GEOPOLYMER CONCRETE: A REVIEW OF DEVELOPMENT, PROPERTIES AND OPPORTUNITIES

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Abstract: Concrete usage around the world is on the increase to meet infrastructure development. An important ingredient in the conventional concrete is cement. The manufacture of ordinary Portland cement (OPC) releases large amount of carbon dioxide (CO2) to the atmosphere that contributes to greenhouse gases emissions and global warming. Therefore, there is a need to find alternative type of binders to produce more environmentally friendly concrete. The use of alternative to binder may reduce the total energy demand for producing conventional concrete and lower the emission of greenhouse gases into the atmosphere from the concrete industry. Since geopolymer is cement and water free inorganic alumino-silicate polymer, it reduces the emissions carbon dioxide than Portland cement.

Geopolymers are binder manufactured by activation of a solid alumino-silicate source material with a highly alkaline activating solution. Fly ash and clay being by product, rich in alumina and silica, can be used as a source material for manufacture of geopolymer. Geopolymers are well-known over the past several decades because of their high performance (high strength and durability) and environmentally maintainable alternative to the ordinary Portland cement. Appearance and life of geopolymer concrete is nice also life of the structure is long without any cracks and braking, it improves the structural integrity.

This paper presents the results from studies on development to enhance workability, strength and durability of geopolymer mortar and concrete. The influence of factors such as curing method and temperature aggregate shape, strengths, moisture content, preparation and grading on workability and strength are presented. The paper also includes the brief details of some recent applications of geopolymer.

Index Terms - **Alumino- silicate binder, cement replacement, geopolymer, fly ash, clay, precast concrete.**

1.INTRODUCTION

1.1 Use of concrete and environmental impact

Concrete is the major construction material in worldwide and concrete industry is the largest user of natural resources in the world. The large use of concrete drives the massive production of cement. For each ton of Portland cement manufactured, it is estimated that one ton of CO_2 released into the environment. The process involves very high temperatures (1400-1500° C), the destruction of quarries to extract raw materials, and the emission of greenhouse gases such as CO_2 and NO_2. The cost associated with the energy requirements is significant.

Readily available commercial by-products such as fly ash, clay and blast furnace slag have been adopted to meet these demands. It was estimated that the amount of fly ash produced annually will be about 780 million tons, providing a means to meet growing demand. The recycled use of these ash material in construction will reduce the cost of disposal and reduce the cost of concrete manufacture overall.

1.2 Geopolymer concrete development

The term “geopolymer” is generally used to describe the amorphous to crystalline reaction products from the synthesis of alkali alumino- silicates with alkali hydroxide / alkali silicate solution. Geopolymer gels and composites are known as low-temperature alumino-silicate glass, alkali activated cement, geocement, alkali-bonded ceramic, inorganic polymer concrete and hydro ceramic. Geopolymer paste can be used to bind loose aggregates and other non-reacted materials together to form geopolymer concrete.

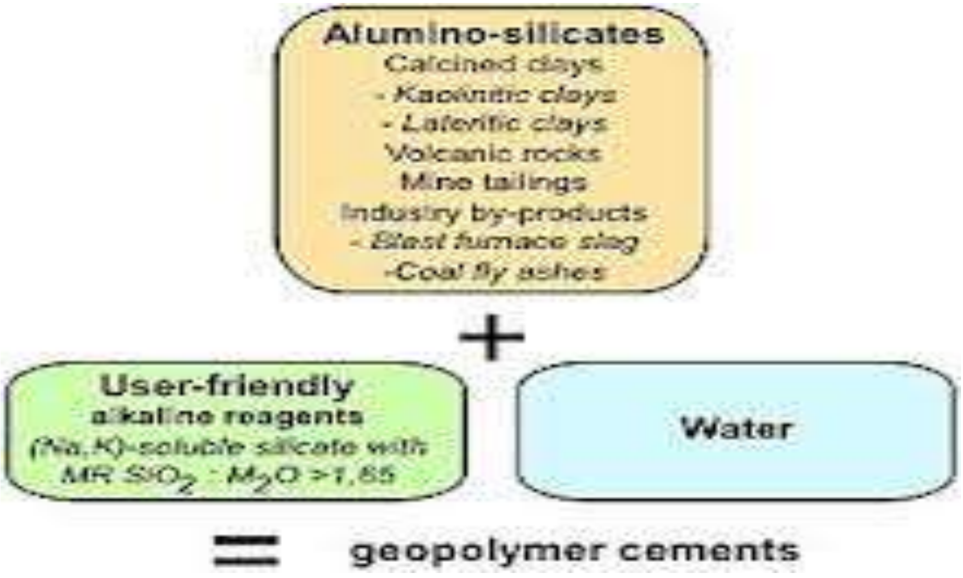

Fig 1: geopolymer cement development

1.3 Properties of geopolymer concrete

High early strength gain is a characteristic of geopolymer concrete when dry heat or steam cured. Geopolymer concrete has been used to produce precast railway sleepers and other pre-stressed concrete building components. Geopolymer concrete has excellent resistance to chemical attack hence it is used in aggressive marine environments, environment with high carbon dioxide or sulphate rich soils. Similarly, in high acidic conditions they showed superior acid resistance and may suitable for the applications such as mining, some manufacturing industries and sewer systems.

2.GEOPOLYMER CONCRETE MATERIALS

Figure 2.1 fly ash

Figure 2.2 clay

Figure 2.3 M-sand

Figure 2.4 alkali activator solution

Fig 2: geopolymer concrete materials.

2.1. Fly ash

Fly ash, also known as flue-ash is one of the residues generated in combustion, and comprises the particles that rise with flue gases. Use of fly ash as a partial replacement for Portland cement is generally limited to class C fly ash. Fly ash can add to the concrete's final strength and increase its chemical resistance and durability. Fly ash can significantly improve the workability of concrete.

More recently, fly ash has been used as a component in geopolymer, where the reactivity of the fly ash glasses is used to generate a binder comparable to a hydrated Portland cement in appearance and properties, but with possibly reduced CO_2 emissions.

2.2. Clay

Clay can be used for the partial replacement of fine aggregate as well as binder. Clay is one of the oldest building materials on earth, among other ancient, naturally occurring geological materials such as stones and organic materials like wood. Clay being relatively impermeable water. Nowadays clay is used in the construction industry as a partial replacement of fine aggregate as well as binder.

2.3. M-Sand

M-Sand is the only alternative to river sand. Dredging of river beds to get river sand will lead to get river sand will lead to environmental disaster like groundwater depletion, water scarcity, threat to the safety of bridges, dams etc.

Usage of M-Sand can drastically reduce the cost since Like River sand, it does not contain impurities and wastage is nil. M-Sand has optimum initial and final setting time as well as excellent fineness which will help to overcome the deficiencies of concrete such as segregation, bleeding, honeycombing, voids and capillary.

2.4. Alkaline liquids

The alkaline liquid used in geopolymerisation is a combination of sodium hydroxide and sodium silicate as activators. Sodium based alkaline solution were used to react with fly ash- clay to produce the binder. Sodium silicate solution was purchased from a local supplier in bulk. Sodium hydroxide in flakes or pellets from with 97-98 % purity was also purchased from a local supplier in bulk. The sodium hydroxide solution was prepared one to two days prior to the concrete batching to allow the exothermically heated liquid to cool to room temperature. The sodium silicate solution and the sodium hydroxide solution were mixed just prior to the concrete batching.

3.ALKALI ACTIVATION

Figure shows the dissolution process of the Si and Al occurs when the fly ashes are submitted to the alkaline solution. Alkali activation of alumino-silicate materials is a complex process. The reaction of alumino-silicate materials in strong alkaline environments results the breakdown of Si-O-Si bonds. After breaking these bonds, new phases arise and the mechanism of their formation seems to be a process that includes a solution. The penetration of Al atoms to the original Si-O-Si structure represents a substantial feature of this reaction. Alumino-silicate gels are mostly formed.

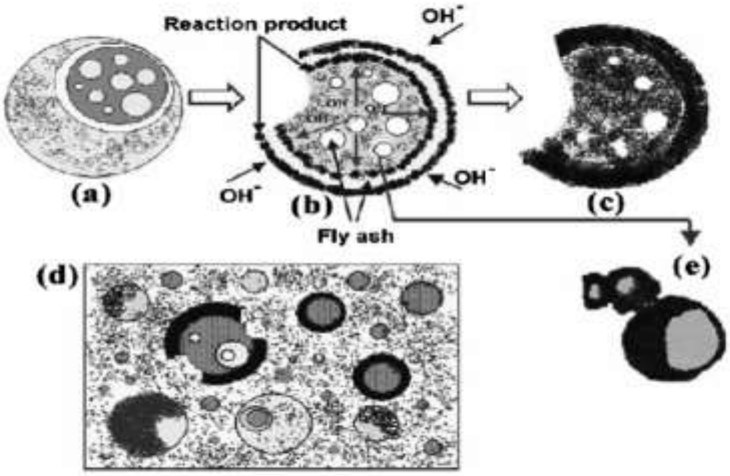

Fig 3: descriptive model of alkali activation of fly ash.

4.FLY ASH GEOPOLYMER CEMENT

Fly ash geopolymer cement can be used to produce structural strength concrete without the considerable emission of carbon dioxide compared to ordinary Portland cement concrete. Sodium silicate (Na_2SiO_3) mixed with sodium hydroxide (NaOH) as an alkaline activator was used in this study. NaOH pellets were dissolved in distilled water to form sodium hydroxide (NaOH) solution.

5.GEOPOLYMER SUSTAINABILITY OPPORTUNITY

Concrete usage around the world is on the increase to meet infrastructure developments. Ordinary Portland cement is the important ingredient of conventional concrete. The production of one ton of cement emits one ton of carbon dioxide to the atmosphere. Moreover, cement production is not only highly energy-intensive, but also consumes significant amount of natural resources.

For sustainable development, the concrete industry needs to explore alternative binders to Portland cement. Such an alternative is offered by fly ash-clay based geopolymer. Since fly ash-clay based geopolymer is cement free concrete, the carbon dioxide emission is less compared to ordinary Portland cement concrete. Also, the energy required to make geopolymer concrete is less that of conventional concrete. Coal burning power stations generate huge amount of fly ash; most of the fly ash is not effectively utilized. Utilization of fly ash from coal burning power stations to make the binder necessary to manufacture concrete.

6.ADVANTAGES OF USING GEOPOLYMER CEMENT CONCRETE

6.1 Advantages

Many advantages of using alkali activated geopolymer cement for commercial concrete are summarized below.

6.1.1 Economic benefit

The production of geopolymer cement reduces the demand for costly production of the clinker required in Portland cements. The high temperatures (1400-1500° C) required for Portland cement production make this is a very costly and energy-intensive.

The pozzolonic materials used in geopolymer cement are readily available as by-products of industrial coal power plants. The utilization these waste materials reduce the problem of disposal and reduce the cost of production of ecofriendly concrete.

6.1.2 Environmental benefit

Production of Portland cement generates more carbon dioxide, this leads to global warming and global dimming. The production of one ton of Portland cement generate one ton of carbon dioxide. Thus we need alternate binders for making concrete. Using geopolymer concrete we can reduce these problems. Furthermore, the utilization of pozzolonic by-products from power plants would prevent these materials from being disposed into the environment in their hazardous, raw state. Currently, unclaimed fly ashes and blast furnace slag are deposited into landfill facilities increasing the risk for leaching metals into groundwater. Geopolymer cement production on a global scale would reduce this risk

6.1.3 Chemical resistance

Geopolymer cements possess excellent resistance to sulfates and various acids. The deterioration of Portland cement is due to the formation of expansive gypsum and ettringite, which causes cracking and spalling in the concrete. The superior performance of geopolymer materials in acidic environments is due the lower calcium content of the source materials. Geopolymer cement produces no gypsum or ettringite formation, therefore no mechanism of sulfate attack.

7.APPLICATIONS OF GEOPOLYMER MORTARS AND CONCRETES

Geopolymer mortars and concretes possess a high potential for use in commercial applications due to their enhanced durability, thermal and chemical resistance properties, rapid development of mechanical strength, adherence to reinforcement / aggregates and economic benefits as an industrial by-product material. Various applications of geopolymer mortars and concrete are described below.

7.1. Concrete pipes

The use of geopolymer concrete for commercial sewer piping is a viable option from the basis of their inherent resistance to sulfates and acidic products. Conventional sewer systems through the breakdown of hydrogen sulfide by aerobic bacteria in the system and is the main factor in corrosion and structural deterioration of the piping networks.

An additional concern regarding concrete longevity is acidic soil in the area of installation. Acidic sulfate soil contains naturally-occurring iron sulfides, mineral iron pyrites (FeS_2) or sulfide oxidation products and main pH level between 1 and 4 which cause major damage to conventional Portland cement concrete. The aggressive acidic environments generated in acid sulfate soils have a serious impact on concrete and steel infrastructure and can lead to structural weakness and failure. Geopolymer concrete products are suited to withstand sulfate environments and would offer an economic alternative to currently used materials and the issues associated with regular repair of the piping networks.

7.2. Structural elements

The increasing worldwide production of Portland cement concrete to meet infrastructure developments indicates that concrete will continue to be the chosen material for construction in the future. A motivation for research into geopolymer cement is an attempt to produce an environmentally friendly concrete out of industrial by-products that would be capable of exceeding the mechanics and durability of traditional Portland cement concrete products. From the perspective of material longevity in adverse environments and large operating loads, geopolymer concrete are viably sound as they possess high compressive strength, experience very minor dry shrinkage and creep and maintain excellent resistance to sulfate attack and acidic environments.

7.3. Heat resistant pavements

The thermal capacity observed in geopolymer concrete make them used for heat resistant pavement applications. Pozzolon-based geopolymer cements do not readily decompose when exposed to high temperatures and appear to be more structurally stable under such conditions than Portland cement concrete. Geopolymer cement utilize more and store less water from solution during particle reaction, and therefore, prevent aged dry shrinkage and strength degradation due to rapid water loss under extreme heat conditions.

7.4. Sub-aqueous seawater applications

The sulfate resistance characteristics of geopolymer cement material make it suitable for sub-aqueous marine applications. Mortars and concrete produced with alkali activated binder perform very stable when immersed in aggressive solutions of various types such as deionized water, seawater, sodium sulfate solution and sulfuric acid. Sodium hydroxide activated geopolymers are more crystalline than those prepared with sodium silicate and therefore are more stable and resistance to these adverse environments.

8.DURABILITY

Geopolymer cements are highly resistant to chemical attack and temperature loading due to their reduced porosity and thermal conductivity characteristics. Durability problems of ordinary Portland cement concrete are due to the calcium content in the main phases. The C_3A reacts with sulfates ions in the presence of $Ca(OH)_2$ to form ettringite and gypsum, which cause expansion and degradation of cement into a non-cohesive granular mass.

8.1 Chemical durability

Geopolymer materials can easily withstand variety of aggressive environments without any deterioration and surface alterations as that of Portland cement-based products. High alkalinity of geopolymer maintains matrix density that tends to prohibit the permeation of corrosive environments.

8.1.1 Sulfate resistance

Heat-cured low calcium fly ash-clay based geopolymer concrete shows high resistance to sulfate attack. Shrinkage of geopolymer concrete is less than that of conventional Portland cement concrete. Also, Portland cement based concrete shows expansion and results sulfate contact thus causes deterioration and spalling of concrete.

8.1.2 Acid resistance

Geopolymers shows excellent resistance to acidic environments. The maximum loss of test specimens was less compared to that of ordinary Portland cement product for the same duration. The extent of damage with acid exposure is directly proportional to acid concentration of immersion solution.

8.2. Heat resistance

Under extreme heat loading, geopolymer form a microstructure based on alkermanite (rather than the initial C-S-H product) which gives superior mechanical and thermal resistance properties. Geopolymer under heat loading do not release toxic fumes, experience low weight loss and are nonflammable in the presence of high temperature.

8.3. Freezing and thawing resistance

Geopolymers are also resistant to the effect of repetitive freezing and thawing cycles. Hence geopolymers proves highly resistant to both temperature extremes.

9.CASE STUDIES

9.1 Current trends in cement and concrete production

The building materials sector is the third-largest CO_2 emitting industrial sector worldwide representing almost 10% of the total anthropogenic CO_2 emissions, most of which are related to concrete manufacture. About 85% of these CO_2 emissions come from the provision of cement. Almost 95% of this CO_2 is released during production and only 5% during transport of raw materials and finished products. It is known that CO_2 emissions need to be reduced from their 1990 levels in developed countries by a factor of 2 in 2020 and by a factor of 4 in 2050. Today's data indicate that it seems technically feasible to design concrete to meet "factor 2" objective, but a technological breakthrough is needed to reach "factor 4" objective. Hydrated ordinary Portland cement (OPC) is the most common binder used in concrete. In cement production, limestone is the major raw material used that is burnt at 1450 °C to produce clinker and is then blended with additives. The finished product is finely grounded to produce different types of cement. During cement production, around 0.92t of CO_2 is released for each ton of clinker produced. This emission is mainly shared between de-carbonation of limestone (0.53t), and the use of carbon-based fuels for heating (0.39t). Average CO_2 emissions associated with grinding processes are in the order of 0.1 t of CO_2 per ton of cement and are mostly associated with electricity production. Because of the importance of the cement industry, many studies are carried out to assess its future prospects in terms of CO_2 reduction potential and compare energy efficiency improvement options.

The two main approaches to reduce CO_2 emissions associated with the cement supplied for concrete manufacture are reduction of CO_2 emissions during clinker production and reduction of the clinker content in cement. Their main factors are involved in assessment of CO_2 emissions during clinker production: the type of raw materials used the type of fuels, and the thermal efficiency of the kiln.

Limestone could be replaced by materials with lower carbon but similar calcium content; such materials are not abundant though and mainly include blast furnace slags (BFS), steel slags, and cement waste. The availability of these wastes is not guaranteed as the world production of BFS was almost 150 million tons in 2005 compared to 2500 million tons of clinker production. Alternative fuels (petcoke, coal, natural gas, used tyres, waste oil, plastic, waste wood etc.) can be used to reduce cost and CO_2 emissions. Most of them though have not been approved as carbon-neutral. These, as defined by the EU legislation, are mainly agricultural and forestry biomass, biodegradable municipal waste, animal waste and paper. Waste materials derived from fossil fuels such as solvent, plastics, used tyres are not regarded as carbon neutral. It is argued though if burning of carbon-neutral waste can be regarded as a GHG sink because they decay to form methane which is much a more powerful GHG than CO_2. Clinker itself can be partly substituted by industrial by-products such as coal fly ash or granulated blast-furnace slag (GBFS). These cements meet European standards and are commonly used. It has to be considered though that cement based materials adsorb CO2 from the atmosphere, as a result of carbonation that takes place during the effective life of a concrete structure as well as after demolition. This issue has to be considered during the assessment of impacts of construction materials.

9.2 Geopolymer vs. OPC concrete

Geopolymerisation has definitely a good potential for the production of "green" concrete and construction materials with lower carbon footprint. In order to accurately assess this potential, the environmental impact of geopolymers has to be quantified by considering also the impact of the byproducts (or wastes) used through Life Cycle Assessment (LCA) studies. Fig. shows a simplified concept of a life cycle system.

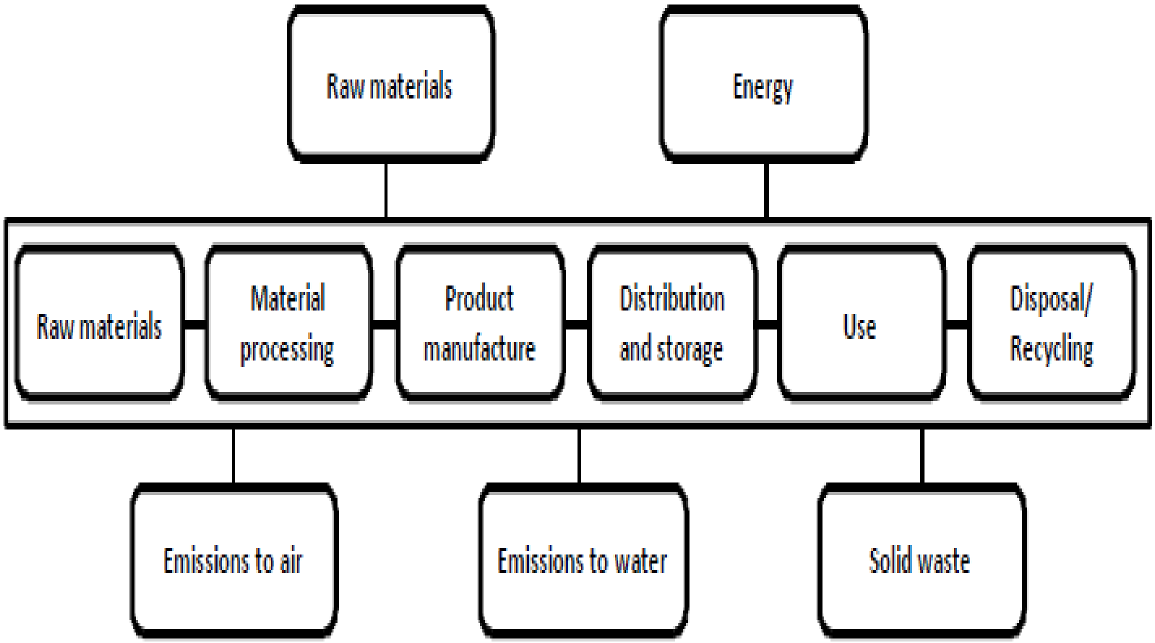

Fig 4: life cycle system

The limited literature so far shows that the production of most standard types of geopolymer concrete has lower impact on global warming than standard OPC concrete. Two geopolymer mix-designs were evaluated based on the LCA principle by considering a few environmental impact categories (global warming, energy and resource depletion). Recently, a detailed environmental evaluation of geopolymer concrete production using the LCA principle was carried out.

This study shows that geopolymer concrete made from fly ash (FA) and GBFS results in lower CO_2 emissions than OPC concrete. The environmental impact of geopolymer concrete is related with the use of sodium silicate solution as activator that results in pollution transfer within all other environmental impact categories. Today, the production of sodium silicate utilizes pure glass cullet but discarded glass cullet could be easily used as alternative silicate source. The best way for the concrete industry to reach its current CO_2 objectives, would be to produce geopolymer concrete from raw material with a suitable Si/Al molar ratio which is recognised as industrial waste and does not have an allocation impact. In fact, geopolymer technology allows the use of waste instead of a by-product from an LCA point of view. Magnesium-iron and ferronickel slags cannot be utilized with the blended cement technology, but can be used as geopolymeric binders. Slag based geopolymer concrete only requires small amount of sodium silicate and therefore has low environmental impact. Furthermore, the use of these wastes reduces environmental impacts associated with their disposal and subsequent generation of hazardous leachates. Concerning MK based geopolymer concrete it has been shown that due to the low Si/Al ratio in MK a high amount of sodium silicate is required causing thus a high environmental impact. The use of thermally activated clays with a higher Si/Al ratio than MK or slag mixed with MK could be also considered. Particle technology could be also utilized for the production of OPC based concrete in order to improve granular distribution and packing reducing thus the quantity of active binder required

10.DISCUSSION

The sustainable city of the future should cover human needs and maintain a superior quality of life. Without asking at this point which will be the future human needs and quality of life, in other words which will be the definition of sustainability in future; it is almost certain that the “zero waste” principle and the development of new materials with a lower carbon footprint will be priority issues. The EU "Thematic Strategy on the prevention and recycling of waste" sets out the objectives and means in order to further improve management of waste and energy resources. The Lead Market initiative in recycling, points out the need to promote innovations in recycling. The Waste Framework Directive sets the waste hierarchy and more ambitious targets for re-use, recycling and recovery of some categories of waste. With respect to the waste hierarchy, this means that a clear priority will be given to prevention, reuse and materials recycling unless "lifecycle thinking" justifies a deviation from the hierarchy. Wastes included in these categories are industrial as well as construction and demolition. It is clear though that the innovative products produced should comply with international products' standards. The building sector embraces aspects such as design, selection of materials, use of natural resources as well as interaction with different socio-economic, regulatory and administrative aspects. Construction activities consume more raw materials by weight than any other industrial sector. In addition, the anticipated future lack of virgin aggregates will definitely increase their cost, while the longer-term trend in cement use in Europe is rather uncertain. The built environment moreover, accounts for the largest share of GHG emissions in terms of energy end usage. Measured by weight, construction and demolition activities produce Europe's largest waste stream, most of which is recyclable. Environmental aspects consider, in an integrated approach, consumption of raw materials, in-door air quality as well as water and energy efficiency to reduce the environmental impact of construction. The market for green building materials is rapidly expanding. Such materials should be environment friendly, durable, bio-based and recycled, and should be characterized by low toxicity and emissions. Green materials often exhibit noticeable potential to reduce indoor ozone and can be used to eliminate human exposure to ozone, which is generally higher indoors than outdoors. Researchers and practitioners have long disagreed about the financial benefits of investing in green buildings. Researchers generally believe that most green buildings can be built at almost no additional cost while practitioners often identify high initial cost premiums as barriers to adopting and investing in green practices. As a result, there is a need for researchers to communicate directly with practitioners in order to use knowledge generated and eventually address gaps, limitations, and problems. The European Spatial Development Perspective strongly advocates the 'compact city' (or the city of short distances) integrating thus land-use, transport and daily activities more effectively. The trend today is for greater densities and mixed land uses so that emissions and energy consumption are significantly reduced. A critical question though is if a similar trend is anticipated in future. In contrast to Portland cement, most geopolymer systems rely on minimally processed natural minerals and industrial by-products or wastes to provide binding agents enabling thus noticeable energy and CO2 savings in the construction sector. Further work is required though to improve the technology and strengthen its potential for commercial applications in order to reduce the environmental footprint in the sustainable city of the future.

11.CONCLUSION

•Since the primary ingredients of geopolymers are an industrial by-product (fly ash), clay; geopolymers are relatively inexpensive to produce.

•Production of geopolymer cements does not generate harmful greenhouse gas emissions and is therefore considered as environmentally friendly

•Geopolymers does not require extended cure durations normally necessary for Portland cement-based materials.

•The resistance of geopolymer with sulfate and acidic environments prevents the formation of ettringite and gypsum which can lead to cracking and deterioration.

•Hardened geopolymer materials do not allow significant heat transfer and perform well in extreme heat environments.

•Geopolymers maintain much of their moisture during reaction, and the result is negligible mass loss.

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