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Geopolymer mortars as sustainable repair material: A comprehensive review

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ABSTRACT

Environmentally sustainable repair materials with reduced carbon footprint have been in great demand by the construction industry worldwide. Gradual deterioration of concrete containing large quantities of Portland cement is inevitable, and requires repair or replacement. Numerous repair materials including cementitious mortars, polymer-modified cementitious mortars, resinous mortars, etc. have been utilized to rectify the problem. Cement-free geopolymer mortars prepared from waste materials with high content of silicate aluminum and alkaline activator solution are emerging as prominent sustainable repair materials. Geopolymer binders are preferred because they generate 70–80% less carbon dioxide with remarkably lesser greenhouse gas emissions than ordinary Portland cement. These new binders are highly sought-after due to their enhanced durability performance, sustainability, and environmental affability. This paper provides a comprehensive overview of state-of-the-art research on sustainable geopolymers for repairing deteriorated and damaged concrete structures as well as restoring their integrity. Present challenges and future prospects of various geopolymer mortars as repair materials are emphasized.

1. Introduction

Perhaps the greatest challenge in fighting climate change comes from the production of cement which is the main constituent of concrete; and the world's appetite for it seems insatiable. Beside the United States fast-growing developing countries like China, India, and yet another wave of countries like Turkey and Indonesia will be using even more. Robert Hutchinson (2016) writes; "Globally we produce over 4 billion metric tons of Portland cement per year — the key ingredient in concrete and responsible for the majority of its CO_2 footprint" Cement production is linked with excessive carbon dioxide emissions. Looking for an acceptable and practical substitute is a daunting task for which research continues. In the construction engineering sector, ordinary Portland cement (OPC) has been widely utilized as effective binder in concrete and other building materials. The production of OPC is widely recognized as a major contributor of greenhouse gas emissions [1–6], which amounts to 6–7% of all the CO_2 emissions as documented by International Energy Agency (IEA) [7].

Still the global demand of OPC will increase to almost 200% by the year 2050 [8–10]. Mitigating those emissions and the problems associated with them, a new type of alternative sustainable green and environmental friendly material so called geopolymer concrete (GPC) is realized [10]. Generally, geopolymer mortars (GPMs) are reported to be much more sustainable than OPC in terms of lower energy requirement for production with significantly less CO_2 emissions [11–13].

The concept of geopolymers was initially introduced as a new material by Joseph Davidovits in 1978 [14,15]. Those three-dimensional aluminum silicate inorganic polymers composed of AlO_4 and SiO_4 tetrahedral ions were mainly prepared from industrial wastes [16,17]. Their unique three-dimensional oxide network structures originating from inorganic polycondensation make them advantageous for repairing. They possess several interesting features such as high strength, corrosion resistance, water resistance, high temperature resistance, enclosed metal ions etc. [18]. Geopolymers find broad range of applications in the field of transportation, emergency repairs, metallurgy, coating, membrane materials, and nuclear waste disposal [19–24]. Despite significant commercial and technological potential geopolymers' easy-brittle character limits their extensive applications [18] where great efforts are made to overcome such shortcomings.

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Numerous studies are dedicated to optimize the strength of geopolymer products and to understand the mechanism of geopolymerization. Bernal et al. [25] examined the evolution of binder structure in sodium silicate-activated slag-metakaolin blends to determine the effects of metakaolin addition on the final binder strength. Silva and Sagoe-Crenstil [26] inspected the Al_2O_3 to SiO_2 ratio dependent setting and hardening of the geopolymer system. This ratio demonstrated the effects of setting time and final strength of the geopolymer. Chindaprasirt et al. [27] studied the influence of SiO_2/Al_2O_3 and Na_2O/SiO_2 on the setting time, workability, and the final strength of geopolymer system. It was acknowledged that the best ratios ranged between 2.87 to 4.79 for SiO_2 to Al_2O_3 and within 1.2 to 1.4 for SiO_2 to Na_2O for geopolymer binder. Bernal and Provis [28] addressed the durability of alkali-activated materials in terms of their recent progress and perspectives. They used the accelerated degradation testing methods to determine the effects of elevated concentrations of CO_2, sulfates and chlorides on the durability.

Over the years, geopolymers have been exploited as protective coating materials for marine concrete and transportation infrastructures [29,30]. However, the bond strength between the substrate concrete and the repair material [31,32] plays a decisive role when selecting geopolymers as repair materials. The properties of GPC [33,34], including modulus of elasticity, Poisson's ratio, and tensile strength are similar to those of OPC concrete. This clearly displays the compatibility between GPC and OPC concrete. Furthermore, similar to conventional concrete GPC can cure at ambient temperatures [35–37]. The degree of degradation of GPC when soaked in acid solution is significantly lower than that of OPC concrete [38,39]. Furthermore, they possess low permeability and excellent anticorrosion properties which are beneficial for effective bonding with cement paste and mortar [40]. Geopolymers can be implemented using the same equipment and practices as used for OPC concrete to repair deteriorated infrastructures such as manholes, pipes, and chambers, [41]. Geopolymers' high temperature stability make them an excellent alternative to epoxy resins [42]. More significantly, the production of FA-based geopolymeric mortars or concretes releases 80 to 90% less CO_2 than OPC counterparts [43–46]. All these notable merits make geopolymer an excellent candidate for pavement repair. Despite much effort in the synthesis and characterization of geopolymers, their durability as repair material is far from being understood.

Generally, the repair work in concrete is widely performed using commercial repair materials possessing good mechanical property and bond strength [47]. However, they are rather expensive. Thus, less expensive alternative repair materials with comparable properties are required. Several researchers [48–51] attempted to utilize geopolymer as a repair material by testing their slant shear, pull-out, and direct shear tests. Hu et al. [48] studied the bond strength between mortar substrate and geopolymer in sandwich specimens. Geopolymer exhibited higher bonding strength than that of comparable OPC mixture. Pacheco-Torgal et al. [49] determined the bond strength between concrete substrate and GPM produced from tungsten mine waste containing calcium hydroxide. They reported that geopolymer binders possess very high bond strength even at an early age as compared to commercial repair products. Songpiriyakij et al. [51] tested the bond strength between rebar and concrete substrate using geopolymer paste (GPP) as the bonding agent. They observed that the bond strengths of rice husk ash and silica fume GPPs are approximately 1.5 times higher than epoxies. Consequently, the bond strength of geopolymer materials is sufficiently high making it suitable as an alternative bonding material for repair works.

According to Chotetanorm et al. [52], OPC is an energy intensive product because it consumes substantial amount of energy and releases high volume of greenhouse gases. In the past, efforts have been made to reduce the use of OPC by introducing other supplementary cementitious materials. In this regard, another form of cement called geopolymer emerged as an environment-friendly solution. The development of GPMs in terms of synthesis, characterization and implementation are happening at a rapid pace. The main objective of this paper is to provide an overview on the past development, recent progress and future prospects of GPMs in the construction sector. The feasibility of exploiting GPMs as effective repair materials for deteriorated concrete and structure protection are emphasized. The potential of geopolymer as construction material with enhanced sustainability, energy-saving, reduced CO_2 emissions, for use in harsh environments is also addressed. Not to mention effective use of recycling industrial wastes and avoidance of depleting natural resources and are also discussed. The results obtained about geopolymer's durability in terms of bond strength between the repair material and the substrate deteriorated concrete are also presented by using the splitting tensile and slant shear tests. The performance of geopolymers as repair materials can be **highlighted** by their bond strength. It is argued that the widespread usage of environmentally affable geopolymers can be a crucial move toward low carbon footprint.

2. Merits and demerits of Portland cement production

The OPC is the workhorse of construction industries. It is manufactured by heating limestone or chalk with clay in a rotary kiln to a high temperature about 1450 °C. In this process hard nodules of clinker are produced which are then ground with a little gypsum via ball milling. The firing process consumes considerable amount of coal or petroleum coke as fuel. Rapid depletion of landscape, dust production during transport, and generation of noise throughout quarrying and raw material processing are considered leading environmental concerns involving OPC manufacturing. Furthermore, as Hutchinson [53] pointed "OPC cannot be made without releasing significant amounts of CO_2, which happens in two stages: through burning fuel to produce the very high kiln temperatures needed; and through a calcining chemical reaction that occurs when the limestone is heated." Even the most efficient plants still release 60 percent or more of CO_2 from this unavoidable chemical reaction. Grinding in the clinker stage that consumes a significant amount of electrical energy is another major environmental concern. Surmounting all these problems mystifies the OPC industry [54,55]. Indisputably, until alternative concrete material to OPC is commercially actualized, OPC will remain the key ingredient in construction materials utilized the world over.

OPC has also shown substandard performance in acid or sulphate environment especially in case of marine structures. The presence of calcium compounds in OPC makes it non-resistant towards acid attack. The easy dissolution of calcium compounds in acidic environment results in the increased porosity and rapid deterioration [56]. Actually, the already built OPC structures over the past several decades are undergoing through inevitable disintegration phase in some places [57]. Undeniably, the durability of OPC is related to the properties of its ingredients which among others are around 60–65% CaO while its hydration product contains about 25% of $Ca(OH)_2$. It is the aggressive response of $Ca(OH)_2$ to the acidic environments that makes OPC a poor water containing system, which is ascribed to the fusion of ice and subsequent contraction resistance against harsh environments. On the top, the evolving CO_2 upon reacting with the $Ca(OH)_2$ leads to fast erosion of the OPC based concrete or mortars [57]. Cracking and corrosion of OPC affect significantly the service life cycles, durability, design life and safety. Such notable demerits of OPC persuaded researchers to find a new binder as an alternative to traditional OPC simply to achieve environmental sustainability as well as ensure the durability of structures.

3. Sustainability of geopolymer concrete

The primary goal of sustainability is to maintain life on earth for the foreseeable future by supporting or caring the ongoing processes without disturbing the ecological balance [58]. Sustainability is based