Effect of different types of Waste as Binder on Durability Properties of Geopolymer Concrete: A Review

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ABSTRACT: Large amount of waste ash are produced by various industries. Some of the major waste ashes produces by industries include fly ash (FA), ground granulated blast furnace slag (GGBFS), Red mud (RM), ferrochrome slag (FS), Metakaolin (MK). Waste ashes also include agricultural residues like rice husk ash (RHA), sugarcane bagasse ash (SBA) and palm oil fuel ash (POFA). These waste ashes plays an enormous challenge while it comes to the dumping of these materials. On other hand, conventional cement concrete consumes huge amount of cement which generates huge amount of CO₂ during the production phase. To overcome these problems, utilization of these waste materials is necessary. Thus geopolymer concrete has been developed as a substitute to conventional cement concrete, where alkali activators react with the binder along with fine and coarse aggregates. The binder for geopolymer concrete can be any industrial or agricultural waste which are rich in silica and alumina that collectively not only lead to the reduction in the environment pollution and waste management problem but also in enhancement of the properties of concrete. The purpose of this paper is to review the durability performance (like Sorptivity, Water absorption, Acid attack, Chloride attack, Wetting-drying cycles) of geopolymer concrete utilizing waste materials like FA, GGBFS, MK, VA, POFA, RM, FS, SBA and RH etc. as binder to determine its suitability in the construction industry. The durability of geopolymer concrete utilizing fly ash and slags as binder have shown good resistance than other binder combinations and therefore proves to be better replacement to the conventional cement concrete.

KEYWORDS: Geopolymer concrete, Durability, Sorptivity, Water absorption, Acid attack, Chloride attack, Wetting-drying cycles.

1. INTRODUCTION

Due to the rapid growth in urban population, large quantity of waste ash produced (like fly ash, GGBFS, Red mud, ferrochrome slag, Metakaolin) by various industries and agricultural residue (like rice husk ash, sugarcane bagasse ash and palm oil fuel ash) which plays an immense challenge while it comes to the dumping of these ash materials due to ecological, health, lack of lands and other issues. To overcome these problems consumption of these waste materials is necessary. In the construction industry, conventional cement concrete which has an extensive use as a construction material consumes huge quantity of natural ingredients and produces huge quantity of carbon dioxide throughout the making of cement which ultimately gives rise to global warming. Moreover, cost of everything including construction materials are increasing hurriedly. It is expected that within 10 years the price of cement will be double. Hence, finding an alternative to cement concrete is of great importance [1-5].

According to past researches in recent years, the most extensively accepted substitute to overcome such a problem is geopolymer concrete which has been developed as a substitute to conventional cement concrete. It is a mixture of any binder (the binder can be any industrial or agricultural waste) which is rich in silica and aluminum oxides which reacts in presence of alkali activators (such as Sodium Silicate or Sodium Hydroxide) along with fine and coarse aggregates to produce geopolymer concrete [5]. Incorporating wastes as binder in geopolymer concrete can not only help to improve environmental credibility of concrete industry, but also...
help to improve concrete strength and durability depending on their pozzolanic activity. Several researcher reviewed about the strength properties of GPC and found that they could be equivalent or even higher compared to the OPC concrete but one of the main difficulty associated with this GPC is the lack of available data on their long term durability properties. This paper studied the durability performance (like Sorptivity, Water absorption, Acid and salt attack, Chloride attack, Wetting-drying cycles) of geopolymer concrete utilizing waste materials as binder to determine its suitability in the construction industry. The wastes incorporated as binder in this reviews are FA, GGBFS, MK, VA, POFA, RM, FS, SBA and RHA which are rich in silica and/or aluminum oxides and very easily available.

Figure 1: Schematic diagram of the feasibility of GPC in sustainable construction.

Table 1: Chemical composition of OPC and different types of waste (%).

| Chemicals  | OPC [2]  | Fly ash [3] | GGBF S [5] | Metakolin [2] | Volcanic ash [20] | POFA [36] | RM [25] | FS [26] | SBA [45] | RHA [16] |
|-----------|----------|-------------|-------------|--------------|-------------------|-----------|---------|---------|----------|----------|
| SiO$_2$   | 21.35    | 50.50       | 31.52       | 53.32        | 46.28             | 53.5      | 5.54    | 33.80   | 64.2     | 93.96    |
| Al$_2$O$_3$ | 7.67    | 26.57       | 12.22       | 42.09        | 15.41             | 1.9       | 18.8    | 25.48   | 9.1      | 0.56     |
| Fe$_2$O$_3$ | 3.31    | 13.77       | 1.14        | 2.33         | 13.32             | 1.1       | 51.8    | 0.61    | 5.5      | 0.43     |
| CaO       | 62.60    | 2.13        | 44.53       | 0.09         | 9.07              | 8.3       | 3.27    | 1.10    | 8.2      | 0.55     |
| MgO       | 3.08     | 1.54        | 4.62        | 0.21         | 6.74              | 4.1       | -       | 35.88   | 2.9      | 0.4      |
| Na$_2$O   | 0.35     | 0.45        | 0.21        | 0.49         | 3.88              | 1.3       | 6.84    | -       | 0.9      | -        |
| K$_2$O    | 0.39     | 0.77        | 0.33        | 0.64         | 1.42              | 6.5       | 0.08    | -       | 1.4      | -        |
| MnO       | 0.05     | -           | 0.36        | 0.02         | 0.19              | -         | 0.04    | -       | -        | -        |
| TiO$_2$   | 0.25     | -           | 1.03        | 0.63         | 2.84              | -         | 0.23    | -       | -        | -        |
| LOI       | 0.95     | 0.60        | 0.79        | 0.08         | 0.4               | 18.0      | 1.90    | -       | 4.9      | -        |
2. DURABILITY PROPERTIES OF THE WASTES BASED GEOPOLYMER CONCRETE

Durability of OPC concrete in aggressive environment always been a problem and this deterioration is determined by means of sorptivity, water absorption, acid attack, chloride attack, Wetting-drying cycles etc. So, effect of GPC exhibited to theses extreme situations are discussed in this study. Though, strength and durability of GPC is also generally affected by numerous factors comprising its role of binder, chemical composition of raw materials, mix design, alkaline activator used, concentration of alkaline activator used, aggregates, accelerator, mixing, transporting, compacting, curing time, curing temperature, curing type and calcium-silicate-hydrate phase etc. However here only the aggressive environmental factors affect the durability of GPC are discussed.

Sorptivity is defined as the rate of absorption of water by capillary suction into the specimen [6]. From sorptivity analysis it was found that concrete with denser structure has less porosity and it was also confirmed by the results of pore size distribution analysis [1]. Sorptivity test results of several days’ cured fly ash and metakaolin based geopolymer samples confirmed that it absorbs lesser water than cement concrete. Test results also indicated that geopolymer might resist better outer medium opening including water and acid than cement concrete that associate to improved permeability resistance [2]. In case of geopolymer concrete based only on fly ash after cureshow lower water absorption than OPC concrete which indicates that porosity is reduced because of fly ash which is finer than cement and it leads to denser structure [7, 8, 9]. But after 28 days, in some casessorptivity increased may be due to the development of capillary porosity network [3]. It was established that by adding nano-silica in geopolymer mortars based on fly ash alone or fly ash blended with 15% GGBFS or 10% OPC enhanced the density of microstructure by decreasing permeability. As a result, the nano-silica improved compressive strength and reduced sorptivity of the mixes [10]. Ambient cured fly ash based nano-silica incorporated geopolymer showed considerable resistance against water absorption than fly ash based geopolymer cured by heat which does not contain nano-silica. This may be because of existence of additional quantity of crystalline compound in nano-silica incorporated fly ash based geopolymer which reduced the diffusion coefficient [11]. Geopolymer concrete made of GGBFS also showed low permeability may be due to the less permeable and denser structure of it [4, 12]. By increasing molarity, curing temperature and alkaline solution to binder ratio of fly ash, GGBFS and silica fume based geopolymer mortars water absorption and voids ratio decreased due to formation of gypsum crystals [13]. The water absorption of reusable

Figure 2: Factor affects the durability of GPC.

2.1 Sorptivity and Water absorption study

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geopolymer aggregates were found to be lesser than reusable OPC concrete aggregates in addition to natural aggregates and the same trend followed by the light weight geopolymer concrete with the increase in amount of fine aggregates [5, 14]. This happened may be due to the filler effect of aggregates which filled the pores in the matrices thus reducing the porosity and the structure becomes denser. Rice husk ash addition in GGBFS based geopolymer concrete reduce its sorptivity than cement concrete as a result of the fillereffect of fine RHA particles [15]. 3% by weight of total fly ash and RHA based geopolymer was replaced with 2% nano-silica and 1% nano-alumina by weight which leads to reduced water absorption. It was due to amorphous and nano-silica particles which speed up the geopolymeric reactions and act as nano-fillers, hence a denser matrix with low water absorption formed [16]. Less permeable concrete has higher strength and higher resistance to weathering. Absorption of water and available pore volume measurements indicated greater concentration and pore enhancementall through the development of gel structure with respect to time, although this is little noteworthy at greater Metakaolin quantity [17]. Fly ash and metakaolin based geopolymersamples shown reduced water absorption than cement paste due to decrease in porosity of geopolymer pastes, which is associated with improved permeability resistance [2]. Geopolymer consisting of ground granulated blast furnace slag (GGBFS) which was water cooled and air cooled slag (ACS) used as binder along with MWCNT shown good resistance against water absorption by decreasing porosity of its matrix [18]. Oven cured volcanic ash based geopolymer concrete shown good resistance against water absorption than ambient cured one due to presence of less amount of open pores [19]. The saturated water absorption percentage of geopolymer concrete based on fly ash reduces with increasing water binder ratio [20]. Water absorption of hardened fly ash and wastepaper sludge based geopolymer mortar reduced with growing paper sludge content at ambient temperature because samples with higher sludge loadings consist of comparatively smaller pores [21]. Geopolymer based on fly ash and palm oil fuel ash shown increase in permeability and sorptivity may be because of the substitution of exchangeable cations in polymers by hydrogen or hydronium ions and development of a few zeolitic phases [6]. Addition of recycled coarse aggregate (RCA) in fly ash based geopolymer concrete adversely affects its properties. Though it gives better results than OPC which contains same amount of RCA. This points towards denser microstructure of geopolymer than the OPC [22, 23]. OPC concrete has lesser sorptivity and water absorption rate than geopolymer concretes based on fly ash and granulated slag (GLSS) but, by adding graphene nano platelets (GNPs) to geopolymer binders the microstructure of geopolymer concrete can be enhanced [24]. For the density variance, metakaolin and red mud based geopolymer concrete has shown greater values of water absorption may be due to the presence of higher porosity in its structure [25, 26]. For ferrochrome slag based geopolymer concrete, water absorption slightly decreased up to 300°C but after that water absorption increased [27]. This may be due to the dehydration of the crystals after exposure to such immense temperature.
2.2 Acid/Salt Attack study

The acidic and salty substances present in environment like sulfuric acid, hydrochloric acid, magnesium sulfate, sea water is very harmful, it leads to deterioration of the strength of OPC concrete but in case of geopolymer concrete it shown superior acid resistance. The struggle of geopolymer pastes/mortar/concrete against acid attack have been evaluated by few researchers. The degree of degradation mainly governed by the density of acid solution and the period when it is exposed [7]. It has been observed that percentage of weight loss of the geopolymer specimen decreased with the increased molar concentration [28]. This performance of geopolymeric substances in acidic surroundings may be because of higher calcium content of original substance [3]. Strength & weight loss found more in magnesium sulphate medium than sodium sulphatemedium. This result was found may be due to the high impermeability of concrete mass [29]. Geopolymer concrete consisting of fly ash along with metakaolin after immersion in 2% sulphuric acid plus 2% hydrochloric acid solution for 28 days has shown far better acid resistance by producing denser microstructure compared to cement concrete specimens [18, 30, 31], which exposed to the acid solutions showed drastic degradation. There is 3.3% mass change in cement concrete but in case of geopolymer concrete it is only 0.7% for the first 28 days of exposure in acid medium, the strength declination was about 10.4% for geopolymer concrete in 28 days which reached to 22.2% after another 28 days and in case of cement concrete for the initial 28 days the strength declination was 34.4% which reached up to 57.8% after another 28 days of exposure [2]. This change in strength of geopolymer concrete may be because of the collapse of some geopolymeric alkaline constituents and emigration of some alkalis into the solution from the samples. Geopolymer specimens based on fly ash showed good resistance to sulphate attack may be due to less pore water and denser structure which point out that there was no formation of gypsum. But there was little mass loss occurred in case of sulphuric acid attack which was less than OPC, that means acid exposure has less effect on geopolymer than OPC [32, 7]. Geopolymer consisting of GGBS and fly ash showed satisfactory performance with a good resistance to sulphate compared to other concretes. Compressive strength slightly decreased instead of increasing after sulphate immersion may be due to the relative humidity [33]. GGBS based geopolymer concrete shown strength gain when exposed to magnesium sulphate and loss in strength when exposed to sulphuric acid [34]. After exposure to sulphuric acid solution, through visual examination it was found that slag based geopolymer specimens showed little surface deterioration with colour change, fly ash based geopolymer specimens shown moderate with no colour change and OPC specimens showed greatest surface deterioration with colour change. But when exposed to magnesium sulphate and sea water they remain structurally intact with no colour change. Increase in weight was witnessed in all samples especially in case of sulphuric acid solution after first 15 days of exposure because of absorption of solution and growth occurred due to gypsum. After one month of exposure, due to deterioration weight loss occurred in all specimens but height and weight loss both occurred in OPC. This has been established that sulphuric acid attack appears to be more dangerous than sea water and magnesium sulphatesolutions for both OPC and geopolymer concretes [35]. Geopolymer concrete based on Palm oil fuel ash (POFA) and dry pulverized fuel ash (PFA) specimen also showed less strength loss than cement concrete (35% compressive strength loss in geopolymer concrete and 68% in OPC concrete) after 18 months of sulphuric acid exposure. This may be due to the nature of the binder gel system [36]. Fly ash along with GGBS and silica fume based geopolymer concrete shown better resistance against sodium sulphate and magnesium sulphate than PPCC and OPCC by forming gypsum which...
leads to denser microstructure and narrower micro cracks[13, 37]. Between sodium sulphate and magnesium sulphate solution, fly ash, GGBS and silica fume showed better resistance against the first one [38]. Fly ash and ground glass fibre (GGF) based geopolymer showed good resistance against sulphate attack by forming gypsum [39]. Fly ash along with geopolymer concrete based on granulated lead smelter slag shown good resistance against sodium sulphate and sulphuric acid than OPC concrete, by forming gypsum. While acting together with sodium sulphate, geopolymer concrete’s compressive strength was reduced because of leaching of sodium hydroxide [25]. Geopolymer based on fly ash showed good strength against 5% sodium sulphate plus 5% magnesium sulphate solution by forming stable cross-linked alumino-silicate polymer structure [40]. Nano silica incorporated fly ash based oven cured geopolymer concrete showed better result than OPC concrete against chemical attacks thanks to low calcium content. On other hand fly ash along with 10% OPC or 15% GGBFS enhanced the density of microstructure by decreasing permeability without oven curing. Nano-silica has a filler effect and improved reactivity of the alumino-silicate origin constituents which improved the pore structure to grow a denser microstructure [10, 41]. Geopolymer concrete based on fly ash prepared using higher alkali content shown good resistance against sulphate attack than lower alkali content by forming gypsum [42]. Resistance to Acid and alkali of fly ash based geopolymer pastes can be improved significantly by calcination at 600°C, though due to it compressive strength reduces almost 30%, because of loss of the structural water and crack appearance [43]. Geopolymer based on fly ash and palm oil fuel ash shown poor strength against acidic peat water owing to change of the replaceable cations in polymers by hydrogen or hydronium ions and development of more or less zeolitic phases [6]. Fly ash based geopolymer mortar samples showed better resistance to nitric acid and hydrochloric acid solutions compared to conventional cement mortar specimens. By increasing water binder ratio the weight loss of specimens in acidic environment could be reduced [21]. Geopolymer based on fly ash shown improved acid resistance than OPC and the deterioration detected in geopolymer was associated to de-polymerisation of the alumino-silicate polymers in acidic medium and development of zeolites that sometimes leads to major strength reduction [44].

Sugarcane bagasse ash based geopolymer concrete also shown decent resistance against sulphate attack but its resistance is lower than metakaolin based geopolymer concrete may be due to presence of more silica in its chemical composition [45]. Metakaolin based geopolymer shown good resistance against hydrochloric acid. From FTIR analysis it was found that exposure to hydrochloric acid formed major alterations in a few of the alumino-silicate spectral bands which gave a further steady cross-linked alumino-silicate polymer structure made in the substance [46].

Volcanic ash based geopolymers samples which were cured at 27°C developed an enhanced resistance towards acid than the samples cured at 80°C due to formation of gypsum. The relation of geopolymer binder with sulphuric acid leads to gypsum formation. The loss of compressive strength was 24% and 60% after 180 days of curing on specimens at 27°C and 80°C respectively. For samples cured at 27°C and 80°C, the loss of weight was reduced with strength and reached 3.51% and 3.1% respectively. The acid resistance of specimen which were cured at 27°C enhances due to presence of Na-rich gel and its pore structures [20].

Compressive strength of both geopolymer based on ferrochrome slag and OPC concrete samples reduces with increment in quantity of MgSO₄ and exposure period but due to production of gypsum and absorption of exposed liquid weight increases slightly in geopolymer [47].

2.3 Chloride content/penetration study
Concrete’s chloride ion resistance rests on the perviousness and interconnectivity of the pore structure than the chemical binding capacity of the paste [24]. In geopolymer concrete with greater density of NaOH, the reduction in chloride penetration found which may be due to the modification of the pore structures and due to poly-condensation reaction and filler effect. The comparatively greater density of NaOH aided the leaching of additional amounts of Silica and Alumina from fly ash which leads to a superior degree of poly-condensation and caused declination of porosity of geopolymer concrete [48]. Ambiently cured fly ash based nano silica incorporated geopolymer shown considerable improvement in chloride resistance than geopolymer based on fly ash cured by heat which does not contain nano-silica. This may be because of the existence of greater quantity of crystalline compound in nano-silica incorporated fly ash based geopolymer which reduced the diffusion coefficient [11]. Fly ash based geopolymer showed good chloride resistance than OPC due to its less porosity which leads to denser structure [7, 8, 9]. GGBS based geopolymer concrete shown strength improvement when exposed to sodium chloride [34]. Geopolymer consist of both fly ash and GGBS showed satisfactory performance with a good strength to chloride ingress caused by its lesser permeability compared to OPC [12, 33]. Addition of rice husk ash in GGBS based geopolymer concrete exhibited good strength to chloride permeability than cement concrete down to the filler effect of fine RHA particles [15]. GGBS and metakaolin based geopolymer concrete shown good resistance against chloride penetration which is controlled by pore solution chemistry and almost no alteration found after curing from 28 to 90 days [17]. Low mass fluctuation observed of fly ash and metakaolin based samples in sodium chloride. Maximum 0.3% mass fluctuation of specimens observed in sodium chloride solution [30]. After six wetting/drying cycles i.e. about 132 days of dipping in NaCl, chloride content of geopolymer concrete based on fly ash (low calcium) has improved by nearly 29% than to the value calculated one day afterwards that may be as a result of the combined outcomes of longer time contact with chloride ions and the wetting/drying cycles [45]. Addition of RCA (recycled coarse aggregate) in fly ash based geopolymer concrete adversely affects its properties. Though it gives better results than OPC which contains same amount of RCA. This point toward denser microstructure of geopolymer than the OPC [24].

2.4 Wetting-drying cycles study

After tedious cycles of drying at high temperature and wetting in salt water, the geopolymer concrete showed degradation of concrete cover and significant weight loss which is less than OPC concrete. But the geopolymer concrete was more vulnerable to corrosion compared to the OPC concrete. Under impressed voltage accelerated corrosion tests their time of failure were 3.86–5.70 times lengthier than OPC concrete. This happens may be due to the increased availability of ions of fly ash and alkaline activators by huge quantities in the geopolymer concrete matrices which can create greater electrical resistance at high impressed voltage which improves the cathodic reaction and decreases speed of corrosion. Due to this tensile stress of the samples has reduced, therefore the possibility of cracking decreased and the period to failure extended [3]. After six wetting/drying cycles i.e. about 132 days of dipping in NaCl, chloride content of geopolymer concrete based on fly ash (low calcium) has improved by nearly 29% than the value calculated one day afterwards that may be as a result of the combined outcomes of longer time contact with chloride ions and the wetting/drying cycles [45]. In case of geopolymer based on fly ash and granulated lead smelter slag, compressive strength varied because of the difference in the internal stresses triggered by the raised temperature and breached sulphates and chlorides [25]. Volcanic ash based geopolymer shown 24% and 14% reduction in strength and no visual wear was detected on the surface after 25 cycles for samples cured at 27°C and 80°C respectively [20].
3. DISCUSSION AND CONCLUSION

In this paper the durability properties of different type of wastes like FA, GGBFS, MK, VA, POFA, RM, FS, SBA, and RHA has been incorporated in the binder during the formation of geopolymer concrete is reviewed. Investigations about geopolymer using wastes as binder shows that, it have great potential for substituting the OPC in construction. GPC have lower calcium content (than OPC) and it forms denser microstructure which in terms makes geopolymer concrete more durable than OPC. This study shows that GPC has a great resistance to sorptivity, water absorption, aggressive environments (like acid and salt attack, chloride penetration), wetting-drying. Moreover, the use of wastes can lead to a safe dumping of these waste products, avoid health issues, reduces the emissions of CO₂ to the climate and cost of concrete. However, it must be taken into consideration that different wastes will give altered reactivity because of their varying chemical compositions. Simultaneously comparing ordinary concrete with geopolymer concrete, it is observed that the second one is more pronounce in terms of durability properties than the former one; therefore proves to be a better replacement to the conventional cement concrete.

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