

Sustainable Construction Practices in Taif City: The Role of Building Materials

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Keywords: Construction Sustainability, Sustainable Building Materials, Resource Efficiency, Green Buildings, Environmental Sustainability, Building Materials Lifecycle, Green Construction, Thermal Performance, Environmental Performance of Buildings

Abstract. Sustainable construction has gradually become the basis of environmental-economic improvement in the built environment. Building materials play a pivotal role in realizing sustainable development, which is addressed in this study, based on the construction industry of Taif City, Saudi Arabia, in terms of thermal regulation, energy consumption, and ecological footprint. Using a descriptive–analytical approach, this article incorporates a comprehensive review of local urban planning regulations in combination with an examination of construction operations. It evaluates alignments of the conventional and contemporary materials with the sustainability standards and investigates the possibility of adopting green concrete, thermally insulated bricks, as well as available resources on the ground. The authors conclude that sustainable material selection can greatly improve the quality of urban environments, occupant comfort, and low life cycle operational costs. The research concludes with a proposal for a regulatory and incentive-based framework in order to make it easier to use sustainable building materials and for innovation and research specific to Taif region’s climatic and topographical conditions.

1. Introduction

Sustainability has been a topic of particular interest throughout the evolution of this technology, as it significantly influences the environment such as energy use, resource consumption and greenhouse gas emissions [1, 2]. International practices from sustainable design and construction seek to lower the external impact to the environment and to improve the social and economic functioning of construction assets [3]. The new paradigm that is emerging in the form of this paper focuses on the incorporation of environmentally responsive design principles, advanced materials, and innovative technologies with the goal of reducing the energy consumption, reducing resource use, and enhancing the well-being of the user throughout the building's full cycle of operational life [2,4].

A. Choosing Building Materials for Sustainability

Construction material selection is of paramount importance for implementing sustainable projects in the construction industry. One feature of these materials is the influence on thermal performance, embodied energy, and lifecycle costs as a result of these materials [5]. Materials sustainable for use, locally sourced, recyclable, low embodied carbon minimize environmental degradation and impact through activities such as construction. Life Cycle Assessment (LCA) methodologies also empower architects and engineers to systematically assess alternatives to materials and make decisions that maximize environmental functionality, economic viability, and functional lifespan of the building over the building lifespan [6].



B. Taif City Specialiy: Climate and Urban Character:

Taif city has a moderate highland climate with a high altitude of about 1,800 m. Taif has relatively softer summers and cold winters than most of the cities of Saudi Arabia [7,8]. They are climatically and topographically unique, providing architectural challenges and opportunities, specifically in thermal comfort, and building material properties. The traditional architecture of Taif reflects the deep-rooted adaptation to the local environment that we have experienced, with stone sourced local to the region, the building's passive ventilation systems, and courtyards planted in shade [9]. Accordingly, by using sustainable materials and building techniques tuned specifically for Taif's specific climate, the energy efficiency of modern construction can be improved and thus the environmental blow reduced considerably [1, 10].

C. Research Problem and Research Questions:

Current construction practices in Taif still disproportionately depend on conventional building materials that may not meet long-term sustainability standards, even though the city adopts a unique environmental context. This concern raises the following central research question:

How do sustainable building materials contribute to the sustainability of the construction system in Taif City?

The following questions arise on the basis of this fundamental question:

- What are the predominant building materials used in current construction projects in Taif, and how well do they align with environmental and climatic suitability?
- What selection criteria are employed for building materials, and to what extent do they account for lifecycle performance and environmental impact?
- What are the comparative environmental and economic advantages of adopting sustainable materials over conventional alternatives?

D. Research Objectives

Main Objective:

To assess the contribution of sustainable building materials to the enhancement of efficiency and sustainability within Taif City's construction sector.

Sub-Objectives:

- To evaluate the environmental and thermal performance of conventional building materials currently utilized in Taif's construction projects.
- To identify sustainable material alternatives that are compatible with Taif's local climatic conditions.
- To conduct a comparative analysis of the environmental and economic impacts of traditional versus sustainable materials.
- To develop a strategic framework or guideline for the integration of environmentally responsible building materials in Taif's construction practices.

E. Research Hypotheses. The main ideas that inform this study are:

- Energy Efficiency and Resource Optimization – Sustainable building materials promote significant improvements in energy efficiency and saving resources utilized in the construction project of Taif City.
- Correlation of the choice of sustainable materials with environmental performance in the building is statistically significant under the harsh climate of Taif, because the choice of sustainable material is significant.
- Costs to implement: The relatively high initial costs of sustainable materials pose a barrier to widespread practice of sustainable materials in building process.

- Knowledge and awareness Lack of awareness and technical knowledge of key stakeholders (engineers, contractors or developers) would negatively affect the sustainable building products' adoption rates in Taif.
- Regulatory impact: By implementing government policies and incorporating sustainability requirements in Saudi Building Code, the role of both regulatory and legislative powers can ensure that environmentally sustainable building materials are utilised more widely in the context of local construction.
- Supply Chain Optimization: Strengthening the local supply chain of sustainable materials could lead to a significant reduction in the cost of procurement and thus increase the economic viability of sustainable construction projects in Taif.

F. Research Methodology.

The study uses a Descriptive–Analytical Approach supplemented by the environmental and economic indicators to evaluate the sustainability of building materials. The methodology focuses on the below key stages:

Data Collection.

- Secondary Data
- Data were retrieved from: Existing literature, Saudi building codes and standards, environmental impact reports, and green building guidelines.
- Primary Data: Gathered through in-situ observations and structured interview or questionnaires addressing:
 - Practicing engineers and builders in Taif City.
 - Deputies of the local government bodies to include the Municipality in the discussion and Ministry of Municipal and Rural Affairs and Housing (where applicable).

Analysis of Existing Building Material Utilization.

- Analyze the dominant materials currently used in Taif's activities, namely but not limited to concrete, bricks, insulation systems, paints and finishing items.
- Analysis of these materials using important sustainability criteria:
 - Energy consumption.
 - Carbon emissions.
 - Life of service and maintenance criteria.

Selection of Climate-Responsive Sustainable Alternatives.

- Selection by thermal climate analysis literature that is specific to Taif.
 - Comparison study of conventional and sustainable materials by:
 - Life Cycle Assessment (LCA)
 - Benchmark environmental and economic performance.

Development of a Sustainability Guideline

Formulation of a strategic guideline to support the adoption of environmentally responsible building materials within Taif's construction sector, aligned with local climatic conditions and regulatory frameworks.

G. Literature Review:

Concept of Sustainability in the Construction Sector:

Sustainability within the construction sector represents a comprehensive and integrative approach to developing built environments that fulfill current functional and societal needs without

compromising the capacity of future generations to meet their own. This approach necessitates a balanced consideration of environmental, economic, and social dimensions throughout the entire lifecycle of a building. Key principles include the efficient utilization of natural resources, reduction in energy and water consumption, and minimization of carbon emissions, alongside the adoption of recyclable and low-impact building materials [2].

In the Gulf region, and in Saudi Arabia in particular, national strategies like Vision 2030 have sped up efforts to transition to sustainable construction practices. These projects focus on energy-efficient design principles and environmentally sound materials used in both public and private sector constructions [11]. Additionally, sustainable construction is not only concerned with environmental measures but also includes healthy, comfortable indoor spaces for occupants as well as the benefit of long-term savings in operating and maintenance costs [12].

Classification of Building Materials: Traditional vs. Sustainable

There are essentially two classes of construction materials: traditional and sustainable materials. Conventional materials, such as reinforced concrete, cement blocks, steel, and other industrial metals, are popular because of their structural reliability and market availability. Yet these materials are usually characterized by high energy consumption and significant carbon emissions at both manufacturing and operational levels [13]. On the contrary, sustainable materials refer to those which are natural, recycled, or low-emission, such as treated wood, locally quarried stone, compressed earth blocks, and cutting-edge thermal insulation materials with eco-friendly properties [2]. The use of materials such as natural stone and wood as part of the construction process in buildings built locally (Taif City, KSA), for instance, including Shubra Palace, provided thermal insulation and responsive architecture for Saudi Arabia and was an example of indigenous materials used in architecture and design that did not necessarily rely on mechanical systems to provide thermal insulation, as was the case throughout the history of Saudi-centered buildings in terms of architecture and energy and was not dependent on a mechanical cooling system.

Evaluation of the Environmental and Thermal Impact of Building Materials

Evaluating the environmental and thermal performance of building materials is a critical component in advancing sustainability within the construction sector, particularly in hot and arid climates such as that of Taif. These assessments focus on key material attributes including thermal conductivity, thermal mass, embodied energy, and carbon emissions throughout the material's lifecycle [14]. Research indicates that conventional materials such as reinforced concrete and cement blocks exhibit relatively poor thermal insulation properties, thereby increasing dependency on mechanical cooling systems and contributing to elevated energy consumption[15]. In contrast, indigenous materials like natural stone and compacted earth blocks, commonly found in Taif's heritage architecture, demonstrate significantly better thermal performance. These materials can reduce heat transfer by up to 40% compared to concrete, offering passive cooling benefits and enhanced indoor comfort [2].

Previous Research in Saudi Arabia or Other Climates in the Region:

Interest in Sustainable Construction in the Region In the past few years, sustainable construction and selection of materials suitable for hot and arid climate construction has been the focus of significant research attention across the region, with Saudi Arabia and the surrounding Gulf countries having led the way in researching sustainable building materials. This research always focuses on the role of choosing adaptable climate-responsive components to optimize energy efficiency and curb carbon emissions.

- Highlights of Regional Research

- Al-Homoud (2005) emphasized that the concordance between the selected building materials and the local climate gives huge returns for energy efficiency and building sustainability.
- Sultan et al. (2021) found that new construction methods in Saudi Arabia place significant emphasis on sustainability standards, in line with the Saudi Building Code and Vision 2030. They implement thermal insulation and low-emission building materials for better energy efficiency and thermal comfort inside.
- Ali and Al Nsairat (2009) conducted an analytical study on sustainable and natural materials use in buildings in Jordan, which is climatically similar to parts of Saudi Arabia, and indicated that application of sustainable and natural materials reduces energy consumption as well as the effects of energy consumption in buildings on long-lived environmental performance.
- The result is that these researchers all offer compelling reasons to shift the construction industry towards more sustainable materials in new projects, and they hint at the need for rethinking our construction processes altogether. Also, they emphasize the importance of adapting the materials selected to the climate related to each city (such as Taif) and use this approach in order to have durable and feasible responses to construction.

2. Characteristics of Sustainable Building Materials:

Sustainable building construction materials features. Sustainable building materials have low environmental effects, do not over-exploit resources and increase human healthcare and comfort during the life cycle of the building. Such materials are endowed with low embodied energy, recyclable, good longevity and, non-toxic substances in general [1]. Local sourcing is a great edge as it reduces transport pollution emissions and also supports local economic development [6]. In addition to these environmental benefits, sustainable materials lead to lower energy consumption in terms of improved thermal insulation and reflectivity, which reduce the necessity of heating and cooling systems[2]. Flexibility has been highlighted as one of its attributes: materials crafted to be dismantled, reapplied, or recycled very quickly have contributed significantly to transitioning to the circular economy [16]. These principles and embedded in building materials will promote environmental efficiency, long-term economic success, and social welfare from sustainable approaches. Their behaviors can thus be broadly divided into three sustainability dimensions: environmentally, economically, and socially.

2.1 Environmental Dimension

The environmental aspect of sustainable building material emphasizes carbon emissions, energy use, and waste reduction in the entire material life cycle, which spans extraction, manufacture, use, and end-of-life (EoL). These materials possess low embodied energy and carbon and are relatively durable, and they can be reused, recycled, or biodegraded, leading to lower overall environmental effects. One indispensable approach of assessing environmental performance during the entire lifespan from cradle-to-grave/cradle-to-cradle is Life Cycle Assessment (LCA), which allows for energy use quantification, carbon footprint estimation, and pollutant emissions identification [17]. Attainment of the embodied energy-carbon reduction process at the early stages of production is essential to minimise the emission of these substances [18]. Environmental impacts also can be minimized by utilizing recycled, reclaimed, renewable, and locally sourced materials, which reduce resource depletion, transport emissions, and dependency on fossil fuels whilst benefiting local economies [6]. Indoor environmental quality is key as well, non-toxic, low-VOC materials create better indoor air quality, occupant health, and comfort [19]. The sustainability of it in the long-term is material's robustness, maintenance, and lifetime, and consequently the replacement needs and save resources throughout construction life cycle [20]. End-of-life practices like

dismantling, recycling, and repurposing are examples as waste management and circular economy planning contribute to waste minimization [21], while prefabrication and streamlined construction practices also help to limit site wastage [22]. There are also environmental certification systems and standards that lead the designer in the selection of sustainable materials [1]. And climate-responsive materials, such as those used together with thermal performance and passive design, may help to achieve long-term eco-friendly energy efficient design suit to climatic suitability as well [23].

2.2 Social Dimension of Sustainable Building Materials:

More than just a technical property, a building's social sustainability means that aspects of environment such as health, cultural continuity, and community development will also be profoundly impacted. First of all, health and safety are an overarching key factor: the use of non-toxic, low-VOC (volatile organic compound) materials lead to sound indoor air quality – while not emitting harmful substances like formaldehyde, which can harm respiratory health, comfort and long-term well-being [19]. Cultural and aesthetic appropriateness is also significant as the inclusion of materials reflecting local styles and heritage is also beneficial for social acceptance, place identity and preventing cultural alienation within the community [24]. In addition to these material choices, they have direct socio-economic consequences at the local level: sourcing for job creation, promoting artisans and small-scale producers, promoting informal economic sectors, reducing social inequality [25]. The comfort and well-being of its people are also affected by the materials, which impact with its thermal, acoustic, and visual nature as well for its impact on mental health, productivity, and in house to work satisfaction [26]. Equitable access and cost must also ensure that sustainable materials are not only utilized in luxury projects but that lower-income groups have access to safe and healthy living conditions as well, staving off “green gentrification” and fostering social equity [1]. Integration of other communities into the design and selection of materials further enriches social cohesion, instills a sense of ownership, and means material selection is reflective of real user needs, values, and expectations [27]. Ethical concerns also must be considered in material production and extraction in which complying to international standards of labor, avoiding forms of exploitation (child labor and unsafe job) and ensuring equitable trade and labor rights along a construction supply chain are the focus of consideration [28]. Lastly, long-term social resilience and adaptability are promoted by flexible, expanding, re-used materials, enabling communities to respond easily to climatic, economic, or disaster changes, modular and adaptive materials, specifically, contribute to sustainable, socially resilient community-built environments [29].

2.3 Environmental Dimension:

Environmental Dimension of Sustainable Building Materials. And from an environmental point of view, sustainable building materials are those that have a smaller carbon emission, energy use, waste generation through the whole life cycle of their uses, including extraction, manufacture, use, and disposal [6]. Traditionally, these materials have low embodied energy, high durability and an ability to be recycled or biodegradable, which results in a smaller overall environmental impact. A Life Cycle Assessment (LCA) framework allows assessment of the environmental performance of materials and is used to quantify the impacts in different dimensions of a material such as extraction, manufacturing, transport, use, maintenance and end of life, and to highlight critical stages of improvement and to inform both cradle-to-grave and cradle-to-cradle approaches while including key elements of the environmental footprint, energy consumption and pollutant emission [17]. Embodied energy and embodied carbon are therefore critical factors to consider, as they encapsulate total energy use and CO₂ emissions arising from the materials’ extraction, processing, manufacturing, and delivery, with particular effect on emissions at the construction phase [18]. Environmental considerations can be further improved by ensuring the consumption of recycled,

reclaimed, rapidly renewable or naturally sourced materials, such as bamboo, cork, and straw bales, to mitigate the depletion of natural resources, environmental damage, and the production of embodied energy [1]. Localisation of materials for materials must also be considered, as this not only makes transportation emissions in a local area less, reduces the consumption of fossil fuels, and economic activities at small scale is also supported by locally based materials, by reducing the fossil fuel utilization, less of the external materials, the amount of power required and dependence on foreign ones [6]. Consider also indoor environmental quality, because in sustainable buildings non-harmful substances with fewer harmful, low emission of volatile organic compounds (VOC) have better air quality, occupant health and comfort [19]. The building's longevity for materials, along with its durability, low replacement rate, its low maintenance and long lifecycle, also is also an added value in the field with lower replacement and resource use costs and longer life cycle environmental effects, resulting from the sustainability of the building in the longer term [20]. End of life solutions, such as those related to disassembly design and product reuse or recycling, minimize landfilling and provide alignment with circular economy principles [21]. Construction waste generation can be reduced by means of prefabrication, modular building systems, and efficient construction design methods as well as on-site waste management strategies that reduce offcuts and material wastage during the construction phase [22]. Systems of environmental certification from LEED to BREEAM, WELL, Green Star to ISO 14001 and ISO 21930 offer clear guidelines on how best to choose eco-conscious materials and to support the developers and players decision-making on sustainability [1]. Lastly, the choice of materials has a substantial impact on climate responsiveness and energy performance, as materials possessing adequate thermal mass, insulation qualities, and passive design features reflective systems, cool roofs, phase change materials can substantially lower energy demand in operation and improve environmental performance of buildings over time [23].

2.4 Economic and Social Dimensions of Sustainable Building Materials:

Economically, sustainable building materials support economic efficiency across the building's life cycle, in terms of energy consumption and maintenance expenses, extending its life span, and with-it local production chains that reduce transportation costs [1]. The social dimension is of course also fundamental, beyond the economic consideration, to establish the sustainability of building materials. Occupant health and safety is a basic social attribute, non-toxic, low-volatile organic compounds (VOC) are predominantly used for indoor air preservation and prevent the emission of toxic chemicals such as formaldehyde, known to cause respiratory diseases and discomfort, as well as long-term health problems [19]. From a cultural and social point of view, materials should be in line with regional architectural traditions and heritage, for improving social acceptance, feeling 'at home', and reducing distance from communities [24]. Economically, the employment opportunities, preservation through long-established artisan crafts and indigenous small producers, and contribution towards inclusive economic development are all directly connected to the employment of locally produced materials via decreased social inequalities [25]. It is also obvious that design material selection plays a decisive role in user experience since thermal, acoustic, and visual comfort affect the mental health, productivity, as well as the satisfaction of residential, educational, and workplace users [26]. Equity mandates also that sustainable materials be affordable and accessible to varied social structures, ensuring health and safety gains do not fall solely on well-developed estates, as well as not enabling social exclusion and "green gentrification" [1]. Participation, as a way of drawing participation from future users and local communities in the choice of materials and design, promotes social solidarity, nurtures a sense of ownership, and confirms that materials are chosen to suit real social requirements and values [27]. Lastly, ethical and long-term aspects encompass labor rights and safe working conditions in the entire process of production and extraction of the material as well as the choice of materials that facilitate adaptability and resilience under changing climatic and socio-economic

conditions [28, 29]. Table (1) highlights the main social Sustainability Aspects and Criteria Related to Building Materials and the Built Environment.

Table (1): Social Sustainability Aspects and Criteria Related to Building Materials and the Built Environment[2, 30, 31, 32, 33 ,34,35] .

Key Area	Focus
Health and Safety	Non-toxic, healthy indoor environments
Cultural Compatibility	Respecting local identity and aesthetics
Economic Empowerment	Job creation, local sourcing, inclusive supply chains
User Comfort	Thermal, visual, and acoustic well-being
Affordability	Access for low-income communities
Community Involvement	Participatory design, social cohesion
Ethical Labor Practices	Fair work conditions in production and sourcing

2.5 Social dimensions of sustainable building materials.

This is the reason for which the analysis of green building materials should have to go further than the analysis of how good they are technically, but should also consider the socio-economic importance of the materials in the life cycle, from extraction to manufacturing to application to end-of-life. Importantly, these social impacts impact occupant health, comfort, community cohesion, and the conservation of cultural values. Sustainability, and the social-building materials. From a social perspective it leads to benefits for occupants as it directly impacts their wellbeing, comfort, and quality of life. Low pollution building materials, indoor air quality materials serve as key ingredients for sustainable living to maintain thermal and acoustical comfort [36]. In such residential and educational buildings with continual exposure to indoor elements, these characteristics become critical for the mental and physical well-being. Responsible sourcing and the use of socially sustainable and responsibly made building materials also aid in socially fair labor practices and promote economic development at the local level. Hence, socially sustainable materials can serve a second role where they serve not just as a function and contribute to the environment but also play a social role as a means to strengthen the resilience of the community. Since the construction sector is a third pillar of sustainability, the social end of the social dimension allows construction practices to be inclusive, culturally responsive, and in the end human centred, rather than purely efficiency- or technology-centered [2].

2.5.1 Social dimension Building materials in Taif.

Construction material in Taif is not limited to environmental and technological parameters but include the social and cultural domains. The stone, adobe and lime plaster are the traditional material found here, already used for so long that has an inseparable relationship with the local identity and a vital element of its collective culture. The stability and ongoing utilization of these materials give community pride and a sense of community to the citizens as users, as well as support indigenous knowledge and artisan skills, traditional knowledge and the practice of traditional skills – vital elements of social sustainability [37]. Simultaneously, a growing reliance on modern industrial raw materials (concrete, steel, and glass) provide structural and functional benefits but, even if with some structural advantages, also result in social and cultural marginalization. Such materials are typically context inapplicable to, or are not well-suited to, local climate and cultural context, such as the local climate or local conditions. Due to the poor thermal adaptation of their thermal profile, the fact that occupants are less comfortable indoors, and therefore rely more on the mechanical cooling systems. This dependence not only affects energy efficiency, but also has severe, negative impacts on the health of inhabitants, which is very important [2].

2.5.2 Social Dimensions of Sustainable Construction Materials

The social sustainability of building materials encompasses a huge variety of human-centered issues, far beyond technical concerns. These include health, equity, cultural relevance, and community empowerment. The major social dimensions described in the literature are elaborated in the following subsections. Health and Safety. Materials used to build sustainable buildings must safeguard the health and safety of construction workers and building occupants. That involves limiting exposure to potentially harmful chemicals, like volatile organic compounds (VOCs) and asbestos, and ensuring safe working conditions for new and existing materials throughout the material life cycle, from extraction to installation[38] . Construction material choices, and their application, directly impact local communities positively (job creation to a certain degree) or disadvantageously (for instance, environmental destruction, noise and displacement). Thus, the voice of society in material choice decision is essential in the development of social legitimacy and participation[39].

2.5.3 Rights of Labour:

Ethical construction materials must comply with international labour standards, ensuring fair wages, safe working conditions, and the absence of exploitative practices such as child labour. Respecting workers' rights supports fair trade principles and strengthens social responsibility within construction supply chains [40]. Local sourcing of building materials contributes to economic empowerment by supporting local industries, developing skills, and enhancing regional resilience, while also reducing transportation-related emissions [37]. Culturally appropriate materials that reflect local values, traditions, and vernacular construction techniques promote social acceptance, reinforce cultural identity, and foster a sense of community belonging [2]. Affordability is essential to social equity, sustainable materials should be accessible to all social groups, particularly low-income communities, to support inclusive and dignified living environments [25]. Finally, material selection significantly influences thermal, acoustic, and visual comfort, directly affecting users' well-being, productivity, and quality of life, making it a key consideration in sustainable design [2].

2.5.4 Education and Awareness:

We must foster awareness among stakeholders including builders, users, and policymakers of the social benefits of sustainable materials. Educational campaigns can promote sustainable changes in behavior in the long term and encourage the move towards more socially responsible building [40]. This framework posits that building materials' social sustainability goes beyond their material characteristics to considerations of the impact on people's lives, work, identity, and dignity. Evaluation of sustainability of material should therefore include in future evaluation systems to consider these human-centered dimensions of material sustainability to create a comprehensive and equitable sustainable living and resilient built environment. Figure (1) displays integration of important environmental and social attributes of sustainable materials by defining resource efficiency, low carbon footprint, and recyclability as environmental aspects, along with user comfort, health and safety, and sustainability awareness as important social aspects. Cumulatively, these dimensions indicate that a multidimensional means of material sustainability is necessary for the attainment of material sustainability.

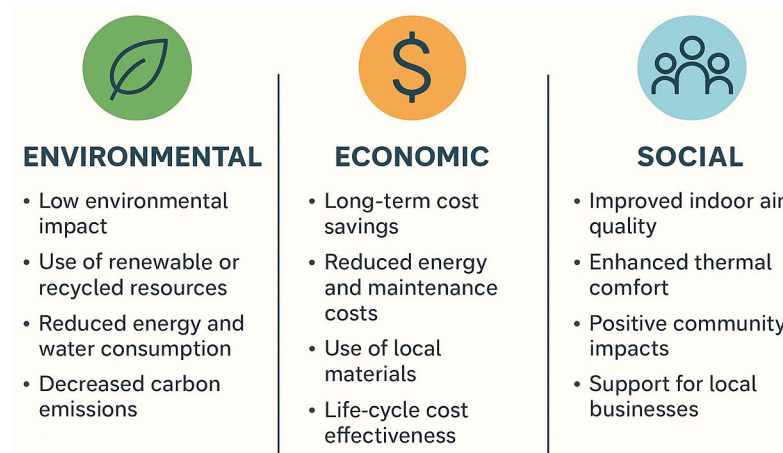


Figure (1): shows the three pillars of sustainable building materials.

We can also explain the characteristics of sustainable building materials across the three dimensions of sustainability through the Table (2) .

Table(2) : Characteristics of Sustainable Building Materials Across the Three Dimensions of Sustainability[2, 5,25 ,33, 31, 30 ,32, 35, 34,38] .

Sustainability Dimension	Key Characteristics	Description / Examples
Environmental	- Low embodied energy - Recyclability and reusability - Non-toxic composition - Energy efficiency (thermal insulation) - Reduced carbon footprint	Materials that minimize energy and emissions during production and use, promote natural ventilation and thermal comfort (e.g., rammed earth, bamboo, recycled steel).
Economic	- Cost-effectiveness over the life cycle - Local availability - Low maintenance and long durability - Resource efficiency	Materials that lower operational and maintenance costs and support local supply chains (e.g., locally quarried stone, stabilized soil blocks).
Social	- Healthy indoor air quality - User comfort and well-being - Safety and adaptability - Support for local employment and fair labor	Materials that improve health and comfort by avoiding VOCs and supporting community welfare (e.g., low-VOC paints, natural finishes, locally crafted materials).

3. Building Materials used in Taif:

A Review (Introduction to the Situation in Taif). Taif, on the high peaks of the Sarawat Mountains in western Saudi Arabia, has a temperate climate, which is characterized especially by summer compared to the rest of the Kingdom. This climatic advantage historically has characterized its architectural identity and mingled some traditional Hijazi elements with modern building practices. Material choices in Taif reflect environmental responsiveness, cultural heritage, and local resources.

3.1 Traditional Building Materials: Sustainability, Thermal Comfort, and Recycling:

Historically, Taif's architecture used locally available natural materials, including clay, stone, wood, and lime-based finishes. The materials were chosen for their climatic adaptability, cultural relevance, and sustainability potential. The next subsections discuss the important conventional substances with regards to environmental performance, thermal comfort, and recyclability.

3.1.1 Clay and Mud Bricks (Adobe)

Adobe is made from a mixture of clay, sand, water, and organic fibers (e.g., straw) and is sun-dried without energy-intensive firing, thus becoming very sustainable [41, 42]. Its high thermal mass contributes to thermo stability in indoor temperature control and proper insulation and humidity control which is beneficial to arid climates [43]. But adobe is moisture-sensitive and structurally restricted to internal partitions, and it cannot withstand heavy loads, thereby serving only for internal partitions and low-rise applications. If the material is properly stabilized, it is a suitable environmentally friendly material to which one can still hold cultural traditions.

3.1.2 For the Mountain (Al Shafa) and Al Hada, timber:

In traditional mountain homes in Al Shafa and Al Hada, wood used is known for its renewability, low thermal conductivity, and recyclability. Locally available wood also has a lower carbon footprint from transport emissions and captures carbon in the growing process, minimizing building footprints [2, 5]. The insulating properties of this material increase thermal comfort [13] in cooler climates. In addition, wood can be reworked or recycled into new construction elements, aiding the movement of circular material [44].

3.1.3 Marble:

It is one of the most widely used natural stones in construction for its beauty, smoothness, and durability. Its capacity to reflect light and appear lavish in appearance are why it is favoured by many interior finishes and building facades [5]. Marble also has a high thermal mass, which is important in natural temperature regulation and increased energy efficiency in buildings [45]. Nonetheless, marble extraction and processing consume energy, and the long-distance transportation of marble results in a large carbon footprint [2]. So local marble in Saudi Arabia will reduce its environmental footprint and promote its sustainable use, while minimizing transport emissions.



Figure (2) shows a picture of King Abdulaziz Hospital, whose facades were covered with natural marble.

3.1.4 Granite:

Granite is characterized by its high strength, durability, and weather resistance traits that make it an excellent candidate for heavy-duty building facades and flooring [5]. Granite also has low porosity preventing moisture from soaking into building components, thereby prolonging buildings' lifetime in regions where temperatures vary. Granite derives a high quality and long-lasting performance due to long durability, however, its extraction and cutting operations consume high energy and produce substantial dust and waste [21]. In countries like Saudi Arabia where granite deposits are relatively plentiful, the use of locally sourced granite supports sustainable building by lowering energy cost from imported granite, and encourages local industry to thrive.



Figure (3): A picture of King Faisal Hospital, whose facades were covered with natural granite.



Figure (4) An archaeological building in the city of Taif, constructed entirely of granite.

3.1.5 Hashmi Stone:

Because of their durability and beauty, along with their significant symbolism, the natural limestone that Saudi Arabia prefers and Hashemite stone that Jordan has chosen are popular materials used in regional architecture [46]. This local abundance also provides a distinct sustainability advantage with respect to reducing transportation energy and emissions while stimulating local economies [2, 47]. The stones both have high thermal mass and absorb and slowly radiate thermal energy, which can give good thermal comfort. This contributes to an indoor equilibrium, which minimizes the use of air conditioning systems [13]. While it is not strictly applied in the concrete industry at the time of construction, the waste produced in cutting and shaping can also be put to use in concrete or landscaping as aggregate, enhancing materials efficiency and enabling a circular economy in construction [48]. As quarrying has produced environmental impacts like land degradation and dust emissions [49], these changes can be counteracted with better quarrying management and waste reutilization strategies. Hence, the responsibility to use such stones locally improves environmental performance and keeps architectural identity, in accordance with the objectives of Saudi Vision 2030.



Figure (5): illustrates the cladding of facades with Hashemite stone.

3.1.6 Basalt Stone:

Basalt is a volcanic stone with a high compressive strength, dark coloration, and durability under extreme thermal conditions. It is commonly employed in paving, structural blocks, and façade elements, mostly in terracing and infrastructure near volcanoes as was done in the Hijaz region [13]. The thermal mass of basalt enables passive temperature control, which is useful for reducing cooling loads in Saudi buildings. However, like all heavy natural stones, quarrying and cutting basalt is an energy-intensive activity [21]. Sustainable methods, such as the utilization of basalt aggregates from nearby quarries and the recycling of discarded stones, can both alleviate environmental impacts and maximize the effectiveness of green construction methods.

3.1.7 Lime Stone:

Limestone is one of the most common and historically utilized natural stones found in Saudi Arabia, mainly used in the western and central regions such as Taif and Makkah, where it has been commonly used in homes, religious, and civic buildings. The light hue, natural texture, and moderate compressive strength make it a suitable choice for its aesthetic, cladding, and ornamental aspects, giving it both strong aesthetic and structural significance [5]. Moreover, due to its porous texture, natural limestone walls promote thermal comfort by facilitating breathability of the wall while reducing heat transfer for passive cooling in the region's hot climate [13]. As for sustainability considerations, the embodied energy of limestone is quite low because of the very low mechanical processing demand for natural stones [2]. The wide local availability of the stone, particularly near Taif, means there is less need for long-distance transport, which reduces carbon emissions and leads towards local economic development [47]. Yet sustainable extraction is required to minimize environmental impacts including dust generation, land degradation, and visual impact on the environment [21]. Limestone is a natural material that is hardly ever recycled in architectural design but rather crushed and reused as aggregate in concrete applications or road base materials, and is considered to be part of circular construction. So, the responsible use of locally sourced limestone provides a very attractive combination of sustainability, thermal comfort, and recycling. It aligns with the environmental goals of Saudi Arabia's Vision 2030, while maintaining the cultural and architectural identity of its western cities.



Figure (6): illustrates a picture of the Taif University Mosque, whose facades were covered with limestone.

3.1.8 Mica Stone:

Mica is a naturally occurring silicate mineral. It is valued for optimal thermal and electrical insulation, robustness, and the way it appears overall mostly in wall finishes, coatings, and decorative panels [5]. From a sustainable development perspective, mica is a rich resource that takes far less energy to produce than other forms of synthetic media and has moderate embodied energy. However, unmonitored mining operation has environmental and social risks, especially where land degradation (and exploitation of labour) could occur [50]. The low thermal conductivity of the mica material, combined with its high heat resistance, makes it a reliable material for thermal insulation of building envelopes in terms of thermal comfort. This reduction minimizes heat transfer such that energy prices and climate adjustments take place in buildings [13]. Mica can be selectively reclaimed from industrial wastes and reused into composite materials or as a coating for surfaces. But it is impossible to conduct large-scale recycling here, for the processing takes place in fragmented units [51]. In the end, mica is the best source of recycled material for ecologically friendly building materials when responsibly collected. The good thermal characteristics, modest embodied energy and partial recyclability of the material now make it a component of use in green housing systems.

3.2 New Building Materials in Today's World:

The Sustainability, Thermal Comfort & Performance Issues Conventional concrete and steel used in construction of buildings and urbanisation has become a standard material since Taif construction experienced both a national trend with an overall trend in development phase. These are what the newest widely applied materials are:

3.2.1 Structural Applications: Reinforced concrete (RC)

Reinforced concrete (RC) in its highest compressive strength but also is known as the oldest and the most versatile building material, and is still one of the most common in construction materials nowadays. Reinforced concrete (RC) is a concrete (compression-strong) and steel (tensile force-resistant) combination with a range of structural members [52]. The use of RC on wall, slab floor and roof roofing systems of residential commercial and industrial buildings is widespread because, with an area having high resistance, there is no drop in structural integrity [53]. Its flexibility allows construction of intricate architectural shapes and structural designs; therefore, it is a good fit for modern architectural design [54]. Moreover, RC will not only withstand fire but also different environmental conditions. The sustainability of cement despite the energy consumption of cement production has been a challenge for many [55]. To resolve these difficulties, a variety of alternative practices were investigated such as SCM supplemented with recycled aggregates, and enhanced environmental aspects for RC structures are discussed, in relation to the SCMs and recycling aggregates [56]. While it has high structural advantages and efficiency in construction, RC has

long been known to have low thermal performance and cultural assimilation against the same materials as conventional constructions [57].



Figure (7): Depicts the application of reinforced concrete in the walls and ceilings of villas in Al-Ward City, Taif.

3.2.2 Concrete Blocks for Walls.

Concrete masonry units (CMUs), also known as concrete blocks, are used as wall building material because of their high compressive strength, durability, and convenience of installation [56]. Conventional concrete blocks from a sustainability point of view are a concern in terms of environmental impact, mainly because of the energy-intensive nature of cement production and its associated carbon dioxide (CO₂) emissions [55]. However, their longevity and low maintenance requirements play a positive role in the building lifecycle performance by decreasing repair frequency and waste materials [2]. Recent developments in green concrete block production involve the use of industrial by-products such as fly ash, slag, and recycled aggregates, contributing to minimizing embodied energy and carbon emissions [21]. The large thermal mass composition of concrete blocks helps in controlling the indoor temperature and consequently, avoids the need for mechanical heating and cooling, thus increasing efficient use of energy [13]. The structural performance, modularity, and sustainable value of concrete blocks is, therefore, an appealing construction option in the context of contemporary low- to mid-rise building typology.



Figure (8): Depicts A picture of a building in Taif made of concrete blocks.

3.2.3 Clay (Red) Bricks. Clay bricks:

known for their strength, durability, and thermal properties are among the oldest and most popular types of bricks among common materials that have attracted growing interest. These bricks are primarily made from natural clay, and are shaped and fired at high temperatures which have great compressive strength and weathering resistance for several structural and also non-structural applications to be made from them [56,55] argues that traditional firing processes are energy and CO₂ intensive, and because of this, are unsustainable from a sustainability perspective. In addition,

clay bricks possess high thermal mass which, in turn, could be utilised in buildings to enhance thermal comfort and energy conservation through reducing temperature range [13]. Red bricks also provide a compromise across efficiency, strength and environmental impact in a traditional and modern building use if produced responsibly and from in-country sources.

3.2.4 Aluminum, Glass, and Cladding – Facade Design

Numerous modern facades are covered with aluminum, glass and a multitude of other types of cladding since they also have aesthetic, structural and architectural functions. Aluminum is lighter and most recyclable, while recycled aluminum also significantly decreases energy consumption and greenhouse gas emissions compared with its primary production [58]. The use of glass helps in daylighting in addition to more energy-saving materials for double or triple glazing and low-emissivity coating, which prevents heat loss in winter, and leads to increased solar gain in summer [59]. The systems of cladding, comprising aluminum panels and composite materials (e.g., panels) give additional facade protection, improved appearance and thermal performance (however the impact of these factors on environmental performance varies from site to site) [5]. Nonetheless, properly constructed facades including aluminum, glass, and suitable cladding materials can increase daylight access, energy efficiency, solar radiation, energy usage and occupant comfort and energy usage efficiency respectively, to decrease glare, humidity, sunlight, and water consumption in the building, using minimal hours of cooling hours, and the energy used in heating. Conversely, in adverse scenarios, weak material selection can lead to overheating and/or energy requirements, highlighting the significance of facade construction in trade-off between ecological and thermal comfort as a necessary component for sustainability as well as energy and/or thermal comfort and thus should be one of the most essential considerations for facade material selection [60].



Figure (9): Depicts the building of the President of Taif University, with its facades clad in metal.



Figure (10): A picture of a building with a glass dome roof in the city of Taif.

3.2.5 Curtain Wall Facades in Saudi Arabia:

Curtain wall facades are increasingly the trend in both commercial and high-rise buildings in the Kingdom of Saudi Arabia. Curtain wall systems (typically made from aluminum frames and glazed panels) have become very popular in construction and high-rise development in Saudi Arabia. They look very trendy and aero, lightweight, and are able to span large areas without stressing the main frame, so that they serve as an attractive visual architecture as well. The degree of transparency in a curtain wall will improve the penetration of sunlight on a daily basis, decreasing the need for artificial light. Furthermore, with the addition of high-performance technologies like double glazing, low-emissivity (low-E) coatings, and thermal breaks, the ability of curtain walls to improve thermal insulation increases and the overall energy efficiency is enhanced when properly engineered [61, 14]. Nevertheless, the hot arid climate of Saudi Arabia is particularly problematic when designing curtain walls. If shading devices are not implemented and selective glazing is not utilized, large glazed surfaces may induce excessive solar heat gain, resulting in substantial cooling demands and operational energy expenditure [62]. Further, due to the dust and extreme weather pattern in the region, there is a need to maintain these areas, including cleaning and sealant replacement, that if not properly detailed will affect performance in the long run. If curtain walls provide a facade with aesthetic elegance and design versatility, their environmental effects in Saudi Arabia are heavily reliant on strategies responsive towards climate. They include deep overhangs, external louvers, reflective or spectrally selective glazing, and hybrid façade systems combining opaque insulated panels with controlled glazing ratios, among others.



Figure (11): Depicts the Taif Chamber of Commerce building, with its facades covered with curtain wall.

3.2.6 Wood Alternatives:

Conventional hardwood alternatives often include manufactured wood products, such as laminated veneer (LVL), cross-laminated timber (CLT) and recycled wood composites. Their eco-friendliness is clear when considering their manufacturing techniques, which are much less energy-intensive than traditional materials, such as steel and concrete. Moreover, usage of recycled materials minimizes their contribution to the overall environmental burden [5]. In addition to that, wood and the subsequent composites also have very good thermal insulation which is reducing the heat transfer, thus reducing energy consumption for indoor air conditioning [45]. Consequently, adopting more recycled, manufactured wood substitutes to find sustainable and thermal-efficient building materials is encouraging recycling and sustainable building.

4. Challenges Facing the Implementation of Sustainable Building Materials in Taif:

While Saudi Arabia's construction industry is making efforts to embed the principles of sustainability in its work, there are still several challenges to mainstreaming sustainable building materials in this industry. One major stumbling block is the relatively high cost of eco-friendly materials, largely due to limited domestic production and dependence on imported goods [11]. Another barrier is the lack of universally accepted criteria for the environmental performance of materials (especially in small- to medium-scale projects). Recycling and material reuse initiatives are underused on construction sites. In addition, the harsh climatic factors in the region, of which the mountainous Taif region is a typical example, make material selection a more challenging task, and the demand for locally adapted remedies must be made for overcoming special thermal and environmental challenges [63]. Nonetheless, government programs such as the Saudi Building Code Sustainability Requirements (2021) are aimed at promoting a transition to efficient and greener materials with regulations, financial incentives, and are aimed at supporting the Vision 2030 ambitions. Through research and institutional support, the construction industry in Saudi Arabia will transform for the better with future development.

5. Future Opportunities for Advancing a Sustainable Construction System in Taif:

A Proposal Next Steps to Optimize a Sustainable Construction System for Taif are further suggested. Taif possesses good promise of a sustainable construction environment which can be tailored to its unique environmental and climatic conditions and for the overall Vision 2030 objective of Saudi Arabia to facilitate sustainable construction activities. One huge opportunity lies in building buildings with greater thermal performance using local materials (stone, clay, wood, etc.), rather than relying on mechanical heating and cooling. This city's temperate mountainous context makes appropriate passive design features such as natural ventilation systems

plus use of the optimal orientation to use of the building (to capture the sunlight and shading) possible [63]. Another opportunity is cultivating exploration and development of new sustainable building materials with local universities and research institutions. This is where sustainable materials that adapt to Taif's semi-arid zone conditions can be produced. In parallel, following the Saudi Building Code – Sustainability Requirements (2021) offers a guiding structure in terms of energy efficiency measures in new construction projects and the adoption of modern green concrete and intelligent thermal insulation as standards [11]. Through this, public-private partnerships can catalyze the movement towards more sustainable construction by providing funding and environmental standards for construction. These partnerships are able to address financing, capacity and execution gaps. In all, Taif's unique terrain and weather conditions present its own unique character as an important candidate to be considered a national benchmark of sustainability in construction. The use of the city's resources, adoption of green strategies from local producers, and inclusion of sustainability in urban design are two ways in which we can move in the direction of a safer built environment that will be both resilient and environmentally secure.

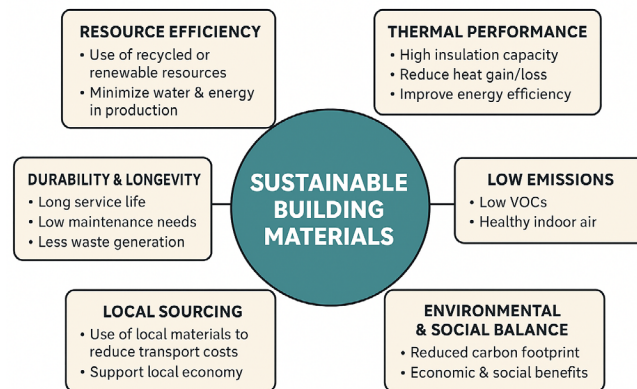


Figure (12): Illustrates the Key Sustainability Criteria for Building Materials in the Context of Taif's Construction Sector.

6. Commonly Used Building Materials in Taif and Their Sustainability Compliance

Construction Materials That are Used in Taif and Sustainability: Conformance. Conventional materials for Taif construction are mostly reinforced concrete, steel and cement blocks such as that used in other cities in Saudi Arabia. Selected building types and types of use, etc. are based on materials such as these for this purpose. Concrete possesses a high strength as a compressive material, and steel has been utilized to structure the design of commercial and multi-storey buildings[57, 63]. As sustainability starts to emerge in the construction industry, data on what kind of durable materials are going to be used (recycled aggregates, low-carbon concrete, lifecycle-based assessments...) is limited. The Saudi Green Initiative and municipal action indicate that consciousness of the environment is on the rise. The biggest one is expansion of green space to 8 million square meters in Taif and the planting of more than 600,000 trees and seedlings in Taif's center nursery for 2024 [64,65]. While the utilization of sustainable materials is still a work in progress but the projects as well as additional exploration/testing and experiments are evidence of a milestone shift towards the global deployment of sustainable building materials. However, new structures and development have to be a seamless blend of new low impact materials with sustainability – as a minimum value compromise of both structural quality as a matter of sustainability, and ecological behavior.

7. Trends in the Development of Sustainable Building Materials

The construction industry has focused on greener building materials to address environmental challenges and the rising energy demands required to keep buildings sustainable. The introduction of recycled industrial by-products (e.g., fly ash and blast furnace slag) into green concrete formulations, which substantially decrease the requirement of standard cement with high carbon emissions, has proven to be an ongoing trend [66]. Another important trend is the development of materials from locally sourced, low embodied energy raw materials (stone, clay, other resources) compatible with regional weather and transportation that reduce transportation emissions [2]. In Saudi Arabia, Vision 2030 has stimulated innovation in sustainable construction initiatives, which lead to the adoption of low-emission, high-performance concrete and sophisticated thermal insulation systems in line with the Saudi Building Code Sustainability Requirements [15]. Cities like Taif and Riyadh are gradually incorporating scholarly investigation and locally developed technologies into climate-responsive building solutions. The emerging changes reveal sustainable construction materials as strategic imperatives and are no longer “nice to have” for the industry but core business for improving resource efficiency and protecting the environment in the construction industry.

8. Comparative Assessment of Traditional and Sustainable Materials:

In Taif, it is therefore essential to investigate whether these traditional and sustainable building materials are more environmentally, economically, and climatically appropriate than the others. Conventional building materials like reinforced concrete, red bricks, and steel, the structural strength and availability of proven conventional materials make them widely used. But their production methods tend to consume energy and are a major contributor to carbon emissions. Green concrete, advanced thermal insulation, and recycled components as alternative options are considered eco-friendly alternatives that improve thermal performance and energy use efficiency [2, 11].

8.1 Eco-Performance:

Studies suggest that sustainable materials can greatly lower carbon emissions and conserve natural resources compared to traditional options. Green concrete and other materials, such as fly ash or slag, reduce the use of cement by 30–40%, thereby directly reducing CO₂ emissions, for instance. Furthermore, use of natural and wood-based insulation substances also enhances thermal regulation, minimizing the significance of mechanical heating and cooling systems [13].

8.2 Lifecycle Cost-Benefit

Although upfront costs of using sustainable materials may be higher, lifecycle analyses demonstrate long-term benefits that yield economic benefit. High-efficiency insulation systems, for example, yield 20–30% savings in annual energy consumption over the building’s operational life. In addition, the option of using recycled materials reduces construction project costs for waste and environmental risks from these resources, increasing the financial sustainability of sustainable construction projects [66].

8.3 Climatic Suitability for Taif

Suitable for the climate of Taif. Taif has a mountainous terrain and a temperate climate—with daily and seasonal temperature variations requiring materials that will respond to thermal fluctuations well. Conventional materials, such as brick or dense concrete, are heat-retaining elements, which could result in a higher cooling burden. Even with minimal energy consumption, sustainable alternatives such as locally sourced wood with high-performance insulation achieve better thermal control and environmental protection from within. They demonstrate the qualities mentioned previously and are very appropriate in the Taif condition [63]. Table (3) provides the

comparative results based on the materials for Taif (traditional and sustainable) and examines their sustainability, culture, and environmental performance.

Table (3): Comparison between Traditional and Modern Building Materials in Kingdom of Saudi Arabia[13, ,41 2, 21, 30, 9, 34, 31, 33, 5, 67, 48,32, 13, 5] :

Aspect	Traditional Materials (e.g., stone, adobe, lime plaster)	Modern Materials (e.g., concrete, steel, glass)
Climatic Suitability	High – Provides natural thermal insulation	Medium to low – Requires additional cooling systems
Environmental Impact	Low – Natural and locally sourced materials	High – Due to industrial production and transportation
Cultural & Architectural Identity	Reflects local heritage and aligns with urban fabric	Often lacks local character
Social Dimension	Supports traditional craftsmanship and the local community	Often depends on external supply chains
Cost	Low to medium (depending on availability)	Medium to high
Ease of Maintenance	Easy to maintain and replace	May require specialized maintenance techniques
Indoor Comfort (Thermal & Acoustic)	High – Natural insulation enhances comfort	Depends on additional processing (industrial insulation)
Long-Term Sustainability	High – Durable with strong environmental compatibility	Depends on ongoing maintenance and technological support

9. Discussion:

This section then provides discussion of results indicated in Tables (1) through (4), the multifactorial action of building materials in developing sustainable construction practices of Taif is accentuated. Table (1) presents the Social Dimensions (S) in Table (1). Table (1) indicates that building materials in Taif fulfill a social need to promote sustainable development. Non-toxic, locally sourced and culturally appropriate materials do not only help the health of the planet, but the health of the community. They are more safety promoting, they support local employment and they safeguard the architectural heritage. Sustainability in Taif requires an ecologically and human sustainable path between eco-mechanical activities and integration with environmental, social and cultural aspects so that built materials are conducive to community living. What we find in Table (2): The Sustainability Triple-Bottom Line. Table (2) reveals that climate-friendly construct materials offer environmental, economic and social dividends. But environmentally, this sort of thing decreases energy use and greenhouse gas emissions, and has some environmental benefits, as well: environmental benefits. They also benefit economically, not just with longevity opportunities (like life cycle savings) but in that they protect our local supply, making them a more cost-effective long-term model. From the societal perspective, they promote healthier living, more peaceful living conditions and sustainability in a natural way for consumers who are living inside in a more sustainable manner. By incorporating them, the three dimensions integrate to make selection of materials one that contributes towards holistic sustainability and enhancing overall performance on a building. Table comparison material performance — summary of points from Table (3). Table (3) A comparison of conventional and modern building materials used in Saudi Arabia. Classic materials — stone, clay, wood — are at their most climatically perfect, environmentally benign and culturally closer. In contrast, the modern materials—those whose performance is improved such as reinforced concrete and steel etc.—have structural and ecological performance advantages, but are often more costly environmentally and less culturally connected. Thus, this comparison reveals that a fusion of old and new practices in terms of environmental, social and technological sustainability is the way to reconcile sustainable practices in Taif. As we transition to Circular and Climate-Responsive Design – insights (Table (4)) Table (4) reiterates

that the maximise the sustainability benefits using locally sourced materials and design-for-disassembly design principles. Such green materials (e.g. materials having a high effect on the environment) can be obtained from local supply value chain processes, transported in a relatively rapid flow, and then assembled and manufactured for reuse or recycling, recyclability, and reusability. A review concluded that in terms of sustainability and thermal comfort, traditional materials derived from nature are more suited to circular economies and design-for-disassembly of climate action.

Table (4): Comparison of materials sustainability, recycling, and thermal comfort:

Material	Sustainability (summary)	Recycling / Reuse	Thermal comfort (effect)
Wood (local, sustainably sourced)	When sustainably harvested, high: renewable, low embodied energy, carbon-sequestering. Impacts rise if transported far or from unsustainable logging.	Excellent: components can be reused, remanufactured, or recycled into composites, biodegradable.	Good: low thermal conductivity, contributes to insulation and stable indoor temperatures, pleasant radiant surface.
Marble	Moderate–Low: natural, durable, long life, quarrying and transport are energy-intensive and cause landscape impact.	Moderate: large slabs are reusable in finish applications, off-cuts can be crushed for aggregate or landscaping.	High thermal mass: absorbs heat and slowly releases it good for diurnal temperature buffering but can feel cold to touch.
Granite	Moderate: reusable as facing material, crushed for aggregate or paving base.	Moderate–Low: very durable and long-lasting (reduces replacement), quarrying & transport energy are significant.	High thermal mass: effective for stabilizing indoor temperature swings, can retain cold/heat.
Basalt	Moderate: natural volcanic rock, durable with long service life, quarrying impacts similar to other stones.	Moderate: reused as crushed aggregate (high quality) or paving, architectural reuse less common.	High thermal mass: good for thermal storage and reducing peak loads.
Crushed stone (aggregates)	Depends: often a by-product of quarrying — useful in circular use if locally sourced, embodied impacts from extraction/transport.	Excellent: inherently recyclable as aggregate in new concrete, road bases, fill.	Low direct insulation: used in mass elements (contributes thermal mass when part of concrete), as loose material offers little insulation
Mica	Moderate: natural mineral with relatively low processing energy, but mining can cause social/environmental issues if unregulated.	Limited–Moderate: some reuse in composites/coatings, fine fragmentation limits direct large-scale reuse.	Good heat resistance and low thermal conductivity (as filler/insulation layer it can improve thermal performance), not typically used as primary insulating element.
Glass (façade glazing)	Variable: high embodied energy for production, but long life and benefits from daylighting/solar control when specified correctly. Recycled cullet lowers impacts.	Moderate: glass is recyclable (cullet) but architectural glass with coatings or laminated layers is harder to recycle.	Poor as a bare layer (single glazing): high heat loss/gain. Good if double/triple glazing with low-E coatings and thermally broken frames improves daylight while controlling heat transfer.

Cladding (aluminum panels, terracotta, fiber-cement, composites)	Variable by type: terracotta/ceramic and fiber-cement have moderate impacts, aluminum panels have high production energy but high recyclability, composites can be less sustainable.	Variable: metals (aluminum, steel) recycle well, terracotta can be reused, composite panels are harder to recycle.	Depends on system: ventilated façades, insulated rainscreens and cladding with cavity/insulation greatly improve thermal comfort and reduce heat transfer.
Cement bricks / Concrete blocks (CMU)	Low–Moderate: relatively high embodied CO ₂ from cement, long life and low maintenance mitigate some impacts, using SCMs or recycled aggregate improves sustainability.	Moderate: masonry can be crushed and used as recycled aggregate, whole units are reusable with effort.	Moderate–High thermal mass: good for stabilizing temperatures but poor intrinsic insulation typically needs insulation layer for comfort in extreme climates.
Clay bricks (traditional fired clay)	Moderate: locally made sun-dried bricks have low impact, fired clay has energy demand for kilns but long life and local production can improve sustainability.	Good: bricks can be cleaned and reused; crushed bricks serve as fill/aggregate.	Good thermal mass and moderate insulation (depending on porosity and cavity design), provides comfortable indoor conditions when combined with ventilative design.

9.1 Proposed Framework:

9.1.1 A guideline or framework to adopt sustainable building materials:

A guideline or framework which will help guide the development of sustainable building materials will be of utmost essence to the construction industry in promotion of sustainable building materials. Policymakers, builders, and construction professionals can take a pragmatic, comprehensive view and develop guidelines for materials efficiency, environmental impact assessments, sustainability assessments, and/or practical suggestions for building new structures. This kind of framework provides clear guidelines for developers, contractors, and engineers to determine the environmental, thermal, and energy properties of the materials to be selected. This advice may include some key aspects, such as Life Cycle Assessment (LCA) that could assess a material's environmental impact throughout its life cycle, thermal efficiency and insulation regulations that would be implemented to minimize power consumption, and how closely a material aligns with the Saudi Building Code – Sustainability Requirements. The framework should also include a classification of materials between traditional and sustainable categories, and guidance to use low emission local sources, recycled materials, and high-performance thermal insulation material. Environmental Performance Indicators (EPIs) in order to measure materials' sustainable performance in a project can also be integrated so that the projects have data-based solutions that will ensure the sustainability of the project as per Vision 2030 objectives. Having a reference in this manner also increases stakeholder awareness and standardizes environmental and sustainable construction practices, in Taif projects on the local level, local experiences demonstrate the long-term effect of this step, as it saves energy and natural resources in the process.

9.1.2 Opportunities and Challenges in Implementing Sustainable Building Materials in Taif:

These are the opportunities and challenges on how to implement the sustainable building materials in Taif. Insights on the integration of the insights in Implementation Stages and Building Materials sector into the theoretical framework of research on the importance of implementation within Taif including opportunities and challenges to sustainable building materials in Taif can be represented in the following matrices underlining the correlation between key influencing factors and their

corresponding strategic policies or interventions. The Table No. (5) presents a holistic framework outlining structural, cultural, and organizational challenges of sustainable construction in Taif, which identifies that, in order to work through them, they must be addressed through multi-stakeholder collaboration and integration of policies, design, training, and awareness in order to meet the sustainability targets for Vision 2030 aspirations set out to achieve locally in terms of Vision 2030 in the region.

9.1.3 Guideline for the Adoption of Sustainable Building Materials

An ideal model for the practical usage of sustainable building materials is the first step towards promoting sustainability in the construction industry. This kind of framework sets concrete, actionable standards for what type of material to use — as per how it influences the environment, thermal performance, and energy efficiency. Underpinning the guideline can be at least the following:

- **Life Cycle Assessment (LCA):** Assessing the environmental impact of materials all the way from sourcing, manufacture and use until disposal.
- **Thermal Efficiency Standards:** Establish a standard for insulation and energy performance to reduce operational energy use.
- **Regulatory Compliance:** Complying with the Saudi Building Code – Sustainability Requirements to ensure alignment with national sustainability objectives.

In addition, the framework should classify materials into traditional and sustainable groups, promoting the use of locally sourced, low-emission materials, recycled content, and advanced insulation technologies. The use of Environmental Performance Indicators (EPIs) provides project teams data to evaluate material sustainability, enabling informed decision-making and linking the products and processes with Vision 2030 objectives. Recent evidence from local initiatives conducted in Taif showed that guidelines of this nature raise awareness among stakeholders, promote standardized sustainable practices, and contribute to long-term resource and energy savings.

9.1.4 Opportunities and Challenges in Taif’s Sustainable Material Implementation:

This study draws on theoretical approaches as it is grounded in practical information received from the building materials sector, thereby mapping the opportunities and challenges of integrating sustainable construction practice in Taif. These are in Table (5) where the relationships of the major forces and strategic interventions are listed. The table reveals the major structural, cultural, and organizational constraints to sustainable construction in Taif that must be addressed. It underscores the importance of a coordinated group response from policymakers, designers, educators, and industry experts to address these issues. Key to success would be for sustainability to be incorporated within the design process, for technical training to be strengthened, for public and professional awareness of the subject to be raised, and for collaboration between sectors to be promoted. There are challenges to achieving sustainability in Taif’s construction industry, and one of them is its need to take a local, multi-dimensional response informed by the unique environmental and cultural background of the city, and be in support of Vision 2030 in general.

Table (5): Challenges Matrix for Sustainable Construction in Taif (Aligned with Vision 2030)

Challenge Area	Architectural / Environmental Implications	Policy / Strategic Response	Stakeholders
Hot and Dry Desert Climate	High temperatures, thermal expansion, material shrinkage, cracking, dust accumulation, reduced durability	Promote climate-responsive design: shading, high-performance insulation, natural ventilation	Architects, Engineers, Municipalities
High Initial Cost of Sustainable Materials	Greater upfront investment compared to conventional materials, delayed ROI	Implement financial incentives: subsidies, tax reductions, low-interest loans	Government, Economic Development Agencies, Developers
Limited Awareness and Technical Knowledge	Improper material selection and installation, suboptimal performance	Launch technical training, workshops, and certification programs	Contractors, Engineers, Developers, Training Institutes
Limited Local Material Availability & Supply Chain Gaps	Dependency on imports increases costs and carbon footprint, inconsistent material quality	Encourage local production, establish supply chains, and certify materials to recognized standards	Material Suppliers, Industry Associations, Local Manufacturers
Weak Regulations and Standards	Lack of enforcement and uniform criteria slows adoption of sustainable construction	Strengthen legislation, enforce SBC Sustainability Requirements, promote environmental certification systems	Government Regulators, Municipal Authorities
Shortage of Qualified Labor & Modern Technology Adoption	Specialized skills required for green construction, limited local experience	Develop capacity-building programs and provide access to advanced construction technologies	Contractors, Technical Institutes, Equipment Suppliers
Cultural Attitudes & Traditional Preferences	Preference for conventional aesthetics may resist sustainable design adoption	Promote awareness campaigns highlighting long-term benefits, market advantages, and social responsibility	Developers, Media, Clients, Industry Associations

The following strategic opportunities show on Table (6) which could help to uplift Taif's sustainable construction process. These resonate with national policies put into place at the country's level through the Vision 2030 framework, availability of locally sourced materials, increasing market demands and continuous technological improvements. And it's these components that are instrumental in promoting the environmental, economic and social aspects of the building process. They are the foundation for the sustainability standards being used and help establish Taif as a model of healthy resilient city development.

Table (6): Opportunity Matrix for Sustainable Construction in Taif (Aligned with Vision 2030)

Opportunity Area	Strategic Potential	Architectural / Environmental Impact	Implementation Leverage
Governmental Support & Vision 2030 Alignment	National policies encourage green construction	Facilitates regulatory adoption of sustainability standards across Taif	Apply SBC Sustainability Requirements as mandatory baseline
Long-Term Economic Efficiency	Reduced operational costs through lower energy & water consumption	Improved thermal comfort decreases HVAC loads and extends building lifespan	Integrate passive cooling + efficient water reuse systems
Local Material Availability	Abundant stone, clay, and natural fibers	Enables production of vernacular-inspired low-carbon materials	Establish local manufacturing units / workshops
Growing Market Demand	Increasing consumer and developer interest in eco-friendly buildings	Enhances real estate value and public perception	Promote certification labels (e.g., “Green-Ready Building”)
Technological Innovation	Adoption of smart shading, energy-efficient glazing, natural ventilation	Boosts building performance in hot-arid climates	Encourage hybrid systems integrating active + passive strategies
Emerging Sustainable Material Technologies	Low-carbon concrete, reflective coatings, green roofs, solar systems	Reduces heat gain and carbon footprint	Pilot projects and R&D partnerships in Taif
Economies of Scale Potential	Increasing demand will reduce sustainable material costs	Sustainable materials become cost-competitive	Aggregate purchasing programs among developers
Environmental & Social Benefits	Lower emissions, reduced heat and noise pollution	Enhances resident well-being and urban livability	Position Taif as “Healthy & Resilient City Model”

Conclusions:

A core conclusion is the main finding from the study over the overall questions and key investigations. Natural stone: the sustainable use of natural stone for Saudi architecture. The traditional stones [marble, granite, Hashmi stone, basalt, limestone] have played a leading role in shaping the character of the Saudi Arabian architectural project and in developing the concept of green building. Marble and granite add strength to style, basalt is used for thermal control and structural integrity, Hashmi stone is locally recognizable and weather-resistant, limestone strikes the right balance between aesthetic and environmental values. In cities such as Taif, having these local stones not only streamlines energy-saving transportation but also sustains the local economy and aligns with resource-efficient and life-cycle sustainability. Because they possess lower embodied energy and thermal mass, the buildings also can be designed with energy-efficient building envelopes that help to set up a facility in the hot arid climate of Saudi Arabia. Still, more effort has to be put into providing real sustainability and not without difficulties: the development of good quarrying techniques, proper waste management and recycling and reuse will all help to achieve it. These strategies, aligned with the goal of Saudi Vision 2030, are expected to boost environmental performance, keep a vibrant culture alive, and give a climate-responsive urban strategy based on local experience. How much can the implementation of building materials that are sustainable in Taif City benefit from the sustainability of the system? Environmental, economic and social components need to be integrated into sustainable building materials as building materials not only in terms of number of sustainable construction materials, the study suggests. Each dimension represents a characteristic that is related to (such as environmental, economic feasibility, community support, and sustainability) elements responsible for the choice and construction methods of sustainable materials. The data on the resources used as above, the

reduction of CO₂ emissions, recycling rates highlight the environmental factors, The social factors refer to user comfort and health & safety of users, and sustainability. We find that deeper social conditions of cultural and ethical relevance, as well as cost, appear in the last chapter, as necessary prerequisites for a socially sustainable built environment. Traditional materials of different quality and usage as compared with more modern types show that what's most viable in Taif can be judged by their practical qualities: traditional materials (stone, brick, lime plaster, etc.) provide superior climatic efficacy, lower embodied energy, and integration with cultural heritage or quality management and artisanal skills. They are instrumental in achieving the sustainability environmental and social wise. On the other hand, modern materials with good structural properties, such as concrete and steel, are more energy-consuming, more industry-dependent, less culture-adaptable and heavily dependent on industry. Hybrid design techniques, such as recycled façade systems, high performance glazing and design-for-disassembly techniques, and the application of both material methods can further increase performance both environmentally and thermally.

What are the most commonly used building materials today in construction works like Taif and how environmentally and climatically suitable are they?

Taif is constructed with reinforced concrete, concrete blocks, red clay blocks, natural stone, steel, insulating and glass panels, gypsum/plaster finishes, and wood (used only infrequently) in the survey. Based on the framework provided in this study, the environmental and climatic fit of these materials to local applications is discussed and shown in Table (7).

Table (7): The most commonly used building materials in current construction projects in Taif and their environmental and climatic suitability for use.

Building Material	Environmental Assessment	Climatic / Thermal Assessment	Recommendation
Reinforced Concrete	Low to medium sustainability due to high carbon emissions	Offers good thermal mass but requires additional insulation	Use with cement substitutes and ensure proper thermal insulation
Clay Brick / Masonry Blocks	Environmentally favorable when locally produced	Excellent thermal balance	Recommended for external walls and double-layer roofing
Natural Stone	Environmentally sound, especially when locally sourced	Exceptional durability and thermal mass	Ideal for sun-exposed façades and exterior cladding
Steel	Moderate to high energy consumption in production, fully recyclable	Poor thermal performance	Best used as structural framing with adequate thermal cladding
Glass / Insulated Panels	Moderate sustainability, energy-intensive manufacturing	Ineffective without shading	Use as double-glazed units with shading devices or louvers
Gypsum / Plaster Finishes	Moderate environmental impact	Neutral thermal properties	Suitable for interior finishes, consider natural alternatives where feasible
Wood (Limited Use)	Environmentally beneficial—renewable and recyclable	Provides good natural insulation	Recommended for interior finishes and decorative applications only

What criteria are adopted when selecting building materials, and do they consider the material's life cycle and environmental impact?

What rules are followed in selecting building materials and do they take into account the life cycle of the material and the environmental footprint? Key criteria for selection of building materials have been identified following a theoretical review of the relevant literature and case studies aligned with the context of this study. These standards stress a need to consider products at every

stage of their life cycle, with special attention to the extent to which they contribute to the environment. Table (8) provides a comparative assessment of conventional practices, lifecycle assessment-based sustainable approaches and proposed best practice for material selection in construction.

Table (8): Comparison of Conventional vs. Sustainable Material Selection Practices With Recommended Best Practice

Selection Criteria	Conventional Practice	Sustainable / LCA-Based Practice	Recommended Best Practice
Primary Decision Drivers	Based on initial cost, availability, and contractor preference	Focused on long-term durability, life cycle cost, and overall performance	Implement Life Cycle Costing (LCC) instead of relying solely on upfront pricing
Environmental Impact	Seldom measured or documented	Assessed using Life Cycle Assessment (LCA) tools (e.g., embodied carbon, pollution index)	Make LCA reporting mandatory for key materials prior to approval
Thermal / Energy Performance	Considered only when required by regulations	Integrated early in design to optimize building envelope and HVAC efficiency	Apply performance-based specifications aligned with thermal performance benchmarks
Durability & Maintenance	Often overlooked, future maintenance costs not prioritized	Materials chosen for extended lifespan and minimal upkeep	Require maintenance cost projections over a 20–30-year period before selection
Recyclability / End-of-Life	Typically disposed in landfills or reused without control	Preference for recyclable or reusable components	Establish material take-back programs and set targets for recycled content
Compliance & Certification	Limited to structural safety and fire regulations	Includes adherence to green standards (e.g., LEED, SBC Sustainability, ISO 14040)	Develop a local certification system for “Approved Sustainable Materials”
Supply Chain Considerations	Selection based on lowest bid	Emphasis on local sourcing and low-emission suppliers	Introduce a supplier sustainability rating system
Decision-Making Stakeholders	Decisions led by contractors or cost engineers	Collaborative input from architects, sustainability experts, and MEP engineers	Require multi-disciplinary review panels for material approval

Environmental and Economic Benefits of Adopting Sustainable Alternatives Compared to Conventional Materials

Benefits of using sustainable alternatives to other materials compared to conventional materials in environmental and economic terms. The results of the research confirm the fact that sustainable building material use is not merely a matter of policy choice but a strategic necessity of constructing an efficient, up-to-date building system in Taif, not a preference of Taif City environment. Well thought-out material selection plays a crucial role in the following:

- Reducing energy consumption.
- Cutting down carbon emissions.
- Improving indoor thermal comfort.

These advantages are especially important given the hot-arid climate in Taif. Through the implementation of such sustainable materials in local construction, we not only improve sustainability, but we also contribute significantly to building socio-cultural and economic resilience, thus promoting an eco-integrated city. The use of these materials is not, however, widely accepted in practice and confronts some limitations.

- High initial costs.
- Limited technical know-how in the industry.
- Lack of common guidelines for evaluating environmental performance.

Recommendations:

To enhance the transformation of Taif to sustainable construction, the following ways are suggested:

- Formulate Locally-based Recommendations for Sustainable Material Selection
- Setting transparent Life Cycle Assessment (LCA) and climate-sensitive considerations.
- Encourage LCC in Procurement Processes
- Transition from upfront cost-based selection to value and performance in the long term.
- Development and Training of Skills

Train architects, engineers, and builders in sustainable design and materials.

- Bring in Incentives for Sustainable Practices in place

Promote projects that focus on sustainable materials and methods for which financial or regulatory incentives may be used to award financial, social, or legal benefits.

- Develop a Local Certificates System.
- Establish a scheme for the certification of “Approved Sustainable Materials” with domestic and international standards as per the new framework.
- Promote Hybrid Design Approaches.
- Facilitate the convergence of traditional and modern materials for better environmental and cultural achievement.
- Promote Collaboration between Stakeholders.
- Require multi-disciplinary review panels that include sustainability experts, architects, and engineers to decide which materials to approve.

Policy Framework for Enabling Sustainable Construction in Taif:

Table (9) presents a strategic matrix of recommended policies designed to accelerate the adoption of sustainable construction practices in Taif. Each policy area outlines targeted actions, responsible stakeholders, policy instruments, and anticipated impacts.

Table No. (9): Shows the matrix of recommended policies to enable sustainable construction in Taif.

Policy Area	Proposed Action	Responsible Stakeholders	Policy Instrument	Expected Impact
Regulation & Compliance	Integrate sustainability criteria into building permit approvals, aligned with the Saudi Building Code – Sustainability Requirements	Municipalities & Regulatory Authorities	Mandatory Guidelines / Permit Conditions	Ensures minimum environmental performance standards in all new construction projects
Economic Incentives	Offer subsidies, fee reductions, or tax benefits for projects using certified sustainable materials	Municipalities & Economic Development Agencies	Financial Incentives	Stimulates private sector investment and lowers financial barriers
Capacity Building	Launch professional training programs on sustainable material selection and life cycle assessment	Engineering Syndicates, Contractors' Unions & Training Centers	Technical Certification & Continuous Education	Improves technical expertise and feasibility of sustainable adoption
Research & Local Innovation	Support R&D initiatives for locally sourced or recycled materials suited to Taif's climate	Universities, Research Institutes & Private Sector	Research Grants & Public-Private Partnerships	Expands availability of affordable, climate-adapted building materials
Performance Monitoring	Develop a standardized framework for environmental assessment of construction materials	Government Agencies & Standards Organizations	Rating / Labeling System	Enables transparent evaluation and benchmarking across construction projects
Public Engagement	Conduct awareness campaigns on the health and economic benefits of sustainable buildings	Media, NGOs & Developers	Communication Campaigns & Public Outreach	Builds public demand and shifts consumer preferences toward sustainable solutions

Adopting Sustainable Alternatives to Traditional Materials

Table (10) outlines the anticipated environmental and economic benefits of using sustainable building materials compared to conventional options. The comparison highlights how sustainable alternatives contribute to improved performance across multiple dimensions, reinforcing their strategic value in future-oriented construction practices.

Benefit Category	Conventional Materials	Sustainable Materials	Overall Advantage
Carbon Emissions	High embodied carbon due to energy-intensive manufacturing	Reduced embodied carbon through low-impact production and recycled content	Environmental
Operational Energy Use	Higher energy demand due to poor thermal performance	Lower energy consumption through enhanced insulation and compatibility with passive design	Environmental + Economic
Resource Consumption	Sourced from non-renewable or imported materials	Locally sourced or derived from renewable/recycled resources	Environmental + Local Economy
Waste Generation	Generates substantial construction and demolition waste	Engineered for recyclability or reuse, reducing landfill impact	Environmental
Maintenance Costs	Requires frequent repairs or replacements over time	Extended lifespan with minimal maintenance needs	Economic
Lifecycle Cost	Lower initial cost but higher long-term operational expenses	Higher upfront investment offset by long-term savings in energy and maintenance	Economic
Indoor Comfort & Health	Limited impact on indoor air quality	Use of low-VOC and breathable materials enhances occupant well-being	Environmental + Social
Market Value	Standard performance with limited differentiation	Increased asset value and market appeal due to sustainability credentials	Economic

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