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Review

Green Material Prospects for Passive Evaporative Cooling Systems: Geopolymers

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Abstract: Passive cooling techniques have been used mostly in countries with hot and arid climates such as Iran, Egypt, and India. However, the use of this important technology has not been seriously considered until a time of energy crisis, and consequently, environmental crisis scenarios, emerge. Scholars have renewed their interest in investigating passive cooling technology, particularly the aspects of new materials, thermal comfort, energy efficiency, new designs, climate, and environmental considerations. This review paper highlights the opportunities to use green materials, such as geopolymers, as evaporative cooling materials with different types of industrial and agricultural waste products as components. Novel ideas for passive cooling design using ancient and nature-inspired concepts are also presented to promote green technology for future applications.

Keywords: passive evaporative cooling; geopolymers; waste materials; design

1. Introduction

The global demand for energy will increase by 33% between the years 2010 and 2035. Such demand will raise energy-related CO_2 emissions by 20%, thereby increasing long-term global temperature by over 3.5 °C [1]. Efforts have been performed to reduce energy consumption consciously in the construction industry given that this industry accounts for approximately 40% of total global energy consumption [2]. One of the main consumers of energy in buildings is the heating, ventilation, and air-conditioning (HVAC) system. The energy consumption of HVAC systems is closely associated with local climatic conditions [3].

The use of HVAC systems requires calibration with regard to passive cooling strategies because of the high energy consumption of such systems. This approach involves the use of both passive and hybrid cooling techniques to reduce energy consumption and improve thermal comfort. Comfort ventilation, nighttime ventilation, radiant cooling, evaporative cooling, and soil cooling are examples of passive cooling techniques [4]. Evaporative cooling is a passive technique [5] that is not only applicable to regions with multiple climatic situations, such as those with hot and dry climate, but also to regions with moderate climate [6].

2. Evaporative Cooling Systems

Evaporative cooling is the process by which air temperature is reduced through the evaporation of water within an airstream. During evaporation, water needs the latent heat of vaporization, which is obtained from ambient air and decreased air temperature [7].

Evaporative cooling systems require less energy input than mechanical vapor compression systems because they obtain such input from ambient air. Numerous studies have been conducted to reduce energy consumption during evaporative cooling [8].

Many researchers have investigated different types of evaporative coolers, such as direct, indirect, and modified coolers [9–12].

2.1. Direct Evaporative Systems

Direct evaporative cooling (DEC) systems rely on the direct channeling of water into the airflow. In an ideal setting, air will maintain an adiabatic trajectory within a psychometric diagram. Heat and mass transfers also occur during this process. However, DEC systems also have limitations, including the growth of Legionella bacteria in water droplets in the airflow supply [13]. The main advantage of DEC lies in the simple construction of its equipment. By contrast, its main disadvantage is the increasing air moisture content, which may be undesirable for certain applications [14].

2.2. Indirect Evaporative Systems

Indirect evaporative cooling derives its effect from the cooling influence of water evaporation, not directly via airflow but through a non-porous wall. Heat transfer occurs between air and the water cooled inside a cooling tower. This approach addresses the problem of Legionella growth within the airflow supply; however, its efficiency is lower than that of a direct system [13,15]. In indirect evaporative cooling, the primary air is cooled but no moisture is added into the air, which can play an important role in building air-conditioning systems [16–19]. The disadvantage of indirect evaporative cooling technology lies in its high dependency on ambient air conditions.

2.3. Modified Evaporative Coolers

In a modified evaporative cooler, air can be cooled to a temperature lower than that achieved via indirect or direct evaporative coolers without altering the humidity of the air. Theoretically, the dew point temperature of the inlet process air can be achieved using a modified evaporative cooler. However, this process requires higher fan power than that for indirect and direct evaporative coolers because of air splitting. The system consists of a plate-type sensible heat exchanger and a direct evaporative cooler [20]. Rusten (1985) investigated the four factors that influenced evaporation rate. He posited that although rates were detailed separately, they were all correlated and influential upon the overall evaporation rate and the cooling rate. The factors discussed by Rusten (1985) included (1) air temperature; (2) air movement (velocity); (3) cooling media (saturation efficiency and surface area of cooling media); and (4) relative air humidity [21].

The performance of evaporative cooling systems is governed by the material of the media, which augments the water evaporation process. Several materials have been analyzed for this system and used for practical applications, such as textile and building materials for cooling buildings. Other materials, including ceramics, have been analyzed for application in evaporative media for both direct [22] and indirect [13] evaporative cooling applications. To control the increase in surface temperatures and create cooler urban environments, Hoyano et al. [23] developed a system known as the passive cooling wall (PCW) to control surface temperature and cool urban environments. PCW comprises moist void bricks that are capable of absorbing water and allows wind penetration, thereby reducing surface temperature via water evaporation. Other methods involve optimizing cooling parameters based on the results derived from a mathematical model in a quasi-steady state condition. The cooling pad consists of corrugated cellulose impregnated with wetting agents, which provides maximum surface area for evaporation and least resistance to airflow. This cooling pad is equipped with a water tank, which allows uninterrupted water trickle [24]. Another approach is the use of a sprinkler on walls or roofs (e.g., Ghosal et al.). An economically efficient method is stretching a canvas over the roof during the day and then removing it at night. The canvas protects a building from the greenhouse effect during summer. The heat flux on the roof of any structure can be significantly reduced when water evaporates from its surface [25]. He and Hoyano recently developed a device that would sprinkle water over TiO_2-coated building walls and glass. To utilize this system better, the design should be quantitatively evaluated, and its cooling influence on urban/built environments should be determined. The decrease in surface temperature via evaporative cooling will reduce the absorption of solar heat on the surfaces of the building. This method also improves the thermal effect of the surroundings. This cooling system represents the application of the super hydrophilicity of TiO_2 coating, which allows water to cover the entire TiO_2-coated surface [26]. Despite the benefits of the aforementioned methods, they require a power source to operate the pump. At present, considerable effort has been exerted to develop a water supply system that keeps an evaporative surface constantly wet.

Different studies on evaporative cooling technologies are summarized in Table 1 [27,28].

Table 1. A summary of different studies on evaporative cooling systems [27,28].

Reference	System Description	Type of Model	Results
Qiu and Riffat [29]	Novel evaporative cooling system	Analytical	-
Zhao et al. [30]	Counter-flow indirect evaporative cooler (IEC) made from plate fin heat exchanger	Simulation	Wet bulb effectiveness (54%–130%)
Zhao et al. [31]	indirect evaporating cooler with five different materials as heat and mass transfer	Analytical	Dew point effectiveness (36%–82%)
Ringvilaikul and Kumar [32,33]	Counter-flow indirect evaporative cooler made from flat sheet, stacked structure heat exchanger	Experimental and simulation	Wet bulb effectiveness (92%–114%)
Bruno [34]	Counter-flow plate type exchanger based IEC	Experimental	Wet bulb effectiveness (106%–124%)
Camargo et al. [35]	Comparison of Direct evaporating cooling (DEC) and indirect evaporative cooling	Analytical	-
Eskra [36]	Two stage evaporative cooling	Simulation	Reduction of energy consumption (60%–75%)
Kulkarni and Rajput [37]	Two stage evaporative cooler	Analytical	Saturate efficiency (64%–89%)
Eskra [36]	Two stage evaporative cooler	Analytical	Wet bulb effectiveness (93%)
Alonso [38]	Cross-flow IEC made from plate fin heat exchanger	Simulation	Wet bulb effectiveness (77%–93%)
Guo [39]	IEC made from plate fin heat exchanger	Analytical	Wet bulb effectiveness (78%–95%)
Zhan [40]	Cross-flow IEC made from plate fin heat exchanger	Analytical	Wet bulb effectiveness (50%–65%)

Table 1. *Cont.*

Reference	System Description	Type of Model	Results
Heidarnejad et al. [41]	Two stage DEC- IEC	Experimental	The effectiveness of the two stages is 108%–111% while the effectiveness of IEC is 55%–61%; 60% power saving.
Heidarnejad et al. [42]	Hybrid system including DEC coupled with of nocturnal radiative cooling, cooling coil	Experimental	The results demonstrate the overall effectiveness of hybrid system is more than 100%.
Phillips [43]	Chilled water coil conjunction with a DEC pad	Experimental	Using DEC in conjunction with a chilled coil results to 35% energy saving comparing the chilled coil for a LEED rated building, this corresponds to four credits for energy conservation.
Bowman et al. [44] and Robinson et al. [45]	Passive down draught evaporative cooling (PDEC)	Simulation	Saving between 50% and 83%, depending upon occupancy and set point. Thermal comfort could not be achieved by PDEC only.
Ibrahim et al. [22] Riffat et al. [46] He and Hoyano [47]	Porous ceramic evaporators (DEC)	Experimental Simulation Experimental	-

3. Potential Porous Materials

3.1. Ceramics

Cooling via porous materials is not a new concept; in fact, it has been used since ancient times. An example of this method is the use of porous jars to help maintain cool temperatures in hot and dry climates worldwide [22]. In general, porous ceramics exhibit excellent mechanical properties, chemical and abrasion resistance, and thermal stability. Cooling is a function of porosity, configuration, and water supply pressure. A high surface area is preferred because the evaporative surface area is crucial to the evaporation rate [48]. Many evaporative cooling systems utilize porous evaporators as their wetting media. Riffat and Zhu [46] merged porous ceramics and a heat pipe to form an indirect evaporative cooler. Porous ceramics [49–51] exhibit properties such as high permeability, low bulk density, high surface area, and low thermal conductivity. These properties rely on solid chemical composition, as well as on final pore volume fraction and structure, with regard to morphology, size, and connectivity.

Researchers [52–55] have used porous mullite ceramics made from china clay such as kaolinite and allophane. They have posited that composition is generally dominated by the glassy phase, mostly because of the presence of amorphous silica or impurities in calcined clay. However, these pores are insufficiently permeable for water or gases.

Okada et al. [56] reviewed an evaporative passive cooling system that used porous ceramics. They discussed several advantages of porous ceramics prepared from the vermiculite and allophone of clay minerals, such as high water absorption, fast absorption rate, and slow water release rate because of their unique porous microstructure. Lotus-type porous ceramics prepared via extrusion using flammable fibers as pore formers demonstrate excellent capillary lift and water evaporation properties from its controlled pore structure [57]. Okada et al. [58] confirmed that lotus ceramics demonstrated excellent capillary rise (approximately 1300 mm) compared with conventional porous ceramics. The high surface temperature on building materials during summer can be reduced by wetting porous materials, which will enable the use of capillary action and accelerate water evaporation [57,58]. This method has been proven to be effective in counteracting the influence of heat islands [47].

Many water-retaining porous ceramics are made from industrial waste products, such as blast furnace slag [59] and akira (i.e., waste generated from the beneficiation process of silica sand and plastic clay) [60]. However, this effect is difficult to maintain for extended periods without a constant water supply given that currently available water-retaining materials have difficulty releasing water to their surroundings. For example, water-retaining materials used on pavements should have a fast water absorption rate and a slow controlled release of adsorbed water. Okada et al. [58] confirmed that the height of capillary rise was greater in ceramics incorporated with Fe_2O_3, particularly for thin samples. This property is assumed to be the result of controlled pore sizes, pore distribution, and pore orientation within porous mullite ceramics. These ceramics can also efficiently reduce the influence of solar heating when the surface is kept wet.

Capillary rise height (h) is related to pore radius (r), as postulated in Equation (1):

$$h = 2\gamma\cos\theta/\rho g r \tag{1}$$

where γ is the surface tension of water, θ is the contact angle between water and the pore wall, ρ is the density of water, and g is the gravitational acceleration. The relationship between capillary rise height and pore radius is expressed as $h = 1.49 \times 10^{-5}/\mathrm{r}$, assuming a contact angle (θ) = 0°, γ = 73 mN/m, ρ = 1 × 103 kg/m^3, and g = 9.8 m/s^2. Thus, capillary rise height is inversely proportional to the pore size of lotus ceramics [61].

Despite high water retention and good cooling effects because of the excellent capillary lift of water in the porous ceramics (lotus ceramics) developed by Isobe et al. [62–64], the applicability of these ceramics will increase even further if they are fabricated using an environmentally friendly process and the requirement for firing at high temperatures will be disregarded. Geopolymers [65] fit all the aforementioned requirements, and thus are excellent choices in the context of this work.

3.2. Geopolymers

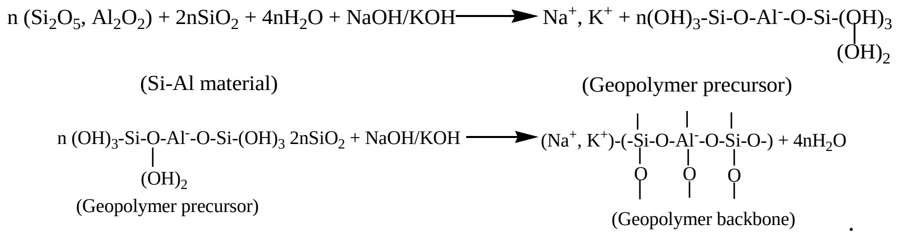
Geopolymers or inorganic polymers have emerged [66,67] as novel engineering materials with the potential to form a substantial element for an environmentally sustainable construction and building materials industries. Given the worldwide interests in geopolymers, the number of scientific publications regarding these materials has increased exponentially in recent years, alongside research organizations, with three milestone technical books published on the subject [68–70]. Although the investigations of geopolymers are mainly focused on concrete applications, they are also regarded as attractive materials for evaporative cooling applications. Geopolymers are considered environmentally friendly materials because of their low manufacturing temperature (<100 °C) and low emissions, which is six times less CO_2 compared with standard types of cement [71].

The term "geopolymer" was coined in the early 1970s to describe inorganic materials with polymeric Si–O–Al bonds formed from the chemical reaction between aluminosilicate oxides and alkali silicates [72]. This framework comprises SiO_4 and AlO_4 tetrahedra that share oxygen molecules. The Al^{3+} in these fourfold coordination induces a local charge deficit that requires balancing via counter ions. From [65], the empirical formula of geopolymers or poly (sialates) is expressed as follows:

$$M_n[-(SiO_2)_z - AlO_2]_n \cdot wH_2O$$

where M is a cation such as K^+, Na^+, or Ca^{2+}; n is the degree of polycondensation; z is 1, 2, or 3; and w is number of water molecules . Other cations such as Li^+, $Ba_2{}^+$, $NH_4{}^+$, and H_3O^+ may also be present.

In general, geopolymerization represents a complicated multi-step process that comprises dissolution, reorientation, and solidification via the following two reactions [73]:



Several scientists have simulated a theoretical structure for K-poly (sialate–siloxo) that is consistent with its nuclear magnetic resonance spectra. Geopolymerization forms aluminosilicate frameworks, which are similar to rock-forming minerals [74]. Figure 1 shows the different structures of geopolymers.

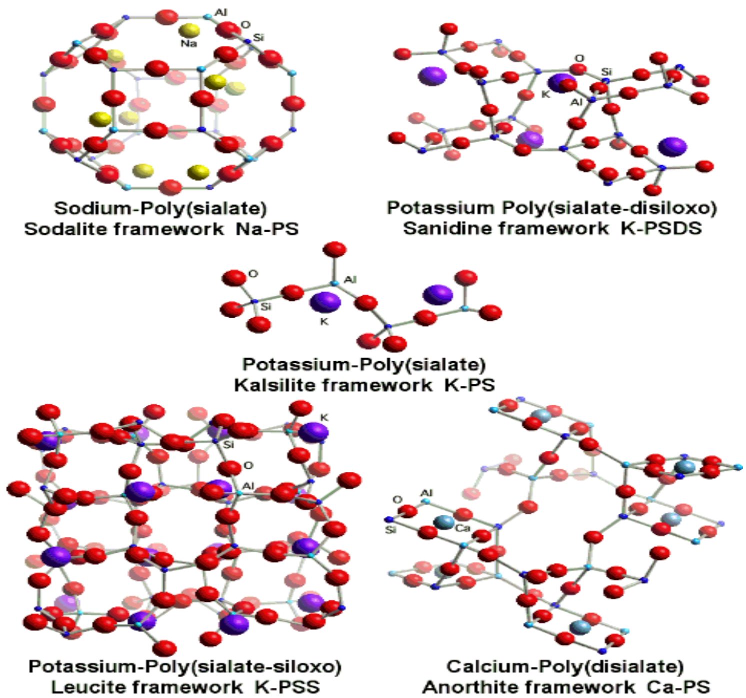


Figure 1. Structures of different geopolymers, reprinted with permission from [75], copyright 2006 Geopolymer institute.

One of the vital attributes of geopolymer technology is its robust and versatile manufacturing process. This attribute allows products to be customized from coal ash sources to other aluminosilicate raw materials, thereby resulting in unique properties that can be economically produced.

Geopolymers have received considerable attention because of their excellent mechanical properties, low shrinkage, fire resistance, and low energy consumption for the purposes of the building industry and the engineering field [76]. The main properties of geopolymers are rapid compressive strength development, low permeability, resistance to acid attack, good resistance to freeze–thaw cycles, and tendency to drastically decrease the mobility of most heavy metal ions within the geopolymeric structure [77]. Geopolymers are suitable for conventional cement types and plastics because of the aforementioned properties. They are also energy efficient and environmentally friendly because of their low-temperature processing. Geopolymers are a class of new materials that share properties with glass, ceramics, and inorganic materials. They can be made from a diverse range of materials, such as slag, fly ash (FA), and kaolinitic substances [78].

The geopolymer/vermiculite composite demonstrates a water absorption rate of 60% and is capable of retaining water for 7 d (Figure 2) [63].

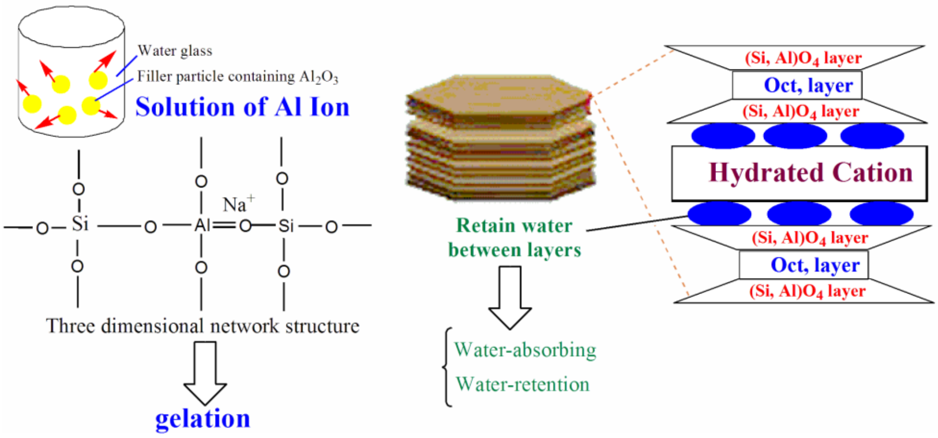


Figure 2. (**a**) Hardening model for geopolymers; (**b**) structure of water absorption and retention in vermiculite, reprinted with permission from [79], copyright 2006 Okada Nakajima Lab.

The addition of vermiculite intensifies the water-retentive characteristic of a material. Metakaolin (MK) typically comprises 50%–55% SiO_2 and 40%–45% Al_2O_3 [80], with small amounts of Fe_2O_3, TiO_2, CaO, and MgO. MK is a common raw material used to prepare geopolymers. The particles are 0.5–5 μm in diameter, which is an order of magnitude lower than that of cement grain particles and an order of magnitude higher than that of silica fume particles. MK is white (silica fume is dark gray/black), which renders it particularly attractive for structural and architectural applications. The processing of MK is highly controlled, thereby resulting in highly consistent MK powders [81]. However, the use of MK to synthesize geopolymers also has problems. For example, its high water demand results in shrinkage and cracking caused by the excessive addition of water.

3.2.1. Application of Byproducts and Waste Products as Potential Raw Materials for Geopolymer Preparation

Geopolymers are typically sourced from a coal combustion product commonly known as FA, which contains amorphous alumina silica and is readily available worldwide. To maximize the perceived benefits of FA, technologies should be developed to devise means to maximize its use. For example, to enhance removal efficiency and adsorption capacity, FA will require a certain number of chemical modifications [82,83]. Xie et al. [83] used FA, slag, and MK to synthesize geopolymers. The maximum compressive strength of the geopolymer is projected to reach 30.79 MPa under optimal loading conditions. Geopolymer matrices have also been tested using a method known as the toxicity characteristic leaching procedure, and the results indicate that heavy metals can be immobilized and solidified within these matrices. The amount of alkali activator and the mass ratio of the origin materials considerably influence these potential applications. Despite the use of FA and slag in currently available commercial geopolymer products, MK represents the most promising feedstock material for geopolymers in the future because it has a more consistent chemical composition than FA and slag, and thus is expected to result in more consistent and predictable products. In addition to the cost and technical challenges of the supply chain, the supply of FA and slag is rapidly depleting given that they are used in the manufacture of blending cement and concrete [84,85]. In long-term applications, the use of MK (perhaps together with other Al- and Si-bearing minerals) as raw material is becoming increasingly attractive and realistic.

Jia et al. [86–88] successfully developed a series of MK-based geopolymer composites and ceramics. Ge et al. [89] synthesized porous MK-based geopolymer spheres using "a suspension and solidification method." Synthesis was divided into two steps. First, foamed geopolymer slurry was prepared by mixing NaOH, sodium silicate, and MK, along with foaming agents such as H_2O_2 and K12. Second, a solid geopolymeric sphere was prepared via continuous injection of the preformed slurry into a polyethylene glycol (PEG) 600 medium at 80 °C. The beads can be dispersed in the PEG-600 medium and can solidify and immediately float (because of low density). This new material can replace organic resin-based absorbents and normal zeolite particles for use in columns for the continuous treatment of industrial wastewater, such as the removal of Cu (II).

Several recent studies have involved the use of MK in synergy with industrial waste materials, such as red mud, rice husk ash (RHA), and FA in geopolymerization [90,91].

Another potential waste material that can be used as a raw material is rice husk, which represents the bulk of agricultural residues and is a byproduct of the milling process. These byproducts are harmful to the environment, readily available nearly everywhere, and highly resistant to natural degradation [92]. RHA is commonly dumped into water streams, thereby resulting in pollution and contamination. However, this practice occurred prior to the identification of RHA as a good constituent and a mineral admixture of concrete [93]. Among suitable silica-rich resources (pozzolanic materials), rice husk–bark ash (RHBA) or RHA is a solid waste generated in biomass power plants that use rice husk and eucalyptus bark as fuel. However, the use of RHA as a potential raw material for geopolymer synthesis has not yet been extensively studied. Blending RHA into concrete structures enhanced compressive strength and degraded water permeability in both the chemical and physical properties of concrete. The addition of RHA reduces material costs and CO_2 emissions because of the reduced utilization of cement [94]. Tangchirapat et al. [95] proved that the use of ground RHBA in recycled aggregate concrete enhanced compressive strength, although an increase in the slump loss of concrete was also observed. Nazari et al. [96] investigated the utilization of palm oil clinker (POC) particles in geopolymer samples. They demonstrated that the use of POC particles induced excellent resistance to water absorption, and thus these particles would be suitable for weightless applications. The addition of gypsum in geopolymers also improves geopolymerization degree [97]. Palm oil FA (POFA) is considered a suitable additive material worldwide, particularly for use as a pozzolanic material [98]. Chindaprasirt et al. [99] analyzed the application of POFA as a pozzolanic material in concrete to achieve adequate material strength. Ground granulated blast furnace slag (GGBS) is a byproduct of steel plants and another potential pozzolanic material for raw materials to produce geopolymers. GGBS comprises non-crystalline SiO_2 with high specific surface area for high pozzolanic reactivity [100]. GGBS can be used as an additive during the formation of geopolymers; it will enhance setting time, microstructure, and compressive strength [97].

Another potential waste material is bagasse ash, which is a byproduct of sugar refineries. When incinerated, bagasse ash and RHA both produce approximately 80% amorphous silica, thereby making them suitable for pozzolan [101]. Bagasse can also be used as reinforcement material in cement composites. The advantages of incorporating natural fiber as reinforcement in cement composites are related to their mechanical and thermal properties and reasonable cost [102].

Investigations on natural fibers such as bamboo, sisal, jute, and cellulose have shown desirable effects on the mechanical and physical properties of brittle organic and inorganic matrices. Wood fibers have also been successfully used to reinforce geopolymer composites with concomitant enhancement in both mechanical and fractural properties [103]. The use of cotton fibers, which is readily available and lighter than synthetic fibers, will reduce processing cost. However, geopolymer composites with 0.7%–1% cotton fibers have weak compressive strength because these fibers ball together and create voids within the matrix [104]. Cotton fibers can also absorb excessive water, which may prevent the initiation of geopolymerization, thereby decreasing bonding strength between the fibers and the matrix. However, the impact strength of composites decreased in tandem with an increase in fiber content of over 0.5 wt %. This material behavior is attributed to the formation of fiber agglomerates and voids because the viscosity of a system is increased by adding cotton fibers, thereby decreasing the adhesion strength of the fiber matrix. Bajare et al. [105] used local industrial waste products and byproducts, such as ashes obtained from burning grass, glass powder recycled from lamp demercuration facilities, and calcined clay minerals to prepare geopolymers. Raw materials have been investigated and treated using calcination and grinding methods to increase their respective activities. Byproducts and industrial waste products are mainly used to synthesize geopolymers. The bottom ashes used in geopolymer composites are extracted from local heating plant furnaces. Wood and barley bottom ashes have been investigated as potential geopolymer compound materials.

FA geopolymers do not require high-temperature processing methods. Al Bakri et al. [82] proved that FA-based geopolymer at a concentration of 12 M NaOH exhibited excellent compressive strength (94.59 MPa) after 7 d of testing.

4. Design Consideration (Greener Prospects)

Environmental protection is a top global concern that requires the reduction of energy consumption. An approach to help achieve this goal is the use of passive and low-energy systems to induce thermal comfort. The use of climatic designs will also translate into reduced energy costs. A suitable design is the initial step to minimize the propagation of climatic stress, and building designs should reflect their surrounding climate to help reduce the dependency on mechanical heating/cooling. This approach enables maximizing the use of natural energy to create comfortable surroundings within a built envelope. Passive cooling for buildings is important to enhance the sustainability of buildings as well as to achieve economic and environmental benefits alongside the provision of the required air-conditioning system. The implementation of evaporative cooling is expected to result in tremendous energy savings [106].

Selecting a suitable cooling design is a complex process. Cooling requirements should be determined, and their advantages and disadvantages should be carefully considered before making a decision. The following checklist facilitates the selection of an appropriate design [107].

1. What is the required cooling need?
2. What is the average relative humidity of the area where cooling is needed?
3. What is the wind condition in the area where the cooling is needed?
4. Is there a good supply of water where the cooling system will be used?
5. What kind of the cooling materials are available?
6. Side effects.

As mentioned previously, an important factor in selecting a suitable design of an evaporative cooling system is the humidity of the environment. An evaporative cooling system is suitable for hot and arid climates, whereas indirect evaporative systems such as water ponds and roof spray cooling systems can also be suitable for humid climates.

Air movement (velocity) influences the performance of an evaporative cooling system. Consequently, configurations that stimulate high air mass flow (velocity) and have large surface areas for seepage flows to navigate have high cooling rates.

Numerous attempts have been made to exclude the recirculation pump in an ordinary system, and instead, utilize the pressure in the supply water line to periodically surge water, thereby eliminating the need for any electrical input. Another DEC design adopts porous ceramics that use their capillary property as evaporators to extract water without using a pump [22,46,47]. Airflow over the ceramic evaporators and the surface influences cooling. Evaporative cooling systems are used in many buildings, such as in roof surface evaporative cooling [108–110], a passive evaporative cooling wall [47,111,112], and passive downdraft evaporative cooling [106,113–118].

5. Ingenious Designs

To create a fluid language for developing a building as an environmental machine, three flow conditions have been considered, namely, human flow, sunlight, and air movement. New ingenious designs have been proposed to utilize multiple renewable energy options to reduce carbon footprint by optimizing heat waste in cooling and heating systems. Most of these designs derive their working concepts from nature.

Dealing with hot and arid climates has enabled researchers to utilize multiple design approaches and strategies. In a biomic architecture project of the Mineral Research and Tourist Hub in Badwater, Death Valley, California, abundant sunlight, salty water bodies, and vast salt plateaus are used as the key variables to produce green energy electricity via solar molten salt technology. The high evaporative rate and the prevailing southwest wind provide advantages for a passive desalination system that applies on-site water evaporation. Freshwater is supplied to the internal courtyard for passive cooling of the redirected air. An active water desalination system uses sunlight to produce pure salt and water, which will be fed to the turbine for daily consumption. Evaporative cooling is the main indoor climatic cooling feature. The air moves from the lower ground to the upper floor because of the negative pressure created from the thermal chimney. The air will then be cooled and refreshed by the wet mesh and the internal garden at the ground floor before it is supplied to the entire building. This cooling strategy will continue at night by using the thermal mass in the chimney, and the upper accommodation area will be evaporatively cooled directly by the air that crosses the ventilation as the skins open [119]. The design and layout of the building reduce energy consumption by maximizing access to natural ventilation and the penetration of natural light into living spaces (Figure 3).

Figure 3. Design of the biomic building (photo credit: Azizul Hakim Musa), reprinted with permission from [119], copyright 2010 play.art.space; Living in Ludic Architecture that interacts.

In another design created by Orlando de Urrutia (Eco-Cybernetic City), a 150-floor building can harness all types of natural sources, including water, wind, and solar energy. The aerogenerators of this machine mounted in the two-tower building can use the airflow passing between the towers to produce electricity (Figure 4) [120].

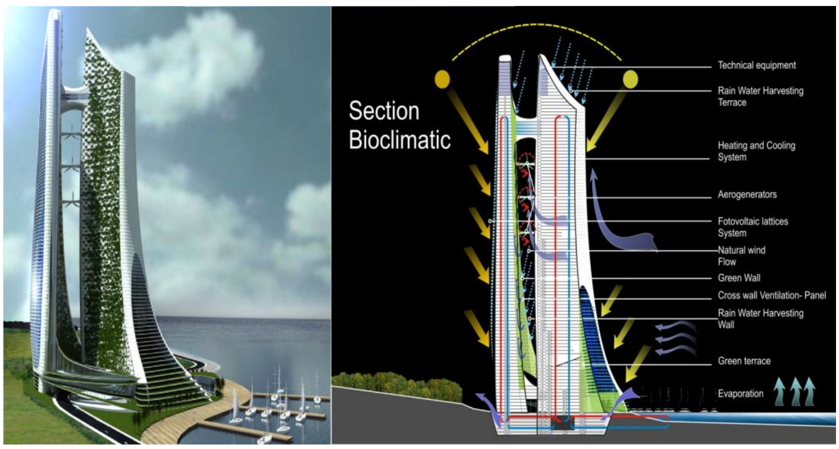


Figure 4. Schematic of the Eco-Cybernetic City (Photo credit: Orlando De Urrutia), reprinted with permission from [120], copyright 2010 InfoNIAC.

The Hydro House is a concept home proposed by the Rael San Fratello Architects (Figure 5). This structure depends on the cooling influence of the evapotranspiration of ponds (fins), both inside and outside the house. Skylights, portholes, and operable windows are some of the media used to provide natural daylight and cooling to desert homes. The Hydro House gathers water as its thermal mass for evaporative cooling. It has a roof pond, which helps provide ambient temperature in deserts. The water running off the roof drips into the hydro walls that enclose the house. The walls absorb the water and utilize the flywheel effect to maintain internal climatic control. The Hydro House is a compact, single-story home formed in the shape of a "V," which encompasses the courtyard and the interior ponds. Private bedrooms and bathrooms are located on one side of the courtyard, whereas the living and dining areas are located on the other side. An operable window enhances cross-ventilation via homes and ponds, thereby producing a cooling draft. Roofs comprise ponds that are linked to the walls. Water accumulates in the walls, and the draft across homes evaporates the water and cools the exterior of the house. Operable skylights allow daylight into the house and extract hot air from inside it [121].

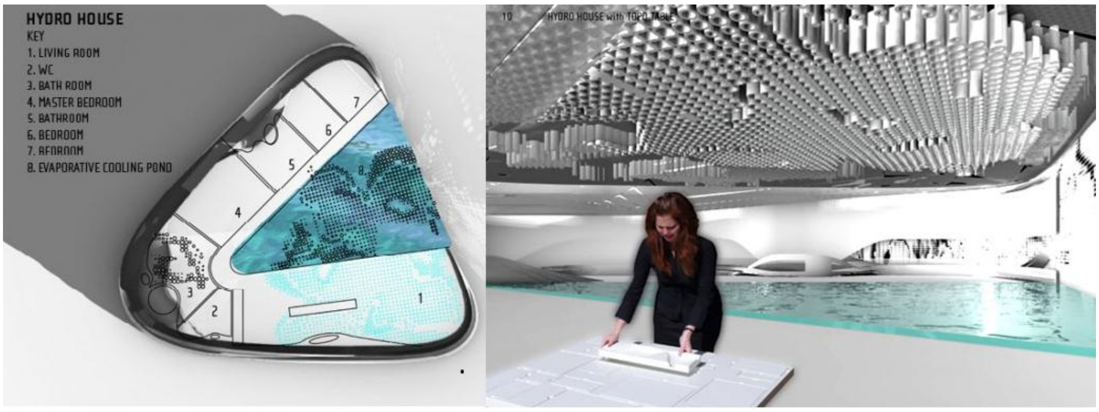


Figure 5. Hydro House concept (Photo credit: Andrew Michler), reprinted with permission from [121], copyright 2010 eVolo.

Sou Fujimoto proposed a nature-inspired design for a tower block known as L'Arbre Blanc ("The White Tree"). The tower block, which is part of a series of "modern follies" exhibited in Montpellier, France, is shaped like a pine cone and equipped with balconies sprouting outward in all directions [122]. The building features a curved body reminiscent of a tree trunk, whereas the balconies of its 120 apartments are designed to fan outward like leaves seeking sunlight. Similar to a tree, the tower will use its locally available natural resources to drastically reduce the energy required for expansion. Passive strategies are also devised to induce comfort, control environmental effects, and reduce emissions. An unconventional yet dialectical process passively cools units with solar fireplaces (Figure 6).

Another design by Sou Fujimoto shows a conceptual master plan for an anonymous Middle Eastern city that comprises tapering towers of stacked arches cooled by waterfalls (Figure 7) [123]. The Fujimoto architects state that "By incorporating multiple waterfalls, instead of one large [waterfall], different mountains of water are created feeding the avenue." "There will be a wide range [of] waterfalls; smaller on the top to prevent any interference from the wind and larger toward the bottom to create evaporative cooling." This design appears to be inspired by water circulating in pipes installed into the walls of the houses of wealthy residents in ancient Rome [124].

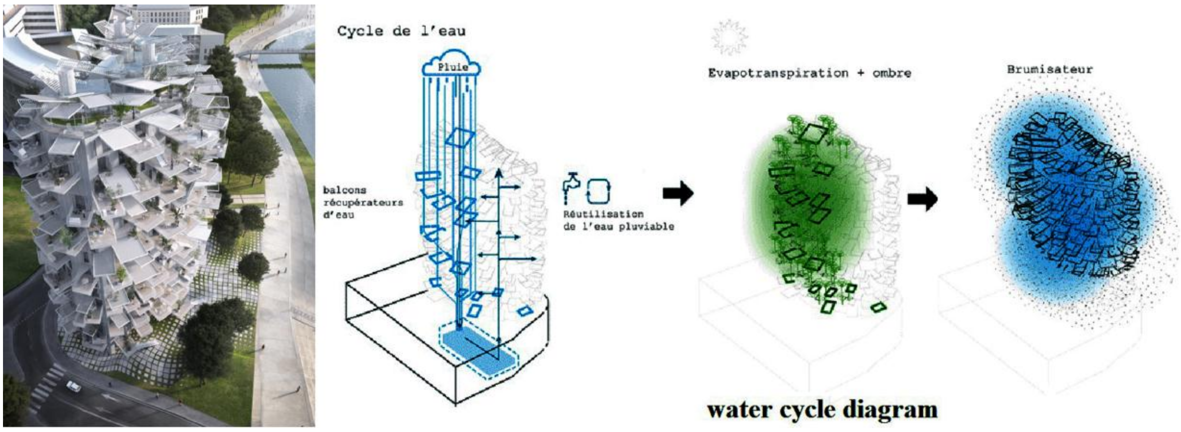


Figure 6. L'Arbre Blanc nature-inspired tower and its water cycle diagram (photo credit: Sou Fujimoto Architects, Nicolas Laisne Associes, and Manal Rachdi OXO Architects), reprinted with permission from [122], copyright 2014 Dezeen magazine.

Figure 7. New design (Photo credit: Sou Fujimoto Architects), reprinted with permission from [123], copyright 2013 Dezeen magazine.

Tree-shaped canopies are proposed by Iñaki Ábalos and Renata Sentkiewicz for the Zhuhai Huafa Contemporary Art Museum, China (Figure 8). These tree canopies provide shading (particularly in summer), water collection (from rain during the monsoon season), air movement (wind-driven downdraft), solar updraft, radiative cooling downdraft at night, and evaporative cooling downdraft (ECD) during the day. In ECD, the surfaces of tree branches will be moist the morning after a rain shower or a dew harvest. As the day evolves and air temperature increases, this moisture will evaporate, cool, and densify the air around the branch(es). A cool downdraft begins to form as falling air from the branches accumulates at the trunk [125].

Figure 8. Tree-shaped canopy design (photo credit: Iñaki Ábalos and Renata Sentkiewicz), reprinted with permission from [125].

Examples of interior designs that utilize evaporative cooling include 3D printed pods and e-coolers. An e-cooler cools the air by using a system of hollow ceramic tiles filled with water. The e-cooler was inspired by two Middle Eastern elements, namely, mashrabiya and jara. Mashrabiya is a traditional architectural element that functions as a mediator between the interior and exterior of a house by admitting air and light, whereas jara is an ancient clay jug that cools water [126]. The 3D printed pods provide energy-free cooling via evaporation. These attractive cooling units can be installed in plazas and public areas to create comfortable microclimates. As water is drawn into the pods, it spreads out over the surface area and evaporates, thereby cooling the air that passes through the pods (Figure 9) [127].

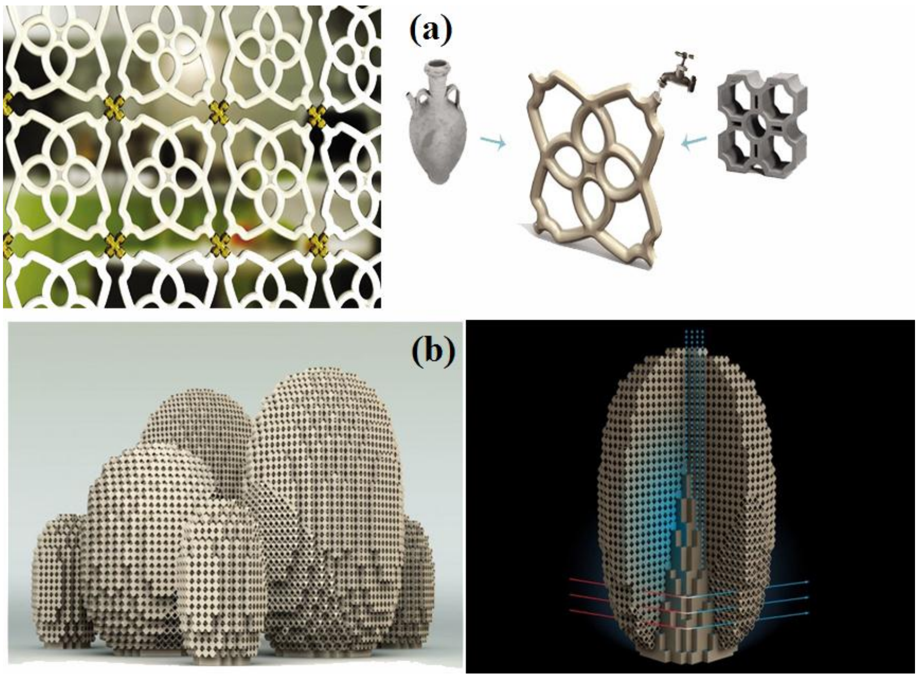


Figure 9. (**a**) E-cooler and (**b**) 3D printed pods concepts (photo credit: Andrew Michler), reprinted with permission from [127], copyright 2010 eVolo.

6. Conclusions

Buildings consume a significant portion of total primary energy for cooling. However, using a passive cooling technology can extensively reduce energy consumption. As an energy-efficient technology, the use of passive cooling technology is becoming increasingly popular because of new improvements in materials and designs. The energy crisis and environmental issues promote investigations on this topic, whereas green prospects in this technology require additional attention. New research attempts to obtain good indoor air quality while achieving thermal comfort in various climates for energy efficiency. Different types of evaporative coolers, such as direct, indirect, and modified coolers could be employed considering their limitations and climate condition. Given the aforementioned parameters, geopolymers are promising green candidates as evaporative cooling system materials because they can be prepared via an environmentally friendly procedure at low burning temperatures and with reduced CO_2 emissions. Meanwhile, industrial and agricultural waste materials can be used as secondary raw materials to prepare geopolymers.

In this paper, we discuss various studies on geopolymers, which can be used in evaporative cooling technologies. In view of significant gains in energy and environmental benefits, conducting green concept studies using geopolymers or similar green materials is essential. Future works can include research on various agricultural and industrial waste products for preparing green geopolymer materials. Moreover, investigating new or improved designs based on ancient and nature-inspired designs is a promising approach to improve energy efficiency, thermal comfort, and living conditions. In addition, feasibility and public acceptance studies on passive cooling technologies in different countries can be regarded as an important issue for further research.

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References

1. IEA. *World Energy Outlook 2011 Factsheet*; International Energy Agency: Paris, France, 2011.
2. Masoso, O.T.; Grobler, L.J. The dark side of occupants' behaviour on building energy use. *Energy Build.* **2010**, *42*, 173–177. [CrossRef]
3. Chan, H.Y.; Riffat, S.B.; Zhu, J. Review of passive solar heating and cooling technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 781–789. [CrossRef]
4. Givoni, B. *Passive Low Energy Cooling of Buildings*; John Wiley & Sons: New York, NY, USA, 1994.
5. Erell, E. *Evaporative Cooling*; Earthscan: London, UK, 2007; pp. 228–261.
6. Costelloe, B.; Finn, D. Thermal effectiveness characteristics of low approach indirect evaporative cooling systems in buildings. *Energy Build.* **2007**, *39*, 1235–1243. [CrossRef]
7. Shukla, A.; Tiwari, G.N.; Sodha, M.S. Experimental study of effect of an inner thermal curtain in evaporative cooling system of a cascade greenhouse. *Solar Energy* **2008**, *82*, 61–72. [CrossRef]
8. Heidarinejad, G.; Moshari, S. Novel modeling of an indirect evaporative cooling system with cross-flow configuration. *Energy Build.* **2015**, *92*, 351–362. [CrossRef]
9. Cerci, Y. A new ideal evaporative freezing cycle. *Int. J. Heat Mass Transf.* **2003**, *46*, 2967–2974. [CrossRef]
10. Handbook, A. *Evaporative Cooling Applications, HVAC Applications*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: N.E. Atlanta, GA, USA, 2003.
11. La Roche, P.M. *Carbon-Neutral Architectural Design*; CRC Press: Boca Raton, FL, USA, 2011.
12. Sharifi, A.; Yamagata, Y. Roof ponds as passive heating and cooling systems: A systematic review. *Appl. Energy* **2015**, *160*, 336–357. [CrossRef]
13. Velasco Gómez, E.; Rey Martínez, F.J.; Varela Diez, F.; Molina Leyva, M.J.; Herrero Martín, R. Description and experimental results of a semi-indirect ceramic evaporative cooler. *Int. J. Refrig.* **2005**, *28*, 654–662. [CrossRef]
14. Porumb, B.; Ungureşan, P.; Tutunaru, L.F.; Şerban, A.; Bălan, M. A Review of Indirect Evaporative Cooling Technology. *Energy Procedia* **2016**, *85*, 461–471. [CrossRef]

15. Duan, Z.; Zhan, C.; Zhang, X.; Mustafa, M.; Zhao, X.; Alimohammadisagvand, B.; Hasan, A. Indirect evaporative cooling: Past, present and future potentials. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6823–6850. [CrossRef]
16. Maheshwari, G.; Al-Ragom, F.; Suri, R. Energy-saving potential of an indirect evaporative cooler. *Appl. Energy* **2001**, *69*, 69–76. [CrossRef]
17. Jaber, S.; Ajib, S. Evaporative cooling as an efficient system in Mediterranean region. *Appl. Therm. Eng.* **2011**, *31*, 2590–2596. [CrossRef]
18. Delfani, S.; Esmaeelian, J.; Pasdarshahri, H.; Karami, M. Energy saving potential of an indirect evaporative cooler as a pre-cooling unit for mechanical cooling systems in Iran. *Energy Build.* **2010**, *42*, 2169–2176. [CrossRef]
19. Shapiro, L.E. *Advanced Energy Saving Through the Use of Evaporative Cooling and Energy Recovery in Hybrid HVAC Systems*; DTIC Document: Los Angeles, CA, USA, 2004.
20. Crum, D. Open Cycle Airconditioning Systems. Master's Thesis, Wisconsin-Madison, Madison, WI, USA, 1986.
21. Rusten, E. *Understanding Evaporative Cooling*; Volunteers in Technical Assistance (VITA): Arlington, VA, USA, 1985.
22. Ibrahim, E.; Shao, L.; Riffat, S.B. Performance of porous ceramic evaporators for building cooling application. *Energy Build.* **2003**, *35*, 941–949. [CrossRef]
23. He, J.; Hoyano, A. A 3D CAD-based simulation tool for prediction and evaluation of the thermal improvement effect of passive cooling walls in the developed urban locations. *Solar Energy* **2009**, *83*, 1064–1075. [CrossRef]
24. Jain, D.; Tiwari, G.N. Modeling and optimal design of evaporative cooling system in controlled environment greenhouse. *Energy Convers. Manag.* **2002**, *43*, 2235–2250. [CrossRef]
25. Ghosal, M.K.; Tiwari, G.N.; Srivastava, N.S.L. Modeling and experimental validation of a greenhouse with evaporative cooling by moving water film over external shade cloth. *Energy Build.* **2003**, *35*, 843–850. [CrossRef]
26. He, J.; Hoyano, A. A numerical simulation method for analyzing the thermal improvement effect of super-hydrophilic photocatalyst-coated building surfaces with water film on the urban/built environment. *Energy Build.* **2008**, *40*, 968–978. [CrossRef]
27. Rafique, M.M.; Gandhidasan, P.; Rehman, S.; Al-Hadhrami, L.M. A review on desiccant based evaporative cooling systems. *Renew. Sustain. Energy Rev.* **2015**, *45*, 145–159. [CrossRef]
28. Santamouris, M.; Kolokotsa, D. Passive cooling dissipation techniques for buildings and other structures: The state of the art. *Energy Build.* **2013**, *57*, 74–94. [CrossRef]
29. Qiu, G.; Riffat, S. Novel design and modelling of an evaporative cooling system for buildings. *Int. J. Energy Res.* **2006**, *30*, 985–999. [CrossRef]
30. Zhao, X.; Li, J.; Riffat, S. Numerical study of a novel counter-flow heat and mass exchanger for dew point evaporative cooling. *Appl. Therm. Eng.* **2008**, *28*, 1942–1951. [CrossRef]
31. Zhao, X.; Liu, S.; Riffat, S. Comparative study of heat and mass exchanging materials for indirect evaporative cooling systems. *Build. Environ.* **2008**, *43*, 1902–1911. [CrossRef]
32. Riangvilaikul, B.; Kumar, S. An experimental study of a novel dew point evaporative cooling system. *Energy Build.* **2010**, *42*, 637–644. [CrossRef]
33. Riangvilaikul, B.; Kumar, S. Numerical study of a novel dew point evaporative cooling system. *Energy Build.* **2010**, *42*, 2241–2250. [CrossRef]
34. Bruno, F. On-site experimental testing of a novel dew point evaporative cooler. *Energy Build.* **2011**, *43*, 3475–3483. [CrossRef]
35. Camargo, J.R.; Ebinuma, C.D.; Silveira, J. Thermoeconomic analysis of an evaporative desiccant air conditioning system. *Appl. Therm. Eng.* **2003**, *23*, 1537–1549. [CrossRef]
36. Eskra, N. Indirect-Direct Evaporative Cooling Systems. *ASHRAE J. Am. Soc. Heat. Refrig. Air Cond. Eng.* **1980**, *22*, 21–25.
37. Kulkarni, R.; Rajput, S. Performance evaluation of two stage indirect/direct evaporative cooler with alternative shapes and cooling media in direct stage. *Int. J. Appl. Eng. Res.* **2010**, *1*, 800–812.
38. Alonso, J.S.J.; Martinez, F.R.; Gomez, E.V.; Plasencia, M.A.-G. Simulation model of an indirect evaporative cooler. *Energy Build.* **1998**, *29*, 23–27. [CrossRef]

39. Guo, X.; Zhao, T. A parametric study of an indirect evaporative air cooler. *Int. Commun. Heat Mass Transf.* **1998**, *25*, 217–226. [CrossRef]
40. Zhan, C.; Duan, Z.; Zhao, X.; Smith, S.; Jin, H.; Riffat, S. Comparative study of the performance of the M-cycle counter-flow and cross-flow heat exchangers for indirect evaporative cooling–paving the path toward sustainable cooling of buildings. *Energy* **2011**, *36*, 6790–6805. [CrossRef]
41. Heidarinejad, G.; Bozorgmehr, M.; Delfani, S.; Esmaeelian, J. Experimental investigation of two-stage indirect/direct evaporative cooling system in various climatic conditions. *Build. Environ.* **2009**, *44*, 2073–2079. [CrossRef]
42. Heidarinejad, G.; Farmahini Farahani, M.; Delfani, S. Investigation of a hybrid system of nocturnal radiative cooling and direct evaporative cooling. *Build. Environ.* **2010**, *45*, 1521–1528. [CrossRef]
43. Rick Phillips, P. Using direct evaporative+ chilled water cooling. *ASHRAE J. Am. Soc. Heat. Refrig. Air Cond. Eng.* **2009**, 16–19.
44. Bowman, N.; Eppel, H.; Lomas, K.; Robinson, D.; Cook, M. Passive downdraught evaporative cooling. *Indoor Built Environ.* **2001**, *9*, 284–290.
45. Robinson, D.; Lomas, K.J.; Cook, M.J.; Eppel, H. Passive down-draught evaporative cooling: Thermal modelling of an office building. *Indoor Built Environ.* **2004**, *13*, 205–221. [CrossRef]
46. Riffat, S.B.; Zhu, J. Mathematical model of indirect evaporative cooler using porous ceramic and heat pipe. *Appl. Therm. Eng.* **2004**, *24*, 457–470. [CrossRef]
47. He, J.; Hoyano, A. Experimental study of cooling effects of a passive evaporative cooling wall constructed of porous ceramics with high water soaking-up ability. *Build. Environ.* **2010**, *45*, 461–472. [CrossRef]
48. Liberty, J.T.; Ugwuishiwu, B.O.; Pukuma, S.A.; Odo, C.E. Principles and Application of Evaporative Cooling Systems for Fruits and Vegetables Preservation. *Int. J. Curr. Eng. Technol.* **2013**, *3*, 1000–1006.
49. Ishizaki, K.; Komarneni, S.; Nanko, M. *Porous Materials: Process Technology and Applications*; Kluwer Academic: Dordrecht, The Netherlands, 1998.
50. Chen, W.; Liu, S.; Lin, J. Analysis on the passive evaporative cooling wall constructed of porous ceramic pipes with water sucking ability. *Energy Build.* **2015**, *86*, 541–549. [CrossRef]
51. Luyten, J.; Mullens, S.; Snijkers, F.; Buekenhoudt, A. Proceedings of the Global Roadmap for Ceramics-ICC2 Proceedings, Verona, Italy, 29 June–4 July 2008; pp. 309–316.
52. Katsuki, H.; Furuta, S.; Shiraishi, A.; Komarneni, S. Porous mullite honeycomb by hydrothermal treatment of fired kaolin bodies in NaOH. *J. Porous Mater.* **1995**, *2*, 299–305. [CrossRef]
53. Saito, Y.; Hayashi, S.; Yasumori, A.; Okada, K. Effects of calcining conditions of kaolinite on pore structures of mesoporous materials prepared by the selective leaching of calcined kaolinite. *J. Porous Mater.* **1996**, *3*, 233–239. [CrossRef]
54. Katsuki, H.; Takagi, H.; Matsuda, O. Fabrication and properties of mullite ceramics with needle-like crystals. *Ceram. Trans.* **1992**, *31*, 137–146.
55. Liu, Y.-F.; Liu, X.-Q.; Wei, H.; Meng, G.-Y. Porous mullite ceramics from national clay produced by gelcasting. *Ceram. Int.* **2001**, *27*, 1–7. [CrossRef]
56. Okada, K.; Matsui, S.; Isobe, T.; Kameshima, Y.; Nakajima, A. Water-retention properties of porous ceramics prepared from mixtures of allophane and vermiculite for materials to counteract heat island effects. *Ceram. Int.* **2008**, *34*, 345–350. [CrossRef]
57. Okada, K.; Kameshima, Y.; Nakajima, A.; Madhusoodana, C. Preparation of lotus-type porous ceramics with high water pump-up ability and its cooling effect by water vapor evaporation. *J. Heat Island Inst. Int.* **2007**, *2*, 1–5.
58. Okada, K.; Uchiyama, S.; Isobe, T.; Kameshima, Y.; Nakajima, A.; Kurata, T. Capillary rise properties of porous mullite ceramics prepared by an extrusion method using organic fibers as the pore former. *J. Eur. Ceram. Soc.* **2009**, *29*, 2491–2497. [CrossRef]
59. Takahashi, H.; Kobayashi, H.; Hinata, H. KAWAPROM ACE®pavement block manufactured by recycling fused sewage slag. *Tech. Rep. Kawasaki* **1995**, *27*, 19–26.
60. Toya, T.; Tamura, Y.; Kameshima, Y.; Okada, K. Preparation and properties of CaO-MgO-Al_2O_3-SiO_2 glass-ceramics from kaolin clay refining waste (Kira) and dolomite. *Ceram. Int.* **2004**, *30*, 983–989. [CrossRef]
61. Washburn, E.W. The dynamics of capillary flow. *Phys. Rev.* **1921**, *17*, 273. [CrossRef]

62. Isobe, T.; Kameshima, Y.; Nakajima, A.; Okada, K. Preparation and properties of porous alumina ceramics with uni-directionally oriented pores by extrusion method using a plastic substance as a pore former. *J. Eur. Ceram. Soc.* **2007**, *27*, 61–66. [CrossRef]
63. Isobe, T.; Kameshima, Y.; Nakajima, A.; Okada, K.; Hotta, Y. Extrusion method using nylon 66 fibers for the preparation of porous alumina ceramics with oriented pores. *J. Eur. Ceram. Soc.* **2006**, *26*, 2213–2217. [CrossRef]
64. Isobe, T.; Kameshima, Y.; Nakajima, A.; Okada, K.; Hotta, Y. Gas permeability and mechanical properties of porous alumina ceramics with unidirectionally aligned pores. *J. Eur. Ceram. Soc.* **2007**, *27*, 53–59. [CrossRef]
65. Davidovits, J. Geopolymers. *J. Therm. Anal. Calorim.* **1991**, *37*, 1633–1656. [CrossRef]
66. Duxson, P.; Fernández-Jiménez, A.; Provis, J.L.; Lukey, G.C.; Palomo, A.; Deventer, J.S.J. Geopolymer technology: The current state of the art. *J. Mater. Sci.* **2007**, *42*, 2917–2933. [CrossRef]
67. Provis, J.L.; Lukey, G.C.; van Deventer, J.S.J. Do Geopolymers Actually Contain Nanocrystalline Zeolites? A Reexamination of Existing Results. *Chem. Mater.* **2005**, *17*, 3075–3085. [CrossRef]
68. Shi, C.; Roy, D.; Krivenko, P. *Alkali-Activated Cements and Concretes*; CRC press: New York, NY, USA, 2006.
69. Provis, J.L.; Van Deventer, J.S.J. *Geopolymers: Structures, Processing, Properties and Industrial Applications*; Elsevier: Amsterdam, The Netherlands, 2009.
70. Pacheco-Torgal, F.; Labrincha, J.; Leonelli, C.; Palomo, A.; Chindaprasit, P. *Handbook of Alkali-Activated Cements, Mortars and Concretes*; Elsevier: Cambridge, UK, 2014.
71. Duxson, P.; Provis, J.L.; Lukey, G.C.; van Deventer, J.S.J. The role of inorganic polymer technology in the development of 'green concrete'. *Cem. Concr. Res.* **2007**, *37*, 1590–1597. [CrossRef]
72. Van Jaarsveld, J.G.S.; Van Deventer, J.S.J. Effect of metal contaminants on the formation and properties of waste-based geopolymers. *Cem. Concr. Res.* **1999**, *29*, 1189–1200. [CrossRef]
73. He, J.; Zhang, J.; Yu, Y.; Zhang, G. The strength and microstructure of two geopolymers derived from metakaolin and red mud-fly ash admixture: A comparative study. *Constr. Build. Mater.* **2012**, 80–91. [CrossRef]
74. Davidovits, J. Geopolymers: man-made rock geosynthesis and the resulting development of very early high strength cement. *J. Mater. Educ.* **1994**, *16*, 91–139. [CrossRef]
75. Examples of geopolymer frameworks. Available online: http://www.geopolymer.org/science/examples-geopolymer-frameworks (accessed on 20 August 2013).
76. Verdolotti, L.; Iannace, S.; Lavorgna, M.; Lamanna, R. Geopolymerization reaction to consolidate incoherent pozzolanic soil. *J. Mater. Sci.* **2008**, *43*, 865–873. [CrossRef]
77. Van Jaarsveld, J.G.S.; Van Deventer, J.S.J.; Lorenzen, L. The potential use of geopolymeric materials to immobilise toxic metals: Part I. Theory and applications. *Minerals Eng.* **1997**, *10*, 659–669. [CrossRef]
78. Škvára, F.; Kopecký, L.; Nemecek, J.; Bittnar, Z. Microstructure of geopolymer materials based on fly ash. *Silikáty* **2006**, *50*, 208–215.
79. Geopolymer/vermiculite composite. Available online: http://www.rmat.ceram.titech.ac.jp/research-e/heatiland-e.html (accessed on 3 July 2013).
80. Poon, C.S.; Lam, L.; Kou, S.C.; Wong, Y.L.; Wong, R. Rate of pozzolanic reaction of metakaolin in high-performance cement pastes. *Cem. Concr. Res.* **2001**, *31*, 1301–1306. [CrossRef]
81. Ding, J.T.; Li, Z. Effects of metakaolin and silica fume on properties of concrete. *ACI Mater. J.* **2002**, *99*, 393–398.
82. Mustafa Al Bakri, A.M.; Kamarudin, H.; Bnhussain, M.; Khairul Nizar, I.; Rafiza, A.R.; Zarina, Y. Microstructure of different NaOH molarity of fly ash-based green polymeric cement. *J. Eng. Technol. Res.* **2011**, *3*, 44–49.
83. Xie, J.; Yin, J.; Chen, J.; Xu, J. Study on the Geopolymer Based on Fly Ash and Slag. In Proceedings of the International Conference on Energy and Environment Technology, Guilin, China, 16–18 October 2009; pp. 578–581.
84. Malhotra, V.M.; Mehta, P.K. *Pozzolanic and Cementitious Materials*; Taylor & Francis: Boca Raton, FL, USA, 1996; Volume 1.
85. Van Deventer, J.S.J.; Provis, J.L.; Duxson, P. Technical and commercial progress in the adoption of geopolymer cement. *Minerals Eng.* **2012**, *29*, 89–104. [CrossRef]
86. Lin, T.; Jia, D.; He, P.; Wang, M.; Liang, D. Effects of fiber length on mechanical properties and fracture behavior of short carbon fiber reinforced geopolymer matrix composites. *Mater. Sci. Eng. A* **2008**, *497*, 181–185. [CrossRef]

87. He, P.; Jia, D.; Lin, T.; Wang, M.; Zhou, Y. Effects of high-temperature heat treatment on the mechanical properties of unidirectional carbon fiber reinforced geopolymer composites. *Ceram. Int.* **2010**, *36*, 1447–1453. [CrossRef]
88. Xie, N.; Bell, J.L.; Kriven, W.M. Fabrication of Structural Leucite Glass–Ceramics from Potassium-Based Geopolymer Precursors. *J. Am. Ceram. Soc.* **2010**, *93*, 2644–2649. [CrossRef]
89. Ge, Y.; Cui, X.; Kong, Y.; Li, Z.; He, Y.; Zhou, Q. Porous geopolymeric spheres for removal of Cu (II) from aqueous solution: Synthesis and evaluation. *J. Hazard. Mater.* **2015**, *283*, 244–251. [CrossRef] [PubMed]
90. Dimas, D.D.; Giannopoulou, I.P.; Panias, D. Utilization of alumina red mud for synthesis of inorganic polymeric materials. *Miner. Process. Extract. Metall. Rev.* **2009**, *30*, 211–239. [CrossRef]
91. Kumar, A.; Kumar, S. Development of paving blocks from synergistic use of red mud and fly ash using geopolymerization. *Constr. Build. Mater.* **2013**, *38*, 865–871. [CrossRef]
92. Kusbiantoro, A.; Nuruddin, M.F.; Shafiq, N.; Qazi, S.A. The effect of microwave incinerated rice husk ash on the compressive and bond strength of fly ash based geopolymer concrete. *Constr. Build. Mater.* **2012**, *36*, 695–703. [CrossRef]
93. de Sensale, G.R.; Ribeiro, A.B.; Gonçalves, A. Effects of RHA on autogenous shrinkage of Portland cement pastes. *Cem. Concr. Compos.* **2008**, *30*, 892–897. [CrossRef]
94. Saraswathy, V.; Song, H.-W. Corrosion performance of rice husk ash blended concrete. *Constr. Build. Mater.* **2007**, *21*, 1779–1784. [CrossRef]
95. Tangchirapat, W.; Buranasing, R.; Jaturapitakkul, C.; Chindaprasirt, P. Influence of rice husk–bark ash on mechanical properties of concrete containing high amount of recycled aggregates. *Constr. Build. Mater.* **2008**, *22*, 1812–1819. [CrossRef]
96. Nazari, A.; Riahi, S.; Bagheri, A. Designing water resistant lightweight geopolymers produced from waste materials. *Mater. Des.* **2012**, *35*, 296–302. [CrossRef]
97. Rattanasak, U.; Pankhet, K.; Chindaprasirt, P. Effect of chemical admixtures on properties of high-calcium fly ash geopolymer. *Int. J. Min. Metall. Mater.* **2011**, *18*, 364–369. [CrossRef]
98. Sata, V.; Jaturapitakkul, C.; Rattanashotinunt, C. Compressive Strength and Heat Evolution of Concretes Containing Palm Oil Fuel Ash. *J. Mater. Civ. Eng.* **2010**, *22*, 1033–1038. [CrossRef]
99. Chindaprasirt, P.; Homwuttiwong, S.; Jaturapitakkul, C. Strength and water permeability of concrete containing palm oil fuel ash and rice husk–bark ash. *Constr. Build. Mater.* **2007**, *21*, 1492–1499. [CrossRef]
100. Nehdi, M. Ternary and quaternary cements for sustainable development. *Concr. Int.* **2001**, *23*, 35–42.
101. Tippayasam, C.; Boonsalee, S.; Sajjavanich, S.; Ponzoni, C.; Kamseu, E.; Chaysuwan, D. Geopolymer development by powders of metakaolin and wastes in Thailand. *Adv. Sci. Technol.* **2011**, *69*, 63–68. [CrossRef]
102. Hajiha, H.; Sain, M. 17–The use of sugarcane bagasse fibres as reinforcements in composites. In *Biofiber Reinforcements in Composite Materials*; Faruk, O., Sain, M., Eds.; Woodhead Publishing: Cambridge, UK, 2015; pp. 525–549.
103. Alzeer, M.; MacKenzie, K.D. Synthesis and mechanical properties of new fibre-reinforced composites of inorganic polymers with natural wool fibres. *J. Mater. Sci.* **2012**, *47*, 6958–6965. [CrossRef]
104. Dias, D.P.; Thaumaturgo, C. Fracture toughness of geopolymeric concretes reinforced with basalt fibers. *Cem. Concr. Compos.* **2005**, *27*, 49–54. [CrossRef]
105. Bajare, D.; Bumanis, G.; Shakhmenko, G.; Justs, J. In Proceedings of the International Scientific Conference on Obtaining Composition of Geopolymers (Alkali Activated Binders) from Local Industrial Wastes, Civil Engineering, Jelgava, Latvia, 12–13 May 2011.
106. Kang, D.; Strand, R.K.; Hammann, R.E.; Newell, T.A.; Vanka, P.S. Advances in the application of passive down-draft evaporative cooling technology in the cooling of buildings. Available online: http://hdl.handle.net/2142/26273 (accessed on 21 October 2015).
107. Odesola, I.F.; Onyebuchi, O. A Review of Porous Evaporative Cooling for the Preservation of Fruits and Vegetables. *Pac. J. Sci. Technol.* **2009**, *2*, 935–941.
108. Jain, D. Modeling of solar passive techniques for roof cooling in arid regions. *Build. Environ.* **2006**, *41*, 277–287. [CrossRef]
109. Kamal, M.A. An Overview of Passive Cooling Techniques in Buildings: Design, Concepts and Architectural Interventions. *Acta Tech. Napoc. Civil Eng. Archit.* **2012**, *55*, 84–97.

110. Ben Cheikh, H.; Bouchair, A. Passive cooling by evapo-reflective roof for hot dry climates. *Renew. Energy* **2004**, *29*, 1877–1886. [CrossRef]
111. Naticchia, B.; D'Orazio, M.; Carbonari, A.; Persico, I. Energy performance evaluation of a novel evaporative cooling technique. *Energy Build.* **2010**, *42*, 1926–1938. [CrossRef]
112. He, J. A design supporting simulation system for predicting and evaluating the cool microclimate creating effect of passive evaporative cooling walls. *Build. Environ.* **2011**, *46*, 584–596. [CrossRef]
113. Hughes, B.R.; Calautit, J.K.; Ghani, S.A. The development of commercial wind towers for natural ventilation: A review. *Appl. Energy* **2012**, *92*, 606–627. [CrossRef]
114. Ford, B.; Schiano-Phan, R.; Francis, E. *The Architecture and Engineering of Downdraught Cooling: A Design Source Book*; PHDC Press: Chicago, IL, USA, 2010.
115. Bahadori, M.N. An improved design of wind towers for natural ventilation and passive cooling. *Solar Energy* **1985**, *35*, 119–129. [CrossRef]
116. Schiano-Phan, R.; Ford, B. 324: Post Occupancy Evaluation of non-domestic buildings using owndraught cooling: Case studies in the US. In Proceedings of PLEA 2008–25th Conference on Passive and Low Energy Architecture, Dublin, Ireland, 22–24 October 2008.
117. Kang, D.; Strand, R.K. Building Simulation. In Proceedings of the Building Simulation of Passive Down-Draught Evaporative Cooling (PDEC) Systems in EnergyPlus, Glasgow, Scotland, 27–30 July 2009.
118. Pearlmutter, D.; Erell, E.; Etzion, Y.; Meir, I.; Di, H. Refining the use of evaporation in an experimental down-draft cool tower. *Energy Build.* **1996**, *23*, 191–197. [CrossRef]
119. Mineral Research and Tourist Hub, Badwater, CA. Available online: https://azizulhakimmusa.wordpress.com/2010/06/20/mineral-research-and-tourist-hub-badwater-ca/ (accessed on 10 August 2015).
120. Eco-Cybernetic City—Environmentally-Conscious Structure. Available online: http://www.infoniac.com/environment/eco-cybernetic-city-environmentally-conscious-structure.html (accessed on 27 July 2015).
121. Hydro House concept. evolo-Architecture Magazine 2010. Available online: http://www.evolo.us/architecture/hydro-house-rael-san-fratello-architects/ (accessed on 3 July 2015).
122. Sou Fujimoto designs nature-inspired towerfor Montpellier "modern follies" project. Available online: http://www.dezeen.com/2014/03/10/sou-fujimoto-montpellier-tower-modern-follies/ (accessed on 3 July 2015).
123. Sou Fujimoto envisions trees and balconies for Université Paris-Saclay building. Available online: http://www.dezeen.com/tag/Sou-Fujimoto/ (accessed on 8 July 2015).
124. Keeping Cool Through the Ages: Slideshow. Available online: http://www.dezeen.com/2013/11/20/sou-fujimoto-designs/ (accessed on 8 July 2015).
125. Ábalos + Sentkiewicz arquitectos wins Zhuhai Huafa Contemporary Art Museum competition. Available online: http://aasarchitecture.com/2014/07/abalos-sentkiewicz-arquitectos-wins-zhuhai-huafa-contemporary-art-museum-competition.html (accessed on 1 July 2015).
126. Yoneda, Y. Ceramic "Ecooler" Screen is a Beautiful Passive Cooling System. Available online: http://inhabitat.com/ceramic-ecooler-screen-is-a-beautiful-passive-cooling-system/ (accessed on 1 July 2015).
127. Art Installations Produce Microclimates. *Evolo-Architecture Magazine* 2010. Available online: http://www.evolo.us/architecture/art-installations-produce-microclimates-postlerferguson/ (accessed on 8 July 2015).

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