Advancements in Civil Engineering and Architecture

Editor: Volkan Kahya



Volume 2: Architecture

ICEARC'19 INTERNATIONAL CIVIL ENGINEERING AND ARCHITECTURE CONFERENCE 2019

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Proceedings of the International Civil Engineering & Architecture Conference,
17 – 20 April 2019, Trabzon, Turkey

Advancements in Civil Engineering and Architecture

Volume 2: Architecture

Editor
Volkan Kahya
Karadeniz Technical University

golden light publishing®

ISBN: 978-605-81854-3-2 (Tk)
978-605-81854-5-6 (2.c)

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Trabzon Teknoloji Geliştirme Bölgesi Yönetici A.Ş.
Üniversite Mahallesi Hastane Caddesi No: 33, 61081 Trabzon
E-mail: info@goldenlightpublish.com
http://www.goldenlightpublish.com | http://www.dynaaca.com

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INTERNATIONAL CIVIL ENGINEERING AND ARCHITECTURE CONFERENCE 2019
ICEARC'19
17-20 APRIL 2019 TRABZON / TURKEY
Karadeniz Technical University

GEOPOLYMERS IN ARCHITECTURE

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Abstract

Cement production is energy-intensive and CO_2-emitting process. The process produces air pollutants in the form of various oxides, particulates and heavy metals which are detrimental to habitat. Thus, the quest for energy efficient alternative materials has been continued around the world. Portland-pozzolan cement (CEM IV), limestone-calcined clay-cement (LC3) are the alternative cements based on reducing the amount of clinker by blending it with pozzolans and as well as limestone which can reduce CO2 emissions by up to 30%.

As a cement-free binder, geopolymer may be regarded as another alternative to ordinary Portland cement. The term "geopolymer" was first coined by Davidovits in 1970s. It is an amorphous three dimensional covalent bonded aluminosilicate binder formed by alkaline activation of aluminosilicate solid materials. Because the limestone is not used in the mixture, geopolymers are more energy-efficient alternative than their counterparts. Geopolymer cement has 70-90% lower embodied greenhouse gas intensity than an equivalent amount of ordinary Portland cement. Hence, in the study recent research done on geopolymer binders; their practical applications in architecture; comparative material properties according to expected performance requirements; available standards on geopolymers are scrutinized and probable assumptions are made on its potential use as an alternative for cement in the future. Research results reveal that geopolymer binder does have the potential to be extensively used in architecture.

Keywords: Geopolymer; cement; material; architecture

1. Introduction

Cement is currently the most widely used construction material throughout the world. In 2017, around 4.100 million tons of cement was produced worldwide (Statista 2017). In 2017, Turkey became the 1st cement producer in Europe and 5th cement producer in the world with its 83.6 Mt/yr of clinker and 135.6 Mt/yr of cement production capacity (TCMA 2017a). 10% of the cement is exported to approximately 80 countries including Senegal, Haiti, USA, Libya, Iraq, Syria, Israel, Bulgaria, Brazil, and Hungary etc. According to the Turkish Cement Manufacturers' Association (TCMA 2017b), Turkey has 52 integrated plants and 20 grinding units.

Cement production is an energy-intensive process and responsible for 5% of anthropogenic global CO_2 emissions (Cement Technology Roadmap 2009). Each ton ordinary Portland cement production causes approximately 1 ton CO_2 emissions (Garcia-Lodeiro et al. 2015a) stemming from cement manufacture including calcination of limestone, heating raw materials within a rotating kiln at temperatures greater than 1400°C and grinding processes. The process produces air pollutants in the form of various oxides, particulates and heavy metals which are detrimental to living world comprising humans, animals and plants. The quest for energy-efficient alternative materials has been continued around the world. Recently, the cement industry develops energy-saving and environmental safety policies which comprise the commercial scale application of binding materials with minimum clinker amount (RILEM TC 224-AAM 2014). Portland-pozzolan cement (CEM IV) is an alternative cement in which the amount of clinker is decreased with 11-35% natural and artificial pozzolan substitution. Limestone-calcined clay-cement (LC3) is new type alternative cement based on reducing the amount of clinker by blending of 15% limestone, 30% calcined clay and 5% gypsum (LC3 2017). As cement-free binders, alkali-activated materials (AAM) or geopolymers may be regarded as other alternatives to ordinary Portland cement. In the study recent research done on geopolymer binders; their practical applications in architecture; comparative material properties according to expected performance requirements; available

standards on geopolymers are scrutinized and probable assumptions are made on its potential use as an alternative for cement in the future.

2. Geopolymer-based Binders

Alkali-activated materials or geopolymers are cement-free binding materials produced by the alkali-activation of various aluminosilicate materials such as industrial by-products (fly ash, slag), natural pozzolans, calcined natural mineral of kaolinite and various wastes including mining, municipal, construction and demolition (Garcia-Lodeiro et al. 2015b). The alkali-activation is made by using any soluble material which includes alkali metal cations such as alkali hydroxides, carbonates, silicates, sulfates, or aluminates. Geopolymers are viewed as a subset of alkali-activated materials with the highest Al and lowest Ca contents (RILEM TC 224-AAM 2014) and are called as 'inorganic polymers, inorganic polymer glasses, mineral polymers, alkali-bonded ceramics, soil cements, hydroceramics' (Provis and van Deventer 2009). When the solid aluminosilicate material and the activator solution react with each other, an aluminosilicate network formed and the hardening starts. The characteristic of the aluminosilicate network (amorphous and/or crystalline) and consequently the properties of a geopolymer, depend on the type of its components, composition, curing conditions (Buchwald et al. 2007)

Geopolymers have high compressive strength (up to approximately 100 MPa, Davidovits 1991) with rapid strength gain under specific curing conditions; resistance to high temperature and fire; resistance to acid and chemical attack; good volumetric stability after hardening; high initial internal pH leading to passivation of reinforcing steel; low permeability (RILEM TC 224-AAM 2014). Fine particles such as sand may be added in order to make geopolymer mortar, and aggregates may be added to make geopolymer concrete (Hardjito et al. 2002). In addition, the CO_2 emission of production of geopolymers is 60–80% less than that of the traditional cement (Zhang et al. 2014) (Table 1) which is mainly because of the absence of a high-temperature calcination process in geopolymer production (RILEM TC 224-AAM 2014). The greenhouse gas emissions during the life cycle of geopolymer concrete are approximately 70-90% lower than that of ordinary Portland cement concrete (Davidovits 2015).

Table 1. Energy-related emissions of CO_2 from the production of binders (Berge 2009)

Types	(gCO_2/kg)
Lime	750
Portland cement	860
Fly ash/Portland cement	670
Blast furnace slag/Portland cement	350
Geopolymeric cement	290

3. Practical Applications of Geopolymer-based Materials

One of the earliest studies for the use of alkaline chemicals to develop an alternative binder to cement was the setting of slag in the presence of dry potash investigated by H. Kühl in Germany in 1930 (Palomo et al. 2014). A.O. Purdon determined that clinker-free cements could be produced by high-calcium slag and caustic soda in Belgium in 1940 (Purdon 1940). V. Glukhovsky worked on the alkali-activation due to the shortage of ordinary Portland cement in post-World War II Eastern Europe in the Ukraine in 1950s (RILEM TC 224-AAM 2014). Glukhovsky determined that low-calcium cementitious materials could be produced by using clays and alkaline metal solutions (1-20%, by mass) and it was called as 'soil cement' (Glukhovsky 1957).

In 1973 J. Davidovits, a French researcher, patented numerous aluminosilicate-based materials (Davidovits 1982) and called them as 'geopolymer' (Davidovits 2011). The main aim of Davidovits was to produce nonflammable and incombustible inorganic polymers against catastrophic fires in France. His studies gained interest from the industrial organizations and government in USA (Malone et al. 1985). P. Krivenko in USSR in 1986, worked on the physical and mechanical properties of alkali-activated slag concretes under the specific name of 'geocement' (Krivenko 1986). In 1999, A. Palomo et al. investigated the possibility of the production of cementitious materials from alkali-activated F-type fly ashes (Palomo et al. 1999).

Over the 60 years, there have been many attempts to investigate the manufacturing and using of alkali-activated materials or geopolymers by many countries such as Canada, India, Brazil, Spain, Bulgaria, Japan, China, USA,

Netherlands, Germany, Czech Republic, Slovak Republic, Romania, Poland, Finland etc. (RILEM TC 224-AAM 2014). Applications of geopolymers in various areas are summarized in Table 2.

Table 2. Applications of geopolymers in various areas

Year	Hydraulic	Road	Architectural & civil engineering	Other applications
1960s	pipes, drainage and irrigation channels, sea breakwaters	railway sleepers, road sections, pedestrian way slabs	flooring for dairy farms, pre-cast slabs, pre-cast blocks for the construction of houses, garages and 15-storey apartment buildings	
1970s		railway sleepers, pavements from cast-in-situ concrete and reinforced concrete slabs, road bases from strengthened soils	binders for grouts and mortars, alkali-activated concrete for flooring slab and external walls of industrial storehouses, production of autoclaved foamed alkali-activated BFS (blast furnace slag) concrete, development of autoclaved aerated concretes by alkaline activation of metakaolin and fly ashes	waste immobilization
1980s			6-storey buildings constructed with alkali-activated concrete, precast beams and columns, alkali-activated binders for roofing tiles	
1990s		pre-mixed alkali-activated concrete for cast-in-situ or precast slab driveways for heavy vehicles, alkali-activated concrete for the rapid placement of runways	alkali-activated concrete for bridge deck overlays, high-rise residential buildings (exceeding 20 storeys) were built using alkali-activated BFS concrete. The exterior walls of the buildings were cast in situ, and the floor slabs, stairways and other structural components were pre-cast.	materials for radioactive waste immobilization
2000s onwards	sewer pipes, tunnel segments, water tanks, sea-shore structures, concretes for marine applications, mortar for the rehabilitation of pipes, structures in civil infrastructure	alkali-activated concrete heavy-duty pavement units, pre-cast footpath panel segments, bridge retaining walls	alkali-activated concrete pre-cast exterior wall panels, large floor beams, columns, deck bridge structures, wall claddings, geopolymer materials as fire-resistant coatings for modular housing, geopolymer foam for thermal insulation material, sprayed geopolymer fire-resistant foam	Immobilization of nuclear wastes, inorganic adhesive and glues, protective coatings against corrosive environments and high temperatures

In the 1950s, alkali-activated cement and concrete production as a structural material became on a commercial scale in Belgium. The brand name of this material was called as ‘Le Purdociment’. In a building given in Fig. 1a,

parts of the first six levels were constructed from Purdociment. In 2010, the building was inspected and determined as it was in good state (RILEM TC 224-AAM 2014).

Beginning from the 1960s, an institute in Ukraine has been worked in order to construct railway sleepers, road sections, pipes, drainage and irrigation channels, pre-cast slabs and blocks and buildings from the alkali-activated blast furnace slag (BFS). After many years, the investigations of these structures reveal that the alkali-activated BFS has high durability and compact microstructure. In addition, in Ukraine the production of precast blocks from the alkali hydroxide-activated BFS concretes was initiated by 'Azovshelezobeton' in the same years. These blocks were used for the construction of the garages, and apartments (Fig. 1b). This company closed in 1980, but later, in 1999, Ilyich Iron and Steel Integrated Works re-started the production of pre-mixed alkali-activated BFS concrete and used the material for precast or cast-in-situ driveways for heavy vehicles, self-levelling concretes in road construction, and load-bearing structures (RILEM TC 224-AAM 2014).

(a)  (b) 

Figure 1. (a) The 'Parking 58' building in Belgium; (b) Residential building in Ukraine constructed from alkali activated BFS precast blocks (RILEM TC 224-AAM 2014)

After 1970s, alkali-activated binders have been used as grouts and mortars in dams, railway sleepers and in waste immobilization in Poland. In addition, the alkali-carbonate activated BFS concretes have been used as external walls and the flooring slabs in a warehouse. This building was inspected 27 years after the construction, and the test results revealed that it exhibits great durability and serviceability. Within the same years, in Russia, the production of autoclaved foamed alkali-activated BFS concrete was started. In addition, in Kiev, the autoclaved alkali-activated aerated concretes by using metakaolin and fly ash as aluminosilicate sources were produced. The 40×40×4 cm panels were foamed using aluminum powder and the density of the blocks was 600 kg/m^3 (RILEM TC 224-AAM 2014).

In 1973-76 J.J. Legrand developed fire-resistant chipboard panels composing of a wooden core faced with two SILIFACE Q nanocomposite coatings (Fig. 2). The manufacturing process is very different because, for the first time, the entire product was manufactured in a one-step process. The hardening of wood chips and organic glue occurred simultaneously with the setting of silico-aluminate (Na-Poly(sialate)/quartz nanocomposite) at 150°C for 5-10 minutes (Davidovits 2002). The Industry Partners were the French companies and the client was the French Government in order to be used for high school and university buildings. It was decided to build a pilot plant, but, in 1976, building policy was changed and the project was stopped.

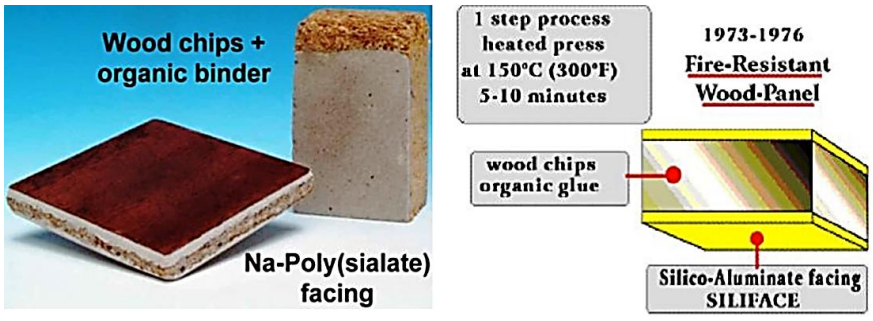


Figure 2. Manufacture of fire-resistant wood-chipboards faced with geopolymer (Davidovits 2002)

Between 1980-1990s ‘The Pyrament Cement’ as a blended portland/geopolymer cement consisting of 80% ordinary Portland cement (OPC) and 20% geopolymeric materials activated with potassium carbonate (Davidovits 1994) was used for the rapid placement of damaged pavements and for bridge deck overlays in the USA and U.S. military (Davidovits 2011). It has a high early strength and its compressive strength increases up to 80 MPa, with 20 MPa achieved within 4–6 h of pouring even at low ambient temperatures (Husbands et al. 1994). Although its production ceased, the Pyrament is still listed as ‘Approved Materials’ in the list of road agencies in USA. Moreover, the durability of the Pyrament is regarded as ‘excellent’ since it has been still in use at airport runways after 25 years (RILEM TC 224-AAM 2014).

An office building consisting of 6 storey was constructed in China from sodium sulphate activated-Portland-BFS cement and crushed limestone coarse aggregate in 1988 (Fig. 3a). The average strength at 28 days was 24.1 MPa. The concrete was mixed on site using a concrete mixer. Because the building is in service at present, it may be inferred as the durability of this alkali-activated concrete is good. Furthermore, in the same county in those years, a workshop area was built using the same material (Fig. 3b). The columns (40x40 cm) were cast-in-situ and the beams (35x45 cm and 12.6 m span) were pre-cast on site and then assembled. Today, there are still no durability issues in the building (RILEM TC 224-AAM 2014).

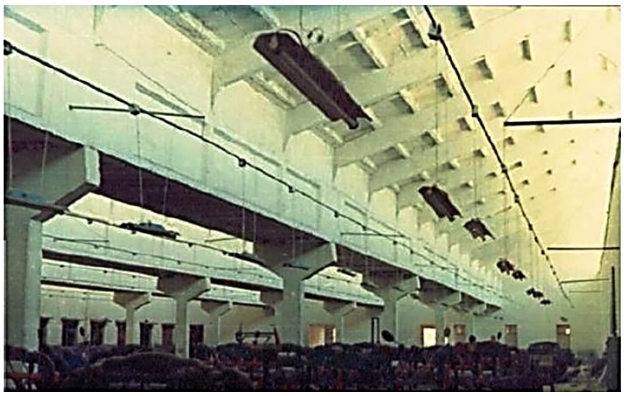
(a)  (b) 

Figure 3. (a) 6-storey building constructed with alkali activated Portland-BFS concrete; (b) Workshop constructed with alkali activated Portland-BFS concrete beams and columns (RILEM TC 224-AAM 2014)

Granulated BFS was activated by sodium silicate and liquid NaOH in order to produce roofing tiles in Finland in 1988. These tiles were installed on the roof of a house (Fig. 4). After 24 years, none of the tiles are damaged, their painted surface is intact and no moss is found (RILEM TC 224-AAM 2014).



Figure 4. House in Finland, roofed with alkali-activated BFS tiles in 1988 (RILEM TC 224-AAM 2014)

Between 1986 and 1994, various high-rise buildings were constructed with alkali-activated BFS concrete in Russia (Fig. 5a). The exterior walls of these buildings were cast-in-situ, and the stairways and flooring elements were pre-cast with steam-cured in a factory. During the same years, cast-in-situ alkali-activated BFS concrete roads were built in Ukraine. After 10 years the properties of the road material were inspected and compared with a side-by-side Portland cement concrete road. Alkali-activated BFS cement concrete road were in a good state while the Portland cement concrete road damaged severely (Fig. 5b) (RILEM TC 224-AAM 2014).

(a)  (b) 

Figure 5. (a) 20-storey residential building built with alkali-activated slag cement concrete in Russia in 1994 (Palomo, 2014); (b) Comparison of cast-in-situ alkali-activated slag concrete (on the left) and Portland cement concrete roads (on the right) (RILEM TC 224-AAM 2014)

Investigations related with alkali-activated materials have grown significantly since the 1990s. According to RILEM TC 224- AAM report, there are more than 100 active research centers (academic and commercial) operating around the world. In 2007, RILEM Technical Committee based on alkali activated materials was initiated in order to bring together the stakeholders from academia, laboratories and industry, to compile the experiences and to develop specifications for the development of standards. In 2014, RILEM TC 224-AAM state of the art report was published under the editorship of Provis and van Deventer (RILEM TC 224-AAM 2014).

Alkali-activated metallurgical slag known as ‘JK cement’ has been used for many years in China (Dong 1999). There are approximately 50 research centers have been worked on the alkali activated materials in China in recent years (Pan and Yang 2010). ‘ASCEM Cement Company’ has been working on the alkali-activation of synthetic glasses for more than 15 years in the Netherlands. ASCEM Cement consists of slags, fly ash and alkali-activators (2 to 5%) (Ascem 2019). The study results demonstrates that pavement units of 2×2 m (Fig. 6a) and sewer pipes (Fig. 6b) can be produced by using ASCEM Cement.

(a)  (b) 

Figure 6. The products which can be produced by using ASCEM Cement (a) slabs; (b) pipes (RILEM TC 224-AAM 2014)

Siloxo and Zeobond are private companies which make significant efforts to develop alkaline activation-based innovation. Siloxo (1999-2005) worked on New Zealand Class-C fly ash in pre-mixed concretes. Since 2005, Zeobond has been endeavoured for the commercial acceptance of alkali-activated concrete in Melbourne, Australia. It developed the E-Crete™ cement binder ('Earth Friendly Concrete' under license of Wagners Group in Queensland) which is produced from slag, fly ash, and alkaline activators. The strengths of the products are in the range of 20-55 MPa (Zeobond 2008). Zeobond company received INNOVIC's national 'The Next Big Thing Award' for E-Crete in 2008 (RILEM TC 224-AAM 2014).
Zeobond completed 'E-Crete pre-cast footpath panels across the Salmon Street Bridge' project in Melbourne in 2009. It has high early strength with 55 MPa and low shrinkage and long term durability properties (Fig. 7a). In addition, E-Crete in-situ footpaths having 25 MPa compressive strength was applied on Brady St. Port Melbourne (Fig. 7b). It was the first of the many pavement projects during these years. In the same year, 40 MPa grade structural concrete was produced for the restoration of the retaining walls of the bridge in Melbourne (Fig. 8a). It was applied by pumping. Moreover, on the exterior of the Melton Library in Melbourne 35 E-Crete pre-cast cladding panels, having 9 m long and 40 MPa compressive strength, were installed in 2012 (Fig. 8b) (E-Crete, 2014).

(a)  (b) 

Figure 7. (a) E-Crete pre-cast footpath panels across the Salmon Street Bridge in Melbourne; (b) E-Crete in-situ footpaths at Brady St in Port Melbourne (E-Crete 2014)

(a)  (b) 

Figure 8. (a) E-Crete retaining wall at the Swan Street Bridge in Melbourne; (b) E-Crete pre-cast panels for Melton Library in Melbourne (E-Crete 2014)

'Earth Friendly Concrete (EFC)' is produced by Wagners Company in Australia (Wagner 2019). It is a geopolymer binder system consisting of blast furnace slag, fly ash and alkali activators. EFC was used for the construction of 43.5 cm heavy duty pavements (including the turning node, the taxiway and the hangars) of Brisbane West Wellcamp Airport in 2014 (Fig. 9). It was considered as the largest commercial application of geopolymer concrete in the world. 25.000 m^3 of concrete pavement and 15,000 m^3 of geopolymer concrete was

used in various applications such as; entry bridge to the airport, precast culverts, footings, piles, pads and the tunnel slab for the terminal building, pavements for median strips and road works and sewer tanks etc. Using geopolymer concrete in this project led to the reduction of 8.800 ton of CO_2 emission compared to conventional cement concrete (Aldred et al. 2015)

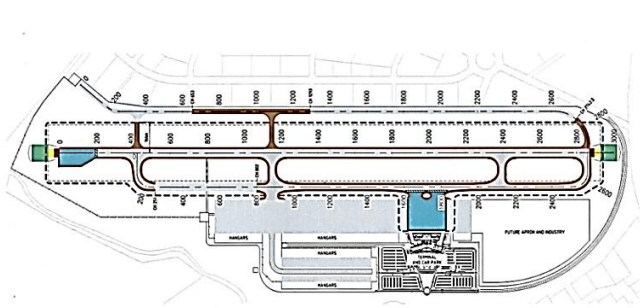
(a)  (b) 

Figure 9. (a) The overall plan and (b) aerial photograph of the geopolymer concrete pavement works at the BWWA (Aldred et al. 2015)

EFC was utilised for the construction of 11m span precast floor beams (40 MPa) used in the three suspended floors at The Global Change Institute Building in Australia (Fig. 10). The precast molds were filled and compacted and cured at ambient conditions during 7 days. With the application of these precast beams, the team showed that the geopolymer concrete could be finished similar to ordinary Portland cement concrete (Bligh and Glasby 2013).



Figure 10. Precast geopolymer beams of the Global Change Institute Building in Australia (Bligh and Glasby 2013)

The residual strength of engineering materials after fire exposure is very important. In 1996, Lyon et al. stated that geopolymer composites reinforced with glass or carbon fibres have higher fire resistance compared to that of composites with thermoset, phenolic or engineering thermoplastics. It can be seen in Fig. 11 that after exposure to severe heat flux (800°C), the geopolymer composites have higher residual strength, which makes them appropriate materials for aircraft cabin fire protection (Majidi 2009).

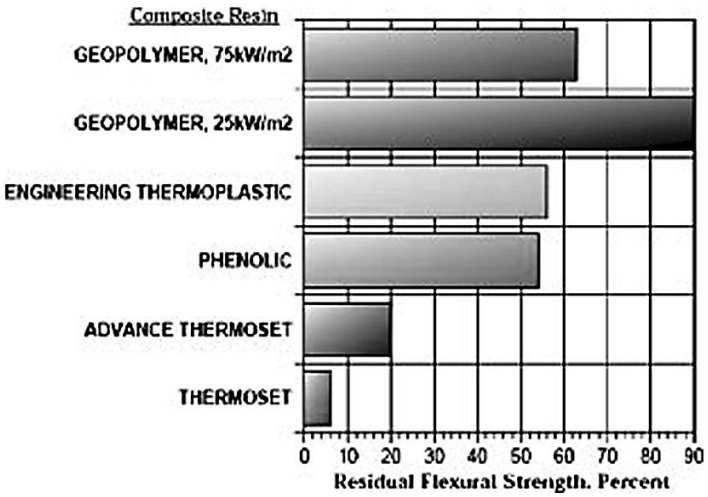


Figure 11. Residual flexural strength of cross-ply laminates after fire exposure (Majidi 2009)

Air Force needs fire-resistant coatings to allow the occupants enough time to escape from the fire. Thus, 'Ceramatec Inc.' has been working on producing fire-resistant geopolymer coatings for modular housing. The company prepared a geopoymer matrix with enhanced thermal stability up to 1350°C and applied it on the polyurethane substrate (Fig. 12a) with a carbon fabric applied on the top of the coating (Fig. 12b) (Boxley et al. 2007). In addition, 'Renca Company' which was founded in 2016 produces a wide range of materials based on geopolymer technology. One of the most important product of the company is sprayed geopolymer fire-resistant foam which has high durability in the case of fire, according to the test applied at 1000°C for 2 hours in compliance to REI 120 class in Italian standard (Fig. 13a). Renca Company also produces acid, sulphate and salt resistant products from geopolymer concrete such as seashore structures (Fig. 13b) (Renca 2019).

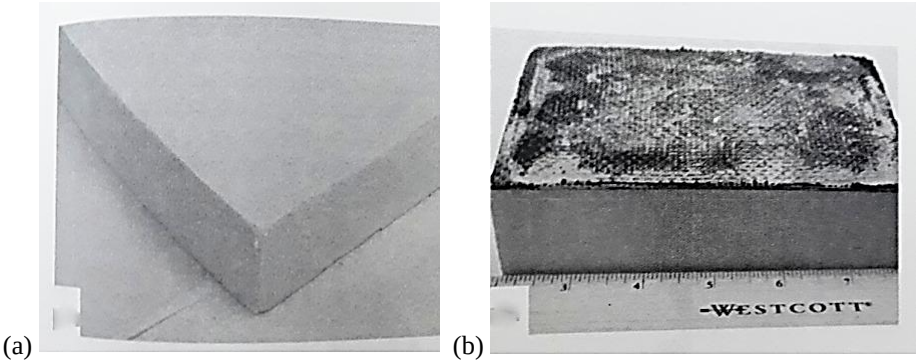


Figure 12. (a) Uncoated polyurethane substrate; (b) Geopolymer coated carbon fabric (Boxley et al. 2007)

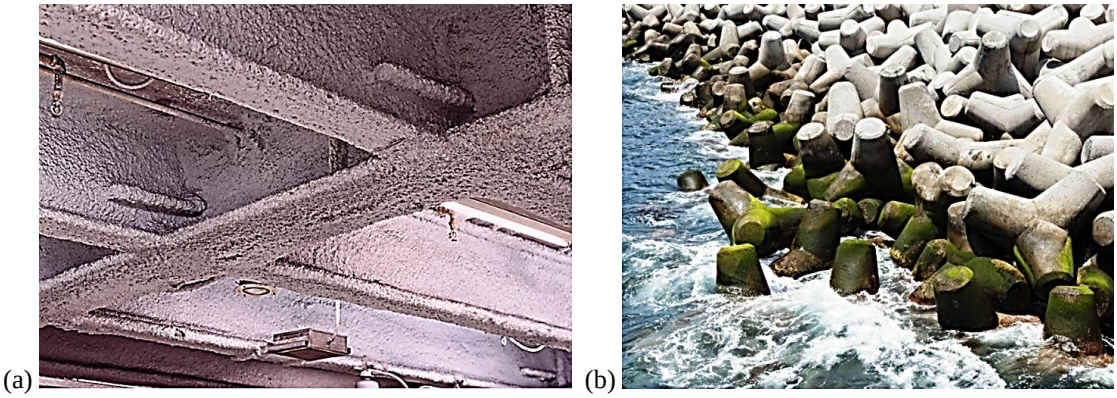


Figure 13. (a) Sprayed geopolymer fire-resistant foam; (b) Sea-shore structures (Renca 2019)

'Milliken Infrastructure' is providing the rehabilitation materials from geopolymer mortar to the infrastructure of construction sector for many years. The sprayed geopolymer mortar is used for retrofitting the storm-water, sanitary and industrial sewers due to its corrosion resistance (Fig. 14) (Milliken 2019).

(a) 

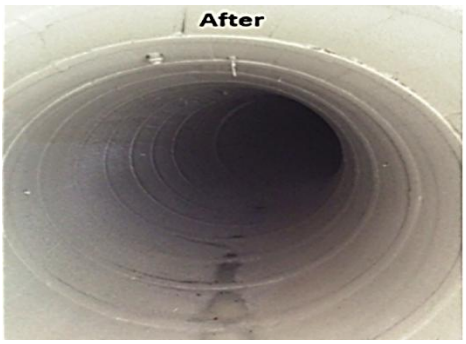
(b) 

Figure 14. The rehabilitation of sewers with geopolymer mortar (Milliken 2019)

In the literature, the physical and mechanical characteristics of fly ash based geopolymer concrete were inspected and compared with ordinary Portland cement concrete (Table 3). According to Bakri et. Al. (2013), when both mixtures have the same binder ratio (fly ash:aggregate 50:50, and OPC:aggregate 50:50) the 28^{th} days compressive strength of geopolymer concrete (approximately 43 MPa) is 1.38 times higher than that of the traditional concrete (approximately 31 MPa). The density of geopolymer concrete is comparable with OPC concrete. The porosity and the water absorption ratio of geopolymer concrete were lower than OPC concrete. The study results have revealed that geopolymer concretes may be in better quality compared to traditional Portland cement concrete.

Table 3. Physical and mechanical characteristics of geopolymer concrete compared to ordinary Portland cement concrete

Properties	Portland cement based concrete	Geopolymer based concrete
Compressive strength (MPa at 28^{th} days)	31	43
Density (kg/m^3)	2200 – 2400	2290 – 2460
Porosity (%)	3.0 – 5.1	1.0 – 1.9
Water Absorption (%)	1.3 – 2.5	0.4 – 1.0

4. Standards for Geopolymer-based Materials

The standards ensure that the materials have generic qualities, appropriate for their intended use, and meet regulatory requirements. Before a new material is launched to the market, it must meet the requirement of the existing standards. However, the existing standards may not allow the development of a non-conventional new material or there may not be a new standard for this new technology and preparation of a new standard may be a long process. Most of the international existing Ordinary Portland Cement standards are not suitable for the products such as geopolymer cement and concrete due to the differences in their composition and hydration products (RILEM TC 224-AAM 2014). Thus, the acceptance of geopolymer technology in the construction sector may be limited.

Approximately 60 standards, which are technical documents for choosing suitable raw materials to use in geopolymer applications developed in the USSR and Ukraine between 1961-2007 and the acceptance of these standards allows the industrialization and commercialization of this type of cements (RILEM TC 224-AAM 2014). The latest standard on alkaline cements was approved in Ukraine in 2009. Ukrainian standard DSTU B V.2.7-181 (2009), classifies these cements according to their composition and 28-day compressive strength. This standard may be regarded as "Ukraine's pioneering activity" and may be the sole inspiration for 'legislators' drafting future standards (Palomo et al.2014).

RILEM TC 224-AAM recommends carrying out a performance-based standard in order to provide description and regulation of alkali-activated binders and concretes. Among the other EN and ASTM standards, ASTM C-1157 (2010) is more amenable than others, because it is a performance-based cement standard and has no

restrictions on the composition of the cement. It covers hydraulic cements for both general and special applications and classifies cements as; (1) General use, (2) High early-strength, (3) Moderate sulfate resistance, (4) High sulfate resistance, (5) Moderate heat of hydration, (6) Low heat of hydration. So, according to the report of RILEM TC 224-AAM, AAM may conform to one of the classified cement types, as long as the performance requirement is met (RILEM TC 224-AAM 2014).

5. Turkey Context

In Turkey, there have been 25 thesis (5 of PhD thesis and 20 of master thesis) published on the basis of geopolymer based building materials since 2010 (Al-Mashhadani 2018; Çetintaş 2018; Aden 2017; Seçkin 2017; Manguri 2016). In addition, a lot of academic studies regarding the physical, mechanical and chemical characteristics of geopolymer/alkali-activated binders, mortars and concretes exist in the literature of Turkey (Yıldızay et al. 2014; Memiş et al. 2017; Aydın and Pehlivanlı 2017; Aydın 2017; Kaya et al. 2018). However, almost all of these studies have been done by the academic world in various universities and there has been any comprehensive attempt to investigate the manufacturing and using possibilities of the alkali-activated materials for practical applications in the building sector. It is necessary to initiate the commercial-scale production of geopolymer-based architectural materials, as given in Section 3, and to determine their possible application areas in the construction sector countrywide.

6. Conclusion

Following conclusive remarks can be stated from the current study:

1. Commercial-scale production of geopolymers has occured since 1950s in many countries around the world. These materials have been used in structural engineering and architectural applications as;
    - Pipes and sewer pipes, sea breakwaters, sea-shore structures, drainage and irrigation channels, tunnel segments and water tanks;
    - Railway sleepers, road sections, pedestrian way slabs, cast-in-situ or precast slab driveways, and pavements;
    - Flooring slabs, precast wall panels, beams, columns, and stairways, roofing tiles, binders for grouts and mortars, fire-resistant foams.
2. Geopolymers which have been in service for various years reveal that they display high durability without problems with regard to service life which may mean they have high resistance to a wide range of climatic and service conditions like freeze-thaw, acid, sulphate, salt, corrosion and fire effects etc.
3. The efforts to show the suitability of using geopolymers in architectural applications are increasing gradually with the contributions of academic researchers, companies, and industry. Recently, more end users have become aware to use of them due to their more environment-friendly properties compared to Portland cement-based materials. However, complete replacement of traditional Portland cement by geopolymer is not so easy, because the traditional Portland cement has a lot of national and international standards and commonly approved throughout the world. Although making geopolymeric products as a widely accepted commodity needs long time, commercial attempts are encouraging. There is still much progress to be made, especially regarding with the drafting of suitable standards to geopolymers. With a proper standardization, the acceptance of geopolymer technology in the construction sector will become widespread.
4. Although there are various academic thesis and research articles regarding with the physical, mechanical and chemical characteristics of geopolymer binders, mortars and concretes in Turkey, the absence of attempts to investigate the manufacturing and using possibilities of these materials in practical applications should be considered carefully. The commercial-scale production of geopolymer-based architectural materials should be started by the cement and concrete production companies, by taking support from academia. All the stakeholders comprising architects, structural engineers, cement and concrete companies, regulators and insurers should be in cooperation in order to determine the suitable construction-applications from the produced new materials. Whether the new-produced alkali activated materials comply with the approved cement and concrete standards of Turkey should be checked. If the existing standards may not allow to the development of new geopolymeric materials, initiatives should be taken to develop new standards. To fulfill this, Turkey may follow these footsteps:
    - Technical documents or codes for choosing suitable raw materials to use in geopolymer binders should be developed.
    - The physical, mechanical and chemical properties of geopolymer binders, mortars and concrete should be determined according to their compositions.

- Authorities should approve officially the geopolymer binders for the construction of structures.
- When the industries work on the production of geopolymer materials, they should benefit from these national codes on the industrialization and commercialization of these products.
- Technical documents should be brought together and a comprehensive performance-based national standard for 'geopolymers in architecture and civil engineering applications' should be approved.
- Last but not least, it is necessary to investigate the industrial scale production of geopolymer technology in Turkey to find out if existing equipment and technology can be used with relatively lower cost.

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