carbon dioxide, methane, nitrous oxide, and others) emissions and suggests that buildings offer enormous abatement opportunities for reducing greenhouse gas emissions in the short-term [15].

In analyzing IEMU's various advantages regarding sustainability, the reduction of cement is notable. Contrary to other forms of masonry, IEMU's do not require the same amount of cement in their application. In a review conducted by Asman et al., the interlocking brick is inherently distinct from conventional bricks because the interlocking mechanism allows for less mortar during bricklaying work [16]. The cement industry is one of the primary industrial emitters of greenhouse gases due to carbon dioxide emissions as the production of cement is an extremely energy-intensive process [17]. Worrell et al. [18], for each ton of cement produced due to the burning of fossil fuels, approximately 1 ton of carbon dioxide is released into the atmosphere as a result.

Making and processing today's building materials accounts for approximately 15% of global climate change impacts, 20% of global energy demand, and up to 40% of global solid waste [19]. According to the United Nations Environmental Program, the continuous reliance on conventional building materials at a global level is nearly unsustainable [15]. IEMU's serve to provide an alternative to conventional building materials. In an environmental Life Cycle Assessment of earthen building materials conducted by Ben-Alon et al., it was quantified that the embodied energy demand is reduced by 62-71% by shifting from wood, steel, or concrete to earthen assemblies. In addition, the embodied global climate change impacts are reduced by 85-91%, the embodied air acidification is reduced by 79-95%, and the embodied particulate pollution is virtually eliminated [20]. IEMU's primary ingredient is earth materials (specifically soil). According to Adam et al., soil is widely available in most regions. In some locations, it is the only local material available [21]. Being that soil is available in most regions worldwide, the materials needed for the fabrication of IEMU's are typically readily available.

IEMU's can also be advantageous due to their thermal mass properties. Due to their high thermal inertia, earthen materials can be specifically advantageous in desert climates that include warm days and cool nights. These advantages can transfer over to colder climates by placing a mass wall within an insulated envelope; the wall can store and retain passive (solar) or active indoor heat within the building interior, and then release this heat slowly over some time (for instance, over a cold night) [22]. In conjunction with the aforementioned thermal mass properties, earthen building materials experience exhibit good hygrothermal properties due to their porosity. Recent research has indicated that various earthen building materials have displayed the ability to regulate both indoor temperatures and indoor humidity to achieve optimal levels regarding occupant health. [23].

However, earth materials have significant disadvantages. In a study conducted by Adam et. al on IEMU-related technology in Sudan, several challenges were identified in instituting earth materials as a building material [21]. Reduced durability was evident among earth materials when not regularly maintained and properly protected, particularly in areas affected by medium to high rainfall and/or extreme weather. In particular, moisture-related deterioration in compressed earth blocks is due to seasonal or continuous alternate wetting (rainfall) and drying which leads to the block retaining sufficiently high amounts of moisture which leads to destructive effects. The softening and abrasive action of moisture lead to erosion of exposed surfaces [6, 24]. Another disadvantage lies in the low tensile strength of earth materials. Given its low tensile strength, a wall composed of earthen material must be thick otherwise it could not remain standing but would rather lean, bend and collapse. Earth materials also tend to have a poor load-bearing capacity making them unsuitable for supporting roofs on large-span buildings [25]. Despite the observed potential in earthen materials' thermal and hygrothermal properties, the quality of both characteristics is highly varied among different soil types used to fabricate IEMU's. Because of this, traditional construction materials such as concrete and wood experience more consistent results regarding their thermal and hygrothermal performance [20].

3.2. IEMU's for Sustainable Construction

IEMU's have also shown that they can be utilized for sustainable (method of) construction. Due to their production using mostly earth materials, IEMU's can make residential construction sustainable mainly due to their potential for onsite soil/material extraction and self-sufficient production processes [26, 27]. However, ascertaining cost variability, ensuring quality assurance, and meeting structural requirements for the use of IEMU's as building materials can be difficult. The cost of producing IEMU's will vary from country to country and even region to region. The reasons for variation in cost could include the availability of soil (whether it is on-site or requires transportation to the site) and the suitability of the soil used in fabrication for stabilization. This includes ascertaining the type, quality, and quantity of stabilizer needed. The current prices of materials (including stabilizers) must also be considered. Another factor includes whether the blocks are to be made in rural or urban areas. This could determine the type of equipment used and the quality of building materials [23].

IEMU's do not require any major amount of worker training for their application in the construction process. As recently as October of 2021, the construction industry added 44,000 jobs [28]. Given the current and projected economic growth, there is a need for both qualified workers and new entrants to meet this demand [29, 30]. In particular, the need for skilled labor has been an evident issue. Coupled with the rise in demand, the U.S. construction industry has recently faced significant challenges in finding craft workers [31]. According to the Association of General Contractors of America (AGC), 80% of general contractors have reported problems hiring enough skilled craft workers to match the level of demand [29]. Until the skilled labor shortage is solved, the construction industry must adapt in order to make up for the deficiency. IEMU's have the potential to expedite the process, particularly in residential construction. Due to their interlocking nature, IEMU's are simple to install in contrast to conventional column and beam construction. To install, you must dry-stack the bricks, pour inexpensive mortar, and add steel vertically to reinforce the walls [32]. Because of the simplicity of the design and construction process of IEMU's, the time dedicated to training workers is potentially lessened. Due to the time of completion being theoretically decreased, the cost of labor would also decline. In practice, the cost of labor when IEMU's are applied can be lowered by as much as 80% [33].

4. DISCUSSION

The triple bottom line (TBL) is a sustainability-related framework that was coined by Elkington [34] using the terms profit, people, and the planet as the three lines. The TBL framework as it pertains to the sustainability of IEMU's can be contextualized into three classifications: environmental (planet), social (people), and economic (profit), as illustrated in Figure 2.

In examining the environmental sustainability dimension (planet) of IEMU's, two factors were analyzed: the availability of the material regarding eco-friendly extraction and the ability to create IEMU's without disrupting the established steady-state equilibrium of the natural environment and key resource systems. IEMU's are fabricated through the use of earth materials. Since earth materials are compromised of mostly soil [21], the main ingredient is widely available and requires minimal processing to fabricate. IEMU's can serve as a potential catalyst for lowering global carbon dioxide emissions. IEMU's do not require the same amount of cement as traditional concrete masonry and because the cement industry is one of the primary industrial emitters of greenhouse gases due to carbon dioxide emissions, IEMU's can assist in minimizing the greenhouse effect [35, 17]. IEMU's also utilize earth materials which serve as an excellent environmentally friendly alternative to traditional masonry. In a study done on IEMU equivalents, it was concluded that they consume less energy with reduced carbon emission at the production stage [36].

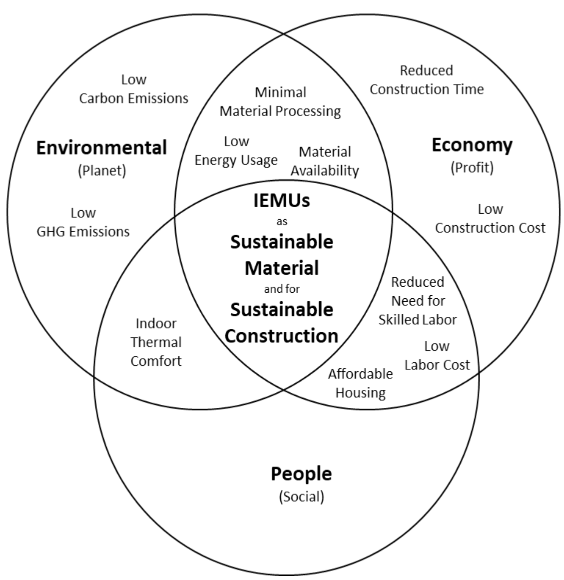

Figure 2. Triple Bottom Line (TBL) Sustainability Framework for IEMUs

The second category concerning the triple bottom line sustainability framework is the economic (profit) dimension. In examining the economic sustainability of IEMU's, two factors were analyzed: the cost of locally available materials and labor efficiency. Earth materials such as soil are typically cheap, abundant, and simple to form into building materials [37, 21]. Because of this, the process for soil/material extraction and material fabrication becomes more financially accessible and efficient [26, 27]. IEMU's also have the ability to simplify the construction process and lower the cost of construction. Due to the simplicity of their interlocking design, installation is made easier. The process of the installation consists of dry-stacking the bricks, pouring mortar, and adding steel vertically to reinforce the walls [32]. Since the construction process is relatively simple, this theoretically relaxes the need for skilled labor, lowers the construction cost, and shortens construction time. [38, 39].

The third category concerning the triple bottom line sustainability framework is the social (people) dimension. In examining the social sustainability of IEMU's, affordable housing constructed from earth materials was analyzed. The number of homeless people worldwide is estimated to be over 100 million [40]. In conjunction, the rapid urbanization of developing nations such as Zambia and Zimbabwe has caused a need for affordable housing [25, 41]. In Zambia, housing construction using conventional materials (brick, concrete) is too expensive for the majority of urban areas [25]. Agarwal and Doat et al. stated that the appropriate use of earth construction produces cost-effective and comfortable buildings [42, 43]. In a study conducted by Hadjri et al., 10 residents living in Zambian rural earth-constructed houses were interviewed. They were asked to give their opinion on five key issues: durability, affordability, living conditions, aesthetics, and their general preference with regard to living in an earth dwelling rather than a 'modern' house. All interviewees agreed that earth dwellings were very affordable in comparison with houses built with conventional materials (brick, concrete) [25].

IEMU's present a potential breadth of noteworthy benefits such as eco-friendliness, material efficiency, cost efficiency, labor efficiency, and affordable housing application. Certain drawbacks such as cost variability, quality assurance, and structural integrity are also remarkable. Most studies regarding the viability of IEMU's have been conducted to determine their structural capabilities, sustainability, and application toward varying construction practices. However, stakeholder acceptance of IEMU's in America has not been formally evaluated as it has been in other nations. Future studies should investigate American stakeholders' perception of the benefits, adoption, and potential implementation of IEMU's. In order to conceptualize this, the technology-organization-environment (TOE) framework may be considered. The TOE framework is an organization-level theory that explains that three different elements of a firm's context influence adoption decisions. These three elements are the technological context, the organizational context, and the environmental context [44]. This framework could be valuable in delivering a comprehensive study on U.S. stakeholder perception of IEMU's.

5. CONCLUSION

In this paper, interlocking earthen masonry units (IEMU's) were reviewed regarding their sustainability in the realm of residential construction. Both advantages and disadvantages were documented and contextualized. In conjunction, this review also serves as a proposal for future research regarding the U.S. stakeholder perception of IEMU's. Due to a lack of formal research, the reason for low U.S. stakeholder adoption of IEMU's is uncertain. Upon contextualization within the TOE framework, the various reasons for this could potentially become clear. The findings for this could lead to an evaluation of viability and feasibility regarding the pervasive adoption and implementation of IEMU's in American residential construction practice.

REFERENCES

[1] AGC (Associated General Contractors of America). (2021). “Construction Workforce Shortages Reach Pre-pandemic Levels Even as Coronavirus Continues to Impact Projects & Disrupt Supply Chains.” https://www.agc.org/news/2021/09/02/construction-workforce-shortages-reach-pre-pandemic-levels-even-coronavirus
[2] NAHB (National Association of Home Builders). (2021). *Building Material Prices Climbing at Record Year-to-Date Pace*. https://nahbnow.com/2021/08/building-material-prices-climbing-at-record-year-to-date-pace/
[3] Leung, J. (2018). Decarbonizing US buildings. *Center for Climate and Energy Solutions*.
[4] Denchak, M. (2019). *Greenhouse Effect 101*. NRDC. https://www.nrdc.org/stories/greenhouse-effect-101
[5] NCMA (National Concrete Masonry Association). (2019). *Design and construction of dry-stack masonry walls.* https://ncma.org/resource/design-and-construction-of-dry-stack-masonry-walls/
[6] Irwan, J. M., Zamer, M. M., & Othman, N. (2016). A review on Interlocking Compressed Earth blocks (ICEB) with addition of bacteria. *MATEC Web of Conferences* (Vol. 47, p. 01017).
[7] Galindez, F. (2009). Compressed earth blocks (CEB) with no added cement. In *Seguridad y Medio Ambiente* (Year 29 Nº 115 third quarter 2009).
[8] Jacquin, P. A., Augarde, C. E., & Legrand, L. (2008). Unsaturated characteristics of rammed earth. In *First European conference on unsaturated soils, Durham, England* (pp. 417-422).
[9] Marcin, T. C. (1987). *The outlook for the use of wood products in new housing in the 21st century*. Forest Products Laboratory.
[10] Spence, R., & Mulligan, H. (1995). Sustainable development and the construction industry. *Habitat international*, 19(3), 279-292.
[11] Taylor, H. (2014). Cost of constructing a home. *HousingEconomics.com*.
[12] Deboucha, S., & Hashim, R. (2011). A review on bricks and stabilized compressed earth blocks. *Scientific Research and Essays*, 6(3), 499-506.
[13] Holliday, L., Ramseyer, C., Reyes, M., & Butko, D. (2016). Building with compressed earth block within the building code. *Journal of Architectural Engineering*, *22*(3), 04016007.
[14] Wasim, J., & Nine, A. H. J. (2016). Climate Change and Low Carbon Emission Green Building. *Military Institute of Science and Technology (MIST)*.
[15] Buildings, U. N. E. P., & Change, C. (2009). United Nations Environment Programme Sustainable Buildings & Climate Initiative: Paris.
[16] Asman, N. S. A., Bolong, N., Mirasa, A. K., Saad, I., Asrah, H., & Lim, C. H. (2018). Life Cycle Assessment of Interlocking Bricks System Construction-A Review. In *Joint Seminar on Science, Engineering and Technology* (pp. 2-4).
[17] Mehta, P. K. (2002). Greening of the concrete industry for sustainable development. *Concrete international*, *24*(7), 23-28.
[18] Worrell, E., Price, L., Martin, N., Hendriks, C., & Meida, L. O. (2001). Carbon dioxide emissions from the global cement industry. *Annual review of energy and the environment*, *26*(1), 303-329.
[19] King, B. (2017). *The new carbon architecture: building to cool the climate*. New Society Publishers.
[20] Ben-Alon, L., Loftness, V., Harries, K. A., Hameen, E. C., & Bridges, M. (2020). Integrating earthen building materials and methods into mainstream construction. *Journal of Green Building*, *15*(1), 87-106.
[21] Adam, E. A., & Agib, A. R. A. (2001). Compressed stabilised earth block manufacture in Sudan. *France, Paris: Printed by Graphoprint for UNESCO*.
[22] Racusin, J. D., & McArleton, A. (2012). *The natural building companion: a comprehensive guide to integrative design and construction*. Chelsea Green Publishing.
[23] Allinson, D., & Hall, M. (2010). Hygrothermal analysis of a stabilised rammed earth test building in the UK. *Energy and Buildings*, *42*(6), 845-852.

[24] Gooding, D. E., & Thomas, T. H. (1995). The potential of cement-stabilised building blocks as an urban building material in developing countries. *Overseas Development Administration, United Kingdom*.
[25] Hadjri, K., Osmani, M., Baiche, B., & Chifunda, C. (2007, September). Attitudes towards earth building for Zambian housing provision. In *Proceedings of the Institution of Civil Engineers-Engineering Sustainability* (Vol. 160, No. 3, pp. 141-149). Thomas Telford Ltd.
[26] Hardin, M. C., Merry, S., & Fritz, W. (2003). Towards an affordable rammed-earth dwelling. In *Proceedings, 2003 PLEA (Passive and Low Energy Architecture) Conference*.
[27] Schroder, L., & Ogletree, V. (2010). *Adobe homes for all climates: simple, affordable, and earthquake-resistant natural building techniques*. Chelsea Green Publishing.
[28] *Nonresidential construction employment rises in October, says ABC*. ABC National. (2021, November 5). Retrieved February 15, 2022, from https://www.abc.org/News-Media/News-Releases/entryid/19092/nonresidential-construction-employment-rises-in-october-says-abc
[29] AGC (Associated General Contractors of America). (2018). "Eighty percent of contractors report difficulty finding qualified craft workers to hire as association calls for measures to rebuild workforce." Accessed November 10, 2021. https://www.agc.org/news/2018/08/29/eighty-percent-contractors-report-difficulty-finding-qualified-craft-workers-hire
[30] Levanon, G., Cheng, B., & Paterra, M. (2014). The risk of future labor shortages in different occupations and industries in the United States. *Business Economics*, 49(4), 227-243.
[31] Olsen, D., Tatum, M., & Defnall, C. (2012). How industrial contractors are handling skilled labor shortages in the United States. In *48th ASC Annual International Conference Proceedings*.
[32] Saari, S., Bakar, B. A., & Surip, N. A. (2017). Strength properties of interlocking compressed earth brick units. In *AIP Conference Proceedings* (Vol. 1892, No. 1, p. 020017).
[33] Anand, K. B., & Ramamurthy, K. (2005). Development and evaluation of hollow concrete interlocking block masonry system. *The Masonry Society Journal*, *23*(1), 11-19.
[34] Elkington, J. (1997). Cannibals with forks – Triple bottom line of 21st century business. Stoney Creek, CT: New Society Publishers.
[35] Walker, P., & Stace, T. (1997). Properties of some cement stabilised compressed earth blocks and mortars. *Materials and structures*, 30 (9), 545-551.
[36] Rahman, M., Rashiduzzaman, M., Akhand, F. Z., & Kabir, K. B. (2016). Compressed Stabilized Earth Block: A Green Alternative for Non-load Bearing Building Block in Developing Countries like Bangladesh. *American Chemical Science Journal*, 12(3), 1-10.
[37] Morris, J., Booysen, Q., & Kofahl, J. (2000). Earth construction in Africa. *Proceedings: strategies for a sustainable Built Environment, Pretoria*, 23-25.
[38] Mohammed, B. S., & Aswin, M. (2016). Properties and structural behavior of sawdust interlocking bricks. In *Proceedings of the 3rd International Conference on Civil, Offshore and Environmental Engineering* (pp. 437-442).
[39] Shi, T., Zhang, X., Hao, H., & Chen, C. (2021). Experimental and numerical investigation on the compressive properties of interlocking blocks. *Engineering Structures*, *228*, 111561.
[40] Hadjri, K. (2005). Experimenting with hybrid construction—guadua bamboo and adobe for housing in rural Colombia. *International Journal for Housing Science and Its Applications*, *29*(2), 165-177.
[41] Zami, M. S., & Lee, A. (2007, March). Earth as an alternative building material for sustainable low cost housing in Zimbabwe. In *7 th International Postgraduate Research Conference*.
[42] Agarwal, A. (1981). Mud, mud. The potential of earth-based materials for Third World Housing.
[43] Doat, P., Hays, A., Houben, H., Matuk, S., & Vitoux, F. (1991). Building with earth. *The Mud Village Society, New Delhi*, 4-11.
[44] Baker, J. (2012). The technology–organization–environment framework. *Information systems theory*, 231-245.