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The Concept of Hybrid Construction Technology : State of the Art and Future Prospects

ABDERRAHIM BELABID
HASSAN ELMINOR
HAJAR AKHZOUZ

*Author affiliations can be found in the back matter of this article

ABSTRACT

Reinforced concrete is currently the most used material in construction, posing a significant environmental concern as GHG emissions and problems related to durability and recycling. Therefore, governments have started to encourage the usage of traditional buildings which offer interesting advantages. However, due to poor mechanical and technical performance, as well as a lack of regulations and know-how their usage is limited. The research work carried out on eco-materials has improved their mechanical performance as well as their water resistance. Despite the importance of this study, it is clear that the proposed ecological models cannot yet compete with modern constructions in terms of mechanical performance, rate of construction and economic efficiency. To combine the advantages of these two construction methods: the modern one with its better mechanical performance and economic efficiency, and the traditional one with its insulating power, ecological and bioclimatic aspects, it is proposed to investigate the aspects of the concept "hybrid building technology" which is less polluting, competitive and capable of reducing the impact of the construction on the environment. This article's goal is to define the concept of hybrid construction technology via an analysis of two modern construction trends: sustainable construction techniques and reinforced concrete buildings. Furthermore, the article discusses several hybridization techniques in the building sector and offers some examples of hybrid construction technology models. Future prospects and recommendations for developing a hybrid building research field are also provided. As a conclusion, this third way in construction will allow for good outcomes in the reconciliation of construction, economics, and man with the environment.

CORRESPONDING AUTHOR:

Abderrahim Belabid

Department of Mechanics, Materials and Civil Engineering, National School of Applied Sciences, Ibn Zohr University, Agadir 80000, MA

abderrahim.belabid@edu.uiz.ac.ma

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1. INTRODUCTION

Since its discovery in the 19th century (Radić, 2008) and until today, reinforced concrete has been the leading construction material due to its qualities; it is strong durable building material that may be employed in any architectural form (Mosley, 1987) with affordable and reasonable cost.

Thus, humanity has abandoned traditional building materials (stone, earth, straw, lime, wood and hemp, etc.) to benefit from the many advantages of reinforced concrete. Nevertheless, this conversion comes at a cost; the environmental consequences are very serious, cement is the third greatest producer of CO_2 after the automobiles and coal-fired power stations (Ali, 2011), and the same is true for steel (Di Schino, 2019), despite significant progress in recycling.

The incorporation of steel in concrete to compensate for its poor tensile strength reduces its lifespan in a significant way (Bertolini, 2008), it's not what we used to imagine; it's just a hundred years (Bowyer, 2013; Demis, 2019). After that, everything must be maintained, if not demolished. The demolition of buildings represents more than 56% of the waste to be recycled during the life of a building (Champiré, 2017). Future generations cannot bear such costs. It is time to review the way we build and live, even if only partially, in order to limit the impact of modern construction on the environment and increase the lifespan of buildings. The architectural heritage of our ancestors provides us hope that we might view things differently; ecological and sustainable construction.

The vision with which we must observe things must be of variable geometry; one eye towards the past to learn how to live in cohabitation with the environment in a sustainable way and another towards the present and future to put at our disposal the most reliable instruments and processes to solve the construction equation; a construction that is ecological, sustainable, resistant, economic and easy to carry out.

The aim of this paper is to define the concept of hybrid construction, a term that architects and building professionals currently use to characterize different mixes of architecture, materials and processes. Hybrid construction is a global approach, a technology that goes beyond simple mixing to be at the heart of solving the problems linked to the question of the construction in our century; an approach aimed at putting innovative methods in materials and processes at our disposal capable of cohabiting the traditional with the modern, the housing with the environment, the materials with the durability and the resistance with the economy.

The approach used in this paper is a qualitative one based firstly on the study of sustainable building materials and techniques, the scientific research carried out to improve their technical and economic performance, as well as the analysis of constraints and perspectives for their successful implementation in our century. Then, in order to illustrate the need to view the construction issue differently, we showed the limits and perspectives of the use of reinforced concrete as a fundamental material in construction. Next, we focused on the use of the term hybrid in the sector of building and public works. Finally, we conclude with the possibility of combining different materials, processes and methods through hybrid construction technology, which is becoming increasingly significant in the modern construction system.

2. SUSTAINABLE CONSTRUCTION IN THE 21ST CENTURY

2.1 SUSTAINABLE CONSTRUCTION MATERIALS

Together with climate change and the environmental impact of construction, it is critical to adopt sustainable and ecological construction techniques, among the alternatives that has arisen is the use of traditional construction materials. These geosourced (earth, stone and lime) and biosourced (wood, natural fibers) materials have excellent environmental qualities (ecological, good thermal insulation, good hygrometric regulation, fire resistance, 100% recyclable and competitive) (Esin, 2008; Oikonomou, 2011; Philokyprou, 2015; Leo Samuel, 2017). They do, however, have compared with engineered concrete; poor mechanical and physical properties, low mechanical strength, poor water resistance such as raw earth, poor resistance to earthquakes (Vargas, 1986), biological attacks for wood (Dinwoodie, 2000), need for periodic maintenance and rapid degradation over time (Miccoli, 2014). Furthermore, the dominance of standardized reinforced concrete construction methods has resulted in the loss of ancestral know-how, coupled with the absence of rules, standards calculation and cultural underestimation, making it difficult to enhance sustainable materials (Djokoto, 2014; AlSanad, 2015; Davies, 2017; Pham, 2020; Omopariola, 2022).

A significant amount of research has been conducted in order to improve the mechanical strength and water resistance of raw earth: some on compaction (Bruno, 2015), others on binders such as air, hydraulic, pozzolanic, organic with activating agent and synthetic (Ouedraogo, 2019) or the addition of fibers such as mineral, animal or plant (Phung, 2018). The addition of binders, especially hydraulic binders, systematically improves water resistance. Although, the improvements in strength vary depending on the nature of the soil, the binder content and the application conditions. The best performances were observed for soils with a hydraulic cement concentration of 20% (Gavigan, 2012). Historically, lime has been the most widely used binder, however, while it has much better ecological performance than cement, the speed of setting remains its main drawback (Lanas, 2004).

The majority of the work on raw earth stabilization using different types of stabilizers (Cement, Lime, Mineral binders, Organic binders) has been synthesized and analyzed by Ouedraogo (2019). Most cement and lime stabilization studies revealed modest improvement in compressive strength when compared to the ratio of added binders. There are concerns regarding this model's environmental advantages due to its large carbon footprint and high rate of incorporation. Despite the ecological advantages of alternative minerals from by-product recycling, their relatively high incorporation rate and slow mechanism of action pose significant obstacles to their exploitation. On the contrary, this model of stabilizers systematically improves the water resistance (main factor to evaluate the durability of the stabilized soil). Some organic binders stabilize the clayey raw earth and improve the compressive strength even without pre-activation (Ovalbumin). The inclusion of binders often reduces the hygroscopic capacities in terms of performance. The comparisons conducted validate the previous connections between the density of the material and the thermal conductivity, indicating that the addition of stabilizers does not necessarily affect this feature.

Inexpensive, durable and easy to work with, stones are also used for masonry. Their mechanical and physical characteristics are very variable depending on the type, origin and formation mechanism (Kaushik, 2007). The adhesion between the blocks is achieved using traditional mortar based on earth or lime; it also allows filling the void, to seal and to limit the punching. Due to its tensile stress and seismic vulnerability (Abrams, 2001; Lagomarsino, 2006; Pereira, 2021), more studies and reinforcements are required before it can be used in high seismicity areas. Historically, masonry buildings have been built in such a way that the masonry works in compression (bearing walls, arches and vaults).

Wood is the most widely used material after earth and stone in traditional construction. It is the material of choice for the construction of individual houses in some countries such as the USA. The use of wood reduces the environmental impact. It is a renewable material that naturally sequesters CO_2 by means of 45g per 100g of dry matter on average (Ponce-Hernandez, 2004), also it requires less energy and causes less water and air pollution. Compared to modern building materials, wood has a low global warming potential, it emits six times less greenhouse gases than concrete and four times less than steel during the life cycle of the material (Cecobois, 2015).

2.2 SUSTAINABLE CONSTRUCTION METHODS

The oldest known earthen constructions date back to around 10,000 years B.C. (Jaquin, 2012) and since then earth has become the most widely used building material in regions with low forest condensation (Anger R, 2009). Different techniques have been used to build using earth, sometimes mixed with other ecological materials such as fibers, stone for foundations, wood as a supporting framework or with manufactured materials such as lime or cement binders. For the most used techniques we find the rammed earth, the adobe ((Mud brick), the cob building, the torchis (wattle and daub) and recently the compressed earth blocks (Wright, 2005; Rodríguez-Navarro, 2012; Fodde, 2009; Carmen, 2006; Pacheco-Torgal, 2012; Revuelta-Acosta, 2010; Radivojević, 2017).

Rammed earth is a concrete of raw earth compacted by combining variable quantities of clays, sands, gravels and small pebbles. To protect the materials from humidity, they are placed in a formwork over a base, which is usually made of stone. The ancient 'rammed earth' building technique has been used in Neolithic architecture sites and modern buildings alike (Niroumand, 2012). Adobe is one of the oldest and most widespread forms of construction, it is a building material made of soil, water and thatch (Illampas, 2009). The soil used must contain a certain proportion of clay and sand. It is a brick shaped by hand and in a wooden mold in a plastic state and dried in the open air to build traditional masonry walls. Adobes were also used by some civilizations such as the Nubians for the construction of roofing elements in the form of vaults (Monnier, 2015). The cob is a traditional technique of construction in earth used since thousands of year; it consists in the construction of load-bearing walls generally without formwork with a mixture of earth, water and plant fibers implemented by successive piling of the balls in earth in the plastic state. The vertical surfaces of the walls are erected by cutting after a short time of drying, while the material is not too hard (Gunawardena, 2008). The technique of CEB (Compressed Earth Blocks) is a recently developed technique, around the 50s we started to build with this technology. Numerous research works have been elaborated in order to define the subject. The CEB is obtained by static compaction of a quantity of earth in a mold of given dimensions. CEB can be stabilized with lime, cement and bitumen. CEB is installed with the aim of using local materials (P'Kla, 2002). The performance depends largely on the nature of the soil used, the conditions of implementation and the stabilization materials.

The torshis (wattle and daub) is a mix of two building materials timber and earth. It is defined as a filling complex composed of a mixture of building earth, plant fibers and water fixed on wood supports. The quantity of plant fibers mixed is extremely variable from one cob to another but this content is homogeneous on a panel or an inter-column space. This proportion is determined according to the specific objectives of the work to be done (ARESO, 2018). The wattle and daub house is always built on a masonry wall to protect the wood/earth structure from moisture. The cob has no load-bearing role; it simply fills the space between the wood frame elements and provides thermal and acoustic insulation (Houben and Guillaud, 1989). In the north of France, a mixture of clay, straw and water is used for the daube, the construction method depends on the nature of the wood frame used (Parc, 1988). The roof is supported by the wooden frame by horizontal lathing. The wooden frame varies from region to region depending on the type of wood used, the type of assembly and the spacing between the elements (Peinetti, 2016).

Stones have been used to construct buildings since 7000 BC (Christou, 2016) and to build temples and monuments for over 3500 years in Greece and India (Raju, 2021). Walls for elevation elements, arches, vaults, and domes for floors and slabs were constructed from stones quarried in the immediate vicinity of the building site (Cassar, 2014). The masonry walls are made of stone and mortar. The stones are assembled bed by bed, with the two facings of a wall regularly connected by breezeblock headers, long stones running through the wall from side to side (Binda, 1999). Mortar fills the joints between the stone blocks, provides adhesion and mechanical connection between the blocks. Mortar is a mixture of water, aggregates (usually sand) and a binder. Its role is to fill the void between the joints and to provide a binding between adjacent blocks to stabilize the masonry. The binder can be clay or lime (air binder). Currently, the technique of Confined Stone Masonry is increasingly used for the realization of ecological constructions based on stone walls; it consists of filling steel cages previously made by stones and then inserting the carpentry, plastering the wall and installing timber roofs (International, 2022). The walls are sometimes covered with a plaster, its role is to uniform and protect the surface of the masonry. Plasters are traditionally made from sufficiently clayey earth mixed with straw or from a mixture of lime and sand. These traditional plasters are characterized by their hygroscopic aspect compared to modern plasters based on portland cement (Ranesi, 2021).

The system of construction in arches, vaults and domes is a thousand-year-old technology used since the 3rd millennium BC in the countries of the Middle East and in Egypt, then the Sassanid, Romans, Byzantines and Muslims before being introduced in Europe (Gaetani, 2016). This technology can be adapted to all construction programs regardless of the span. The construction materials of arches, vaults and domes are diverse and depend on several parameters; the availability of materials, the geometry of the site, the construction method, the loads, and the environment, we can mention masonry, stone, wood, steel and concrete constructions. The design of the arches aims at searching a geometry for which the material works mainly only in compression by limiting the shearing forces and the bending moments which must be null (the funicular polygon) (Dahmen, 2012).

Timber constructions have been widely used all around the world, especially in countries with high forest density. Different wood construction techniques have been developed throughout human history. Hut or mocambo (hut) is a rudimentary shelter made with the base of a frame of bamboo thatch or wood log filled by bamboo, bushes, straw or by a combination of these materials that also serve as a roof for the structure. The first structures are discovered in Asia, Africa and America (De Araujo, 2016). Log home is a traditional technique used in regions of high forest density, it consists in making vertical walls (load-bearing, separating and insulating) in solid wood by stacking horizontally the pieces of wood (logs, planks). The pieces fit perfectly on each other to ensure water and air tightness. The pieces are crossed at the corner or assembled in dovetail. A lining can be associated in order to reinforce the waterproofness of the walls. The roofs are realized according to the traditional techniques of the realization of the wooden frames.

Timber framing allows for the construction of strong buildings made from self-supporting wooden structures fixed with connections between the elements. Traditionally the timbers were joined by hand-made "mortise and tenon" joints. Lightweight framing techniques (Martins, 2014) have been used in the United States since the 19th and early 20th centuries: Balloon framing is the construction of a full-height wood wall frame for a two-story building. Since the middle of the 20th century, platform framing has dominated the timber construction market, with each floor built on top of the other using short framing (Secu, 2015). Modern timber construction techniques have evolved from the old systems, taking advantage of the advent of easier joints (pins and bolts) that replaced traditional timber frame joints (mortise and tenon) and wood panels (plywood) that replaced board bracing and hoarding (Paradis, 2004). The most widely used contemporary techniques are paneled timber or cast laminated panel constructions (load-bearing walls in the form of panels) and post-and-beam structures (posts and beams with large spans of 3 to 6 m have large, relatively stable cross-sections with no infill forming the framework of the structure) (Wacker, 2010).

2.3 CHALLENGES AND RECOMMENDATIONS FOR SUSTAINABLE CONSTRUCTION DEVELOPMENT

Faced with environmental issues related to pollution and economic issues related to the escalation of prices of building materials, it is very useful to promote traditional construction through the implementation of commercial models with better economic efficiency and mechanical performance without touching their ecological and bioclimatic aspects. This requires a perfect mastery of materials and techniques and a critical analysis of the research work done in the field**.**

From a technical point of view, the majority of the research works that have been carried out on the raw earth; adobe, cob, compressed earth brick and torchis have focused on the improvement of the mechanical characteristics and the water resistance of the earth through binders or fibers. The studies must be continued in order to improve the seismic behavior of traditional buildings and to implement adapting anti-seismic standards. In this objective, it is very useful to deepen the studies already started on the antiseismic reinforcement of traditional structures by composite materials (Corradi, 2015). Also thinking about recycling plastic waste and tires in improving the ductility and energy dissipation power of traditional materials; a technique already tested on concrete and has demonstrated its usefulness in improving the anti-seismic behavior of materials (Kara, 2021).

The economic profitability of traditional buildings also depends on the used construction method; as a result, adopting modern technologies will improve their competitiveness. If the stone masonry walls continue to be built using more efficient construction processes such as confined stone walls. Arch, vault and cupola construction elements have been abandoned because of the difficulties of implementation. It is time to think about applying modern construction processes to traditional building projects to take advantage of the economic, technical and ecological benefits of modern technology, especially prefabrication (Tam, 2007). Then the prefabrication of the vault and cupola elements can be a promising alternative.

Lime presents a better balance between mechanical and ecological performances as lime allows recovering a significant percentage of CO_2 emitted during its manufacture by calcination of calcium hydroxide and requires less energy for its production. But it has two major drawbacks; low setting speed and swelling (Chabannes, 2018). Carbon cure or sequestration of carbon dioxide in concrete, a technology widely tested on hydraulic binders (Ravikumar, 2021) proves to be more suitable for its application on lime concrete treatment to accelerate the setting at the same time participate in the fight against climate change.

If wood remains the most preferred ecological material with better ecological and mechanical advantages, the promotion of wood construction depends on other considerations namely the limit in quantity available for construction which has caused a surge in prices lately. The solution lies in the promotion of afforestation.

It is well noted that the recommendations proposed in this paragraph are based on the principle of mixing and homogenization to improve the technical and economic aspects of sustainable construction materials and processes. Hence the need to study and analyze in depth these techniques of hybridization emerging for years in order to inventory all the possible paths able to make the ecological construction a competitive alternative to reinforced concrete.

3. REINFORCED CONCRETE: LIMITATIONS AND FUTURE PROSPECT

3.1 CONCRETE AND STEEL: A POLLUTING INDUSTRY

Reinforced concrete is a construction material that combines the mechanical properties of concrete with those of steel. It combines the compressive strength of concrete with the tensile strength of steel. Embedding steel in concrete protects it against corrosion due to concrete PH value, generally varies from 12.5 to 13.5 (Deschner, 2012). Concrete is an artificial rock obtained by hardening a mixture of aggregates, hydraulic binders and water. Hydraulic binders are standardized industrial products, so their performance corresponds to specific requirements. The properties of concrete also depend on the aggregates (gravel and sand): inert materials added to the concrete to reduce the cost of production and to reduce shrinkage and cracking.

Cement is a fine powder obtained by firing a mineral mixture (usually limestone plus clay) at high temperature (1510°), which is then ground to obtain a mineral powder consisting essentially of lime silicates and aluminates. This powder can hydrate with water to give a paste capable of setting and hardening progressively. When the clinker is ground, a small amount of calcium sulfate is added to the clinker to regulate the setting (Rahman, 2015).

Secondary additives are added to cement in the form of mineral additives such as blast furnace slag, fly ash, silica fume, natural and artificial pozzolans, limestone fillers, marl and tuff. These additions of low commercial value reduce the energy content of the concrete (lower cost, less shrinkage and less cracking). They are thus valorized and also participate in the fight against pollution by partially replacing the clinker used in cements. They are used to correct the granular skeleton and for their pozzolanic and hydraulic power (Bye, 1999).

Cement is a basic material in construction worldwide. It is produced and consumed in large quantities (4.6 billion tons in 2015) (Planetoscope, 2022). This process demands a significant amount of energy (1t requires 4 million Btu) (Arachchige, 2019) usually fossil fuels mixed with high calorific waste (tires – paper – packaging – plastic). Despite the advantage of using waste such as getting rid of waste and conserving fossil energy for future generations, the cement industry remains a very polluting industry: On the one hand there is air pollution caused by the release of CO_2 (40% is due to combustion for heating, 50% to lime decarbonisation and the rest is due to transport and handling activities): about 1000kg for 1 ton of clinker (Rehan, 2005). On the other hand there is solid waste such as rock cuttings and kiln dust. Emissions from burned waste can be very harmful to the environment (volatile organic compounds, heavy metals lead, cadmium and mercury) (Arachchige, 2019).

Pollution is also produced by the metallurgical industry in the manufacturing of structural steel from iron: Pollution from the blast furnaces represents the majority, so during the casting operation, carbon compounds are formed such as CO_2, iron and magnesium oxides. In the same way, during the oxygen blowing period, polluting particles appear such as CO_2, heavy metals and fluorides (Doushanov, 2015). Although the production of steel from scrap generates less pollution, the steel industry remains one of the most polluting in the world by what it produces 5 to 7% of global CO_2 emissions (Lesechos, 2022).

3.2 REINFORCED CONCRETE, A LESS SUSTAINABLE MATERIAL

Concrete alone is an extremely durable material, as seen by the famous Pantheon in Rome and the Colosseum (Wayman, 2011) both of which built over 2000 years ago. This is not the case for reinforced concrete as the steel corrodes over the years, as embedding steel in concrete does not guarantee steel's eternal protection. Common hardened concrete has a porosity of 15%, high performance concrete 10 to 12% and very high performance concrete 7 to 9% (Ollivier & Torrenti, 2008). Over time, in the presence of the partially filled porosity, the CO_2 naturally present in the air diffuses into the gas phase of the concrete to dissolve in the wet pore solution to form carbonate ions. The Ca^{2+} ions of the calcium hydroxide $Ca(OH)_2$ formed in the hardening phase of the concrete react with the carbonate ions CO_2^{3-} to form $CaCO_3$ (Šavija, 2016), thus the alkaline reserve of the concrete decreases (PH decreases from 11–13 to 8–9) which initiates the corrosion of the reinforcement in the presence of moisture. This corrosion is accompanied by the swelling and bursting of the concrete, so the reinforcement will be exposed to the open air (Concrete Cancer) (Broomfield, 2003).

Although, carbonation is the main cause of degradation of reinforced concrete structures, other factors can influence the durability of concrete, namely (Ollivier & Vichot, 2008):

- Attack by aggressive waters that cause the reaction between gypsum sulfate and tri-calcite aluminate to form ettringite and Candlot salt, a highly expansive salt that results in a decalcified and erosion-sensitive cement paste.
- Actions of seawater that cause the formation of Candlot and the degradation of the binding properties of C-S-H by substituting CaO with MgO.
- Alkali-Granulate reactions where certain siliceous aggregates (Opal, Chalcedony…) or dolomitic aggregates ($CaCO_3$, $MgCO_3$) react with the cement alkalis (K_2O and Na_2O) to form very swelling gels.
- The penetration of chloride ions due to pollution triggers the process of steel corrosion.
- Mechanical actions and the freeze/thaw cycle also contribute to the degradation of concrete structures.

This spectacular invention of the 19th century, the reinforcement of concrete with steel reinforcements, later proved its limits. Concrete constructions do not last as long as previously thought, only about a hundred years if the construction is carried out according to the rules of art. Thus the relatively short life cycle analysis of reinforced concrete shows a very high environmental impact from the production of the building materials to the waste management of the demolition. GHG emissions, especially CO_2 (the important part related to the manufacture of steel and cement), the consumption of natural sand reserves, and demolition waste are the main sources of pollution related to reinforced concrete and modern urbanization (Mehra, 2022).

3.3 HOW TO MAKE REINFORCED CONCRETE LESS POLLUTING AND SUSTAINABLE

To reduce the impact of reinforced concrete on the environment, it is necessary to increase the life span of the structures in question by:

- Reducing the porosity of concrete to limit the diffusion of aggressive agents in the concrete (Gonen, 2007). This parameter is often neglected during the design and construction phase to the detriment of the consistency and strength of the concrete.
- The development of alternatives to steel (Younis, 2020) (stainless steel, aluminum bronze, carbon fiber and glass bars). However, the competitive cost of steel compared to other materials limits their use.
- Consider cathodic protection of steels for large projects and other technics for corrosion control of steel-reinforced concrete (Chung, 2000).

Then, it is necessary to improve the environmental optimization of steel (Sutherland, 2007) and cement production through the recycling of scrap metal for steel production and the optimization of clinker production technologies for cement by substituting fossil fuels with industrial waste and biomass (Benhelal, 2013). The recycling of demolition concrete (Bonoli, 2021), materials and by-products of industrial processes (Meyer, 2009) can partly replace natural aggregates, whose reserves are running out.

Finally, alternatives to reinforced concrete should be considered, namely the use of traditional construction based on bio- and geo-sourced materials. These materials of natural origin, recyclable and abundant with a negligible impact on the environment have limitations (water resistance, poor mechanical performance, biological attacks, and need for periodic maintenance). With these advantages and disadvantages, traditional construction was always used by all civilizations before the industrial revolution; it was their habitat, but also a purely natural, bioclimatic and ecological habitat. Nevertheless, the success of one model or another also depends on other socio-economic and cultural considerations often overlooked by researchers, of which the traditional is not a good example. Faced with this fact, it is necessary to consider developing alternative construction models that will allow the advantages of each recognized construction methods to coexist: the modern one by its better mechanical performance and its economic efficiency and the traditional one by its insulating power and its ecological and bioclimatic aspect, it is the hybrid construction. This variable geometry vision combines traditional materials with modern materials and processes in order to extend the life span of buildings, improving their mechanical performance and reducing their carbon footprint as much as possible.

4. HYBRID CONSTRUCTION CONCEPT

4.1 HYBRID: ETYMOLOGY AND USE IN CONSTRUCTION

According to the French Academy, the term "hybrid" is derived from the Latin term hybrida, similar to the Greek term hybris, "excess", from ibrida, "bastard". Which is composed of elements of different origins or natures. The centaur, the mermaid and the satyr are hybrid imaginary beings often with a pejorative nuance. Hybrid architecture, belonging to different styles. A hybrid work, participating in several genres. A political regime, a hybrid constitution, of a composite and ill-defined nature (Académie, 2022).

The term hybrid in the field of building and civil engineering is used to refer to architecture, a construction processes or a material composed of elements of different origins. In the negative sense of the term it is used by architects to characterize the anarchic mixing of architectural styles. This mix can be about service: a modern architectural style that has developed in the 21st century to meet the needs of modern cities where the building can be multi-purpose; it can serve to accomplish several functions at the same time. "Building functions are mixed, disparate uses combined; structures collected here are "Hybrid Buildings" with respect to use" (Steven Holl, 1985) More ecological and sustainable hybrid building forms have emerged in China in the 21st century to mark the largest wave of rural exodus and urbanization ever seen in human history. "In the 21st century, what is the potential of Hybrid Buildings? Certainly, the hyper-urbanization of cities in China, such as Shenzhen, Beijing and Chengdu, can act as catalyst incubators for new and experimental architectural types" (Holl, 2014). This new approach to hybrid construction makes it possible to condense all services (housing, work, leisure and services) into a single structure composed of buildings linked by pedestrian bridges, which will limit the use of transport. The old vision of linear and planimetric urbanism is outdated to the detriment of a new concept with a diagonal and vertical character which presents a great ecological potential through the development of the concept of the green building based on the use of green energy (solar/geothermal), the recycling of water and the establishment of a microclimatic vegetation (Steven Holl, 2014). This concept goes beyond the simple mixing of different activities in a single building (mixed-use) without connection, it is a new living environment where the private and the public alternate permanently in the same place which functions full time, this concentration of interest is based for its survival on the consensus and not the traditional.

An advanced concept resulting from this evolution of hybrid technology has been developed by the French group Bouygues BHEP and is called Hybrid Building with Positive Economy based on six sources of ecological value creation ; optimization of uses thanks to the connected building, productivity gains through improved well-being, convertibility and reversibility of buildings, valorization of local physical flows, reuse or recycling of materials, valorization of positive externalities) (Bouygues DD, 2019). As example, the Sways building (Figure 1) achieved on November 25, 2021 were the first building project designed on the HBPE model.

Some architects use the term hybrid to criticize the anarchic mixing of traditional architecture or materials with modern architecture and artificial materials often practiced in the outskirts of towns and cities in an illegal and non-standard way. "The adoption of new imported construction processes, standardized and disassociated from the environment in the service of a decontextualized modernity, has given rise to new forms of habitat, "hybrid", at odds with the environment, but also with the culture and identity of the inhabitants" (Kharmich, 2019). As an example, the Figure 2 shows a concrete case of this practice commonly used in the old Moroccan Medina, which consists in incorporating reinforced concrete elements into the old structures based on raw earth.

Beyond the architectural concept of the term, the term hybrid is also used in the field of Civil Engineering to describe the mixing of different materials and processes with the aim of improving certain aspects of the building.

Figure 1 Sways building, the first building project designed on the BHEP model by Bouygues (Bouygues site web).

Figure 2 Anarchic hybridization of different materials, old medina Ouarzazate, 2019 (Authors).

Indeed, the combination of materials (wood/earth – wood/steel – wood/concrete – reinforced concrete/steel) allows to benefit from their advantages and to overcome their limits. This multi-aspect technique makes it possible to construct buildings with an efficient structure and optimal service while minimizing investments and the impact on the environment "It is this need for hybridization of the wood material that the architect can seize upon, to make this constraint strength of the project" (Arguelle, 2018). The Figure 3 shows a practical example of a hybrid structure built by mixing steel and wood. It combines the highest mechanical characteristics of steel with the hygroscopic properties and beauty of wood.

The mixing of different construction methods is common on civil engineering sites in order to increase efficiency and speed up the production rate; the most

Figure 3 Wood-steel hybrid structure (Tonelli, 2022).

commonly used hybridization is the integration of precast reinforced concrete elements with in-situ elements, the objective being to combine the production rate, finish and better performance of precast concrete with the flexible and economic aspect of in-situ concrete.

The term 'hybrid project' is also used in the field of building rehabilitation to describe the integration of new elements and structures with old elements in order to meet new service requirements and to give the building the best functionality "'Hybrid projects' is a phrase, used for the benefit of this research, to define a type of adaptation project where new elements or buildings are combined with existing buildings to completely modify it in order to provide better functionality and meet increased spatial requirements" (Adeyeye, 2010).

Thus, the term hybrid is used to describe the mixing of elements of different character in a single structure; it can concern its architectural or structural aspect, or even the construction process or the renovation and rehabilitation technique. This hybridization aims at mixing objects with different characteristics in order to obtain the best possible performance. A perfect building is a building that has the best architectural design (ideal service and perfect integration with its environment) and a resistant structure that minimizes costs and impact on the environment; this is the trend of the 21st century.

4.2 HYBRID CONSTRUCTION TECHNOLOGY; TOWARDS A GLOBAL APPROACH

Mixing materials to improve certain aspects of construction is a long-standing tradition that extends back to the beginning of human civilization. The application of this approach became very common with the industrial revolution and scientific development; the mixing that marked in a very significant way the history of construction is the mixing of concrete with steel reinforcement (Joseph Monier (1823–1906) and Francois Coignet (1841–1888)) (Lafarge, 2022), reinforced concrete became the most used material on earth after water for construction so each person consumes an average of three tons of concrete every year (Gagg, 2014). A century later, this ideal mix is beginning to show its limits in terms of its heavy ecological balance, but also in terms of the life span of the building. In the search for more ecological and sustainable alternatives, many paths have been taken: The return to traditional construction and materials with partial hybridization (stabilization of materials with artificial binders and integration of modern construction processes), also the development of alternatives to steel such as glass and carbon fiber even less competitive; cost and rigidity (Najafiyan, 2013).

It is true that the abundant materials on earth that can be useful for construction have been studied in depth, but it is also true that not all possible mixtures have been studied in detail that can be useful for constructing ecological, resistant buildings at affordable costs. If hybridization is perceived for a long time as a bad practice, because it is practiced in an anarchic way and without scientific basis and norms, there is still a way to make the mix a point of strength and richness for the building, it is up to our scientists to develop and implement it.

It is more than ever useful to define the hybrid as an indispensable approach that can solve the challenges of construction and urbanism of our century. This multi-scale approach can affect the project as a whole (design, structure and construction method) or partially depending on the needs, objectives and purpose of the project. It can be at the heart of the design of a new model of urbanism for the construction of the cities of the future as it can be the magic key to build the small isolated houses in the countryside of tomorrow: ecological, economical and sustainable.

The hybrid is the only possible approach to meet the challenges of our century, since we have exhausted all other possibilities. We know the minerals that make up the earth's crust, their physical and chemical characteristics, and even their usefulness and possible applications. We have even studied the rarest earths, which have become indispensable for today's advanced technology, so we should not think of discovering materials in large quantities that are useful for construction, and we should not think of continuing at the same devastating pace of life on earth. There is no such thing as a construction without impact on the environment, but there are constructions that can have less impact with the same level of comfort, or even more; it is the hybrid, it is the future, it is up to us to find the best recipe for the mix that can limit the ecological damage of modern civilization.

Many requirements have to be considered while carrying out a construction project: Needs, preferences, customer wants, facilities, and comfort are examples of service requirements. Aesthetic requirements include artistic appearance, environmental integration. Structural stability, material strength and durability are all safety requirements. Economic requirements comprise minimizing investment costs, decreasing maintenance costs, completing the project within the contractual timeframe, increasing profitability, and minimizing the construction cost. Environmental and ecological requirements such as minimizing the impact of construction on the environment, minimizing GHG emissions, solid and liquid waste during the building's life cycle, minimizing energy usage, and minimizing water consumption. Meeting all the requirements for a given project is a challenging and often impossible task, however, we can still achieve our needs while limiting the environmental effect of our intervention by adopting hybrid approaches through:

- Mixing materials with the aim of developing sustainable materials that satisfy our requirements with a low carbon footprint.
- Integrating modern construction processes with traditional approaches to increase competitiveness.
- Adopting hybrid architectural and urban planning approaches that offer great ecological potential compared to traditional styles

4.3 HYBRID CONSTRUCTION; FROM CONCEPT TO APPLIED TECHNOLOGY

Thanks to the application of this concept, we will be able to implement a new generation of technology capable of meeting the ecological requirements of our century through the reconciliation of construction, economy and environment, such as the technology of monolithic structures, the technology of seismic fibers, the carbon cure applied to lime concrete and many others.

The technology of monolithic structures is based on the application of modern construction techniques on traditional buildings in order to cohabit the advantages of each of the known construction techniques in a single structure. This technique allows the mass production of green buildings through the design of a monolithic metal formwork with a high reuse rate for the bonding of the structure working mainly in compression. This structure is generated from an arched frame. Ecological concretes of low compressive strength can be used for the filling such as earth or lime concrete. This frame is composed of vaults supported by shear walls as shown in Figure 4 which represents our first model generated from this technology. The buttresses illustrated in Figure 4 take up the thrust forces at the supports of the vaults. Contrary to traditional construction approaches, the architectural design and the load-bearing structure are studied simultaneously from the formwork design phase as this structure mobilizes its shape to guarantee its stability. This technique eliminates the use of wood and steel for roofing and makes traditional techniques and materials more cost-effective. The technology of monolithic structures will increase the life of buildings through the elimination of steel, reduce the cost through the industrialization of construction techniques and reduce the carbon footprint of the structure through the use of ecological materials.

Lime concrete using carbon cure technology is based on injecting smoke from cars and factories into the lime concrete to accelerate the setting of the lime. This technique has been tested on cement-based concrete (Zhang, 2017) with encouraging results despite the controversy among the scientific community about its environmental performance. The application of this technique to hydraulic lime is more logical and cost effective at the same time since it contains a higher percentage of calcium hydroxide capable of reacting with carbon dioxide. This technique allows to gain on several levels at the same time: firstly, to accelerate the production rate of the elements based on lime concrete, then to valorize economically the smoke of cars and factories and finally to sequester carbon dioxide and other harmful gases.

The seismic vulnerability of traditional buildings present a great obstacle to their use, so the implementation of seismic technologies adapted to this model of buildings generally of low height will be a

Figure 4 Perspective of a monolithic building design on the basis of monolithic structure technology (Belabid, 2022).

great advance. It is clear from the state of the art done before that the increase in strength and stiffness to take the seismic force is very complex. It remains to mobilize the ductility of materials to dissipate the seismic energy. The research work carried out on the recovery of waste tires in concrete shows a clear increase in the ductility of the material except that in the totality of the studies had used rubber as aggregate (Mohajerani, 2020). The idea of seismic fiber technology propose to recycle tires in lime or stabilized earth concrete as ductile fibers to improve the ductility of the material and structure. This technique allows the recycling of tire-based waste and even improves the seismic resistance of materials.

The list of technologies that can be developed from this concept is not exhaustive as the prefabrication applied to traditional buildings and many others. It is up to us to focus our efforts in this way in order to make this concept an indispensable asset in solving the city and environment equation.

5. CONCLUSIONS AND PERSPECTIVES

The application of the hybrid construction concept will allow the development of a new generation of buildings with important ecological and economic advantages through:

- The implementation of diagonal and vertical urban planning approaches that condensing services in structures composed of connected buildings that limit the use of transportation, optimize the use of space and improve the living environment at the same time.
- The adoption of hybrid architecture with a high ecological value through the implementation of concept of green buildings (use of green energy and positive externalities – recycling of water – the establishment of microclimatic vegetation – the valorization of physical flows).
- The increase of the life span of buildings through the development of alternatives to steel, at least for low-rise buildings.
- The development of alternatives to reinforced concrete through the valorization of low carbon footprint materials by mechanical and modern construction processes (Prefabrication of arches, vaults and domes – The technology of monolithic structures).
- Increasing the profitability of traditional construction and the use of local materials through the industrialization of construction techniques.
- CO_2 sequestration via the use of lime concrete in construction for load-bearing structures by applying carbon cure technology to traditional building.
- The implementation of innovative antiseismic solutions for traditional buildings by applying the concept of hybrid construction as the technology of seismic fibers which consists in valorizing the waste of tires to improve the ductility, the rate of

damping and the dissipation of the energy of the lime concretes.

The adoption of this concept is extremely important for the future of the city in relation to the environment because it maps out the best way to develop innovative solutions for this issue through the mixing of materials, tools and techniques according to well-founded scientific and technological methodologies. This mixing according to the stated norms will allow the definition of a third approach ''the technology of the hybrid constructions'' able to overcome this duality; on the one hand the reinforced concrete which is an affordable material but also, pollute and less durable and on the other hand the techniques of sustainable construction hard to promote. This model able to coexist the advantages of each one of the known modes of construction will necessarily give satisfactory results as it is in depth a reorganization, an adaptation and a mixing of the technologies that have previously demonstrated their usefulness in other applications and uses. In short, this concept will make it possible to achieve satisfactory results in the reconciliation of construction, economy and man with the environment.

The big challenge for this concept today is to incarnate it as a reality in construction and in the city by making the hybrid construction a research and development priority. If this article defines a third way to pursue ''the technology of hybrid constructions'', it is very important to expand research efforts in this framework in order to:

- Identify other possible mixing paths in the light of the rules defining the concept.
- Evaluate the usefulness of this hybrid construction model, as well as the set of techniques and technologies that are derived from it using measurable quantitative parameters.
- To expand efforts to produce practical and commercial models based on this concept at the city and building scales, following Steven Holl's lead on the architectural aspect of the concept.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR AFFILIATIONS

Abderrahim Belabid orcid.org/0000-0003-0677-3242
Department of Mechanics, Materials and Civil Engineering, National School of Applied Sciences, Ibn Zohr University, Agadir 80000, MA

Hassan Elminor orcid.org/0000-0003-4923-8362
Department of Mechanics, Materials and Civil Engineering, National School of Applied Sciences, Ibn Zohr University, Agadir 80000, MA

Hajar Akhzouz orcid.org/0000-0001-6234-574X
Department of Civil Engineering, Euromed University of Fez, Fez 30000, MA

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