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A Comparative Study on Strength and Thermal Properties of Conventional and Geopolymer High-Density Concrete

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ABSTRACT: Ordinary Portland cement concrete with normal aggregates provides low fire resistance compare to hematite and magnetite aggregates and hence proves normal aggregates are highly vulnerable in fire hazard situations. Geopolymer concrete with high density aggregates is cement less concrete binder which is based on alumina silicate reaction of fly ash and GGBS (Ground Granulated Blast Furnace Slag) with high density aggregates such as Hematite and Magnetite etc. This project mainly aims on effects of mechanical properties of conventional and geopolymer concrete with hematite and magnetite under various temperature conditions (up to 900°C). The thermal properties of geopolymer concrete can be increased by replacing cement with fly ash and GGBS (FA45-GGBS 50-SF-5), normal aggregates with hematite and magnetite using Sodium silicate ($Na2SiO3$) and Sodium hydroxide ($NaOH$) solutions as alkaline activators. The mix design is done for geo polymer and conventional concrete using both the aggregates, trials have been conducted for water cement ratios for M70 mix design. The types of mixes were CHNM (conventional concrete with normal aggregates), CHHM (conventional concrete with hematite aggregates) and CHMM (Conventional concrete with magnetite aggregates), GHNM (Geopolymer concrete with normal aggregates), GHHM (Geopolymer concrete with hematite aggregates) and GHMM (Geopolymer concrete with magnetite aggregates). Specimens were casted and cured for 7 and 28 days in curing tank. The mechanical properties of conventional and geopolymer concrete is determined under various temperature conditions via compressive strength. Compressive strength and thermal properties like thermal conductivity is found out by hot-wire method. The residual strength of all the specimens was calculated. The test results obtained, showed that the compressive strength of GHMM mix subjected to 450 ^{0}C and 600 ^{0}C temperature was 89% and 62% more compare to all other mixes.

KEYWORDS: Aggregates, high-temperature, thermal conductivity, specific heat, strength.

I. INTRODUCTION

Concrete is a durable, versatile material widely used for its strength and inherent fire-resistant properties, including low thermal conductivity and high density. Fire resistance is crucial for structural safety, as concrete helps prevent flame spread, maintains integrity, and withstands high temperatures. High-density concrete (HDC) and geopolymer concrete (GPC) are innovative types designed to enhance these qualities. HDC incorporates dense aggregates like hematite and magnetite, offering better strength retention and fire resistance at elevated temperatures, minimizing spalling, and effectively dissipating heat. This makes HDC ideal for applications requiring longevity under fire, such as nuclear power plants and tunnels.

Geopolymer concrete, made from industrial by-products like fly ash or slag, reduces CO_2 emissions by up to 90%, making it eco-friendly. Known for excellent durability, chemical resistance, and low shrinkage, GPC performs well in fire-prone or industrial settings. Thermal properties, such as conductivity and specific heat, are essential to concrete's performance. High-density concrete typically has increased thermal conductivity due to its dense aggregates, making it suitable for heat dissipation in nuclear and industrial environments. However, in energy-efficient buildings, balancing thermal conductivity with high specific heat is crucial for insulation. High specific heat allows concrete to retain heat, aiding in temperature regulation and energy conservation. Optimizing these properties enables engineers to create safe, resilient structures in various demanding environments.

II. LITERATURE REVIEW

Nikolaos Nikoloutsopoulos, et.al., Jan 2022. Physical and Mechanical Properties of Fly Ash Based Geopolymer Concrete Compared to Conventional Concrete. The research explores the physical and mechanical properties of fly ash (FA)-based geopolymer concrete (GC) in comparison to traditional Portland cement concrete (CC)[19]. The study finds that GC demonstrates competitive compressive strength to CC, achieving its maximum strength at just three days and maintaining it over two years [20]. The tensile strength of GC is comparable to CC and meets the limits specified by Eurocode 2. However, GC's modulus of elasticity is about 50% lower than CC's, affecting its deformation capacity, which is up to 35% greater than CC [21]. The study concludes that GC, particularly with 750 kg/m³ FA being optimal for balancing engineering performance and environmental impact [22].

*Binita Yumkham, Chitra Shijagurumayum et. al., June 2022. The Fire Resistance of Concrete Structure***.** The review paper "Fire Resistance of Concrete Structure - Concrete's fire resistance is primarily attributed to its non-combustibility, low thermal conductivity, and non-toxicity, which enable it to slow down heat transfer and protect structures from fire damage [23]. Fire resistance depends on factors such as aggregate type, moisture content, density, and thickness. Research shows that concrete's compressive strength decreases with increasing temperatures, remaining acceptable up to 400°C but significantly dropping beyond 600°C [24]. Incorporating polypropylene fibers enhances tensile strength even at elevated temperatures up to 800°C. To further improve fire resistance, additional fibers like glass and natural fibers such as coir can be used.

Shashikant Chaturvedi, Ajitanshu Vedrtnam, Maged A. et.al., December 2022. Fire-Resistance Testing Procedures for Construction. This paper highlights Fire accidents pose significant risks to both human life and civil infrastructure, leading to the development of various fire-resistance testing standards worldwide, such as ISO 834, ASTM E119, and BS 476. While these standards provide guidelines for evaluating construction materials during fire exposure, they may not fully capture realistic fire scenarios due to variations in fire location and intensity. Researchers often employ specialized setups and full-scale non-standard fire tests to address these limitations [25,26]. The article emphasizes the need for regular updates to fire standards to include new construction materials and regional fire scenarios, noting that many countries follow the British standard, which offers detailed guidelines for traditional materials. There is a call for standards to consider advanced engineering materials to improve the reliability and relevance of fire-resistance testing [27].

Pooja Kumble, Prashant Shreelaxmi et.al., November 2023. Bond strength of alkali-activated fly ash-based masonry system for sustainable construction. This paper examines the bond strength of various masonry unit and mortar combinations to assess their adhesion performance. It focuses on traditional clay bricks and alkali-activated fly ash bricks paired with either conventional cement mortar or alkali-activated fly ash mortar [28]. Experimental results show that alkali-activated bricks with alkali-activated mortar offer superior bond strength across compressive, tensile, shear, and flexural tests compared to other combinations [20,21]. This pairing not only enhances structural performance but also supports sustainable construction by reducing carbon footprints. The study highlights the benefits of using matching alkali-activated materials for improved uniformity and strength in masonry structures. Future research should address long-term durability and perform environmental impact assessments to further support sustainable building practices [29].

Ganesh awchat, Mr. Sujit Kumar P Sulakhe et.al., October 2021. The Effect of Fire on Concrete and Enhancement in Fire Resistance Capacity of Concrete. This paper presents that Concrete is widely used in infrastructure but is vulnerable to fire damage, which affects its physical properties and the reinforcing steel. This paper presents a methodology for assessing fire-damaged concrete by testing cubes subjected to various temperatures [27]. It compares normal concrete with M20 grade and concrete mixed with carbonated aggregate. Results show that normal concrete exhibits a greater loss in compressive strength compared to fire-resistant concrete, with strength degradation increasing significantly at temperatures above 300°C [20]. Testing conditions such as air cooling, water quenching, and hot states affect surface hardness and mass loss, with the greatest strength reduction occurring after exposure to 900°C.

Siti Nooriza Abd Razak, Nasir Shafiq et.al., Jan 2021. Fire Performance of Fly Ash-Based Geopolymer Concrete: Effect of Burning Temperature This study investigates the fire performance of fly ash-based geopolymer concrete (GPC) compared to ordinary Portland cement (OPC)-based concrete [1]. Both types of concrete were exposed to flames at 500°C and 1200°C, followed by cooling and testing. The results show that GPC exhibited superior fire resistance, with increased strength at 500°C, minimal mass loss, and no spalling, unlike OPC concrete, which experienced significant spalling, cracking, and higher mass loss [4,27]. GPC also showed less surface cracking and maintained better structural integrity under fire conditions. Overall, GPC demonstrates enhanced fire resistance and durability compared to OPC-based concrete [30].

Salmabanu Luhar, Demetris Nicolaides et.al., February 2021. Fire Resistance Behaviour of Geopolymer Concrete. This review highlights the promising potential of geopolymer concrete (GPC) as a sustainable and fire-resistant building material [27]. Geopolymer concrete, made from aluminosilicate materials like fly ash and activated by alkali solutions, demonstrates superior fire and thermal resistance compared to ordinary Portland cement (OPC) concrete [31]. GPC maintains mechanical strength, reduces spalling and cracking, and exhibits greater chemical stability at high temperatures. Its performance under fire and thermal stress, along with its lower energy costs and environmental impact, positions GPC as a competitive alternative to OPC for future construction needs, promoting a shift toward more sustainable building practices [28].

Suha Ismail Ahmed Ali · Éva Lublóy. June 2022. The Fire Resistance Properties of Heavyweight Magnetite Concrete in Comparison with Normal Basalt- And Quartz-Based. This study evaluates the fire resistance of three types of heavyweight concrete: magnetite-based, basalt-based, and quartz-based. Magnetite-based concrete demonstrated superior heat resistance, with minimal changes up to 500°C and significant spalling only at 800°C [16]. Basalt-based concrete showed good resistance up to 500°C but experienced cracks and spalling at higher temperatures. Quartz-based concrete had the lowest fire resistance, with significant damage and spalling observed at 500°C and 800°C. Magnetite-based concrete maintained better mechanical properties and thermal stability, while basalt and quartz concretes exhibited increased porosity and strength reduction at elevated temperatures [32]. SEM analysis revealed microcracks and degradation in all concrete types, with the most severe effects in quartz-based concrete.

*Athika Wongkvanklom, Patcharapol Posi. February 2021. Strength, thermal conductivity and sound absorption of cellular lightweight high calcium fly ash geopolymer concrete***.** This study investigates the impact of foam content on the mechanical, thermal, and sound absorption properties of cellular lightweight geopolymer concrete (CLGC) [16]. Varying foam content from 2-12% by weight affected the unit weight, compressive strength, water absorption, and porosity of CLGC. Higher foam content led to lower unit weight and compressive strength but increased water absorption and porosity [20]. Thermal conductivity decreased with more foam, and sound absorption improved, making CLGC suitable for thermal and acoustic applications. The 4% foam content mix is ideal for structural lightweight concrete, while 8% and 10% mixes are suitable for masonry blocks, meeting ASTM standards for lightweight concrete [9].

Ni Komang Ayu Agustini, Andreas Triwiyono et.al.,26 May 2021. Mechanical Properties and Thermal Conductivity of Fly Ash-Based Geopolymer Foams with Polypropylene Fibers. This paper examines the impact of polypropylene (PP) fibers on the mechanical and thermal properties of fly ash-based geopolymer foams [17]. The study used Class C fly ash, activated by a mixture of sodium silicate and sodium hydroxide, with foam added at 40% and 60% volumes. Varying PP fiber content from 0% to 0.50% increased the tensile strength of the foamed geopolymer by enhancing crack connectivity [21]. While porosity reduced compressive strength, PP fibers improved the bonding within the geopolymer matrix, thus increasing strength [20]. The thermal conductivity was slightly higher than gypsum board and comparable to lightweight concrete, indicating that PP fibers significantly influence the thermal properties [9].

LIEW YUN MING, ANDREI VICTOR SANDU et.al., September 2023. Compressive Strength and Thermal Conductivity of Fly Ash Geopolymer Concrete Incorporated with Lightweight Aggregate, Expanded Clay Aggregate and Foaming

Agent. This research investigates the thermal stability of materials developed through alkali activation of slag, fly ash, and metakaolin compared to Portland cement mixture [16]. Using X-ray diffraction (XRD), thermogravimetric analysis (TGA), and high-energy X-ray computed microtomography (μCT), the study identified alkali-activated fly ash mortar (FA/M) as the most thermally stable material, with minimal damage when exposed to 650 °C. FA/M demonstrated superior heat dissipation, handling up to 565 °C in 50 mm of material without cracking, attributed to its favourable pore size and distribution [27]. In contrast, Portland cement mixtures suffered significant damage, while FA/M exhibited only a 10% increase in porosity after temperature exposure. Future research will explore the effects of high temperatures on compressive strength and nanomechanical properties [20,17].

III. METHODS AND METHODOLOGY

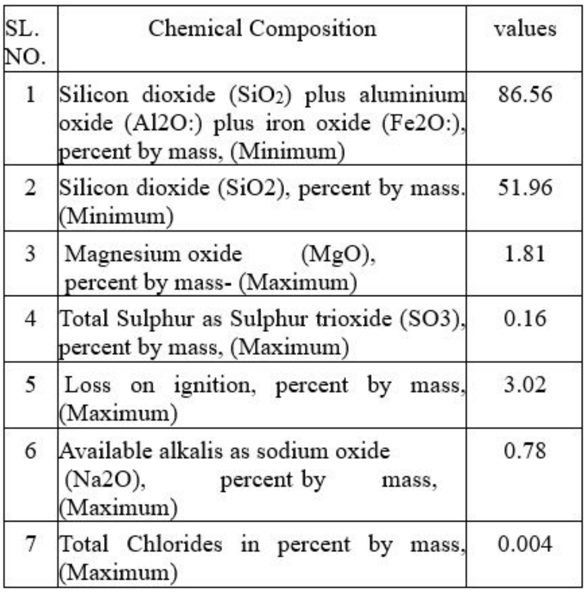
a. Materials used

Cement: The chemical composition of cement used (53 grade OPC) is given in Table 1.The Specific gravity of Cement, fly ash, GGBS and Silica Fume are 3.07, 2.13 and 2.14 are chemical composition are used.

Aggregates: Coarse aggregate, Hematite aggregate and magnetite aggregate (size<20 mm) were used. The specific gravity of coarse aggregate is 2.67, hematite aggregate is 4.07 and magnetite aggregate is 3.6.

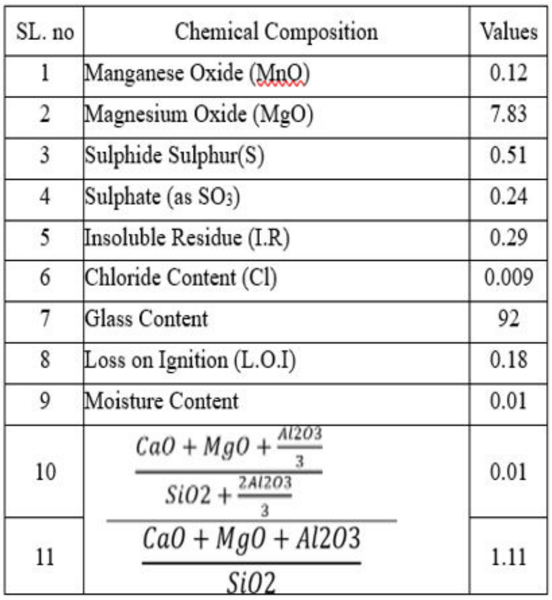
Fine aggregate: River sand passing through 4.75 mm sieve was used. Its specific gravity andfineness modulus were 2.3 and 3.8 respectively.

Table 1 Chemical Composition of fly ash.



SL. NO.	Chemical Composition	values
1	Silicon dioxide (SiO_2) plus aluminium oxide (Al2O:) plus iron oxide (Fe2O:), percent by mass, (Minimum)	86.56
2	Silicon dioxide (SiO2), percent by mass. (Minimum)	51.96
3	Magnesium oxide (MgO), percent by mass- (Maximum)	1.81
4	Total Sulphur as Sulphur trioxide (SO3), percent by mass, (Maximum)	0.16
5	Loss on ignition, percent by mass, (Maximum)	3.02
6	Available alkalis as sodium oxide (Na2O), percent by mass, (Maximum)	0.78
7	Total Chlorides in percent by mass, (Maximum)	0.004

Table 2 Chemical composition of GGBS



SL. no	Chemical Composition	Values
1	Manganese Oxide (MnO)	0.12
2	Magnesium Oxide (MgO)	7.83
3	Sulphide Sulphur(S)	0.51
4	Sulphate (as SO_3)	0.24
5	Insoluble Residue (I.R)	0.29
6	Chloride Content (Cl)	0.009
7	Glass Content	92
8	Loss on Ignition (L.O.I)	0.18
9	Moisture Content	0.01
10	$\dfrac{CaO + MgO + \frac{Al2O3}{3}}{SiO2 + \frac{2Al2O3}{3}}$	0.01
11	$\dfrac{CaO + MgO + Al2O3}{SiO2}$	1.11

3.2.Mix proportion

Several trail mixes were conducted on the conventional high-density concrete; the mix design was carried out for M70 grade of concrete. Cementitious materials were cement, Fly ash (15%), Silica fume (5%). The procedure of the mix design is taken from the code book IS 10262-2019. Three trial mixes were made with use of different aggregates (coarse aggregates, Hematite aggregates and Magnetite aggregates) hence the aggregates content changed with respect to their densities and water cement ratios was kept constant for all the three mixes i.e., 0. 26. In the same way several trail mixes were conducted for Geo-polymer High-Density concrete, the mix design was carried out for M70 grade of concrete. Cementitious materials include fly ash (40%), GGBS (50%) silica fume (5%). The procedure of the mix design is taken from the (Abhishek C Ayachit et.al., 2016). Three mix design were carried out by changing the aggregates (coarse aggregates, Hematite aggregates and Magnetite aggregates). The Water-geopolymer solids ratio were kept constant for all the three mixes i.e., 0. 26, Ratio of NaoH to Na2Sio3 was 2.5. The mixes were proportioned by absolute volume method and mix proportions were calculated for all the mixes.

3.3. Test Procedure

Compressive strength test was carried out by compression testing machine. The compressive strength can be defined as capacity of a material to withstand loads which tends to reduce the size of material. The test was carried in compression testing machine whose load bearing capacity was 2000kN/m. The concrete samples are kept in High temperature furnace for 2 hours which was maintained at different temperature conditions (27°C,150°C, 300°C, 450°C, 600°C, 750°C and 900°C). Figure shows the samples kept in temperature furnace for 900°C. The compression strength test was carried out after the samples were cooled to room temperature (27°C) as per IS 516-1959. The compression test was conducted on the sample after cooling for room temperature. The materials required for Thermocouple based Transient Hot Wire method are Nichrome wire, Multimeter that measures temperature, DC source, Wires. figure 1 shows that the cube samples which are kept in high temperature furnace for 900o C. If the temperature is goes on increasing, the strength will be decreasing.

Figure 1 Temperature furnace at 900 ^{O} C

IV. RESULTS AND DISCUSSION

a. Compressive strength

Compressive strength increases with replacement of normal aggregates by hematite and magnetite aggregates. The compressive strength of all the geopolymer mixes was high compared to conventional. Geopolymer concrete shows better strength in all the thermal properties compare to conventional concrete. The compressive strength of CHNM mix, CHHM mix, CHMM mix, GHNM mix, GHHM mix and GHMM mix was found to be same at temperature conditions. The geopolymer magnetite mix is more strength of 82.42 Mpa compared to hematite and normal coarse aggregate of geopolymer and conventional coarse aggregate. figure 2 shows that the compressive strength of different mixes. The compressive strength of GHMM mix is highest strength compare to all other mixes. figure 2 shows that the compressive strength results which is more in magnetite concrete mixes compare to all other mixes.

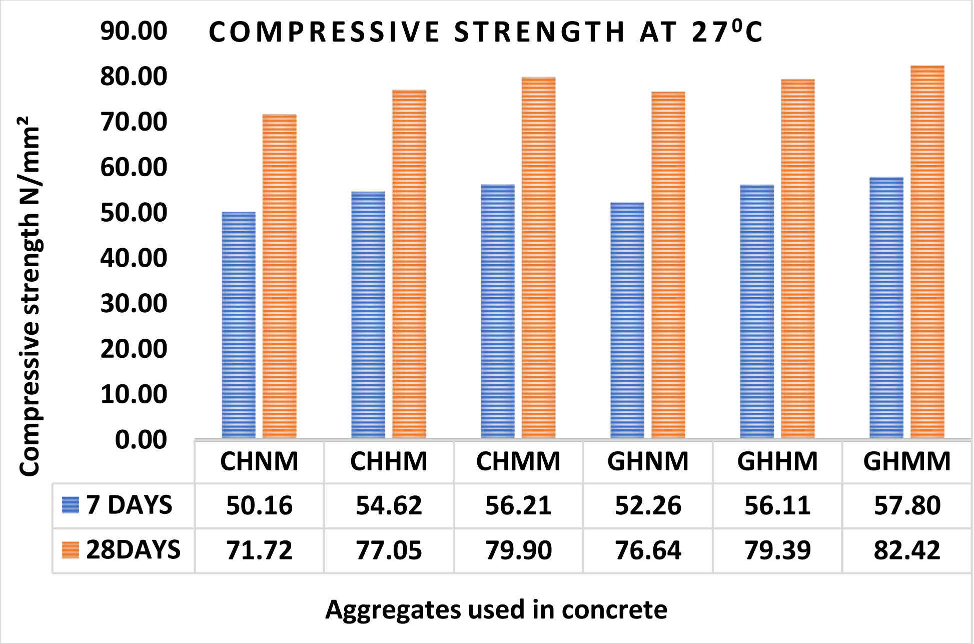
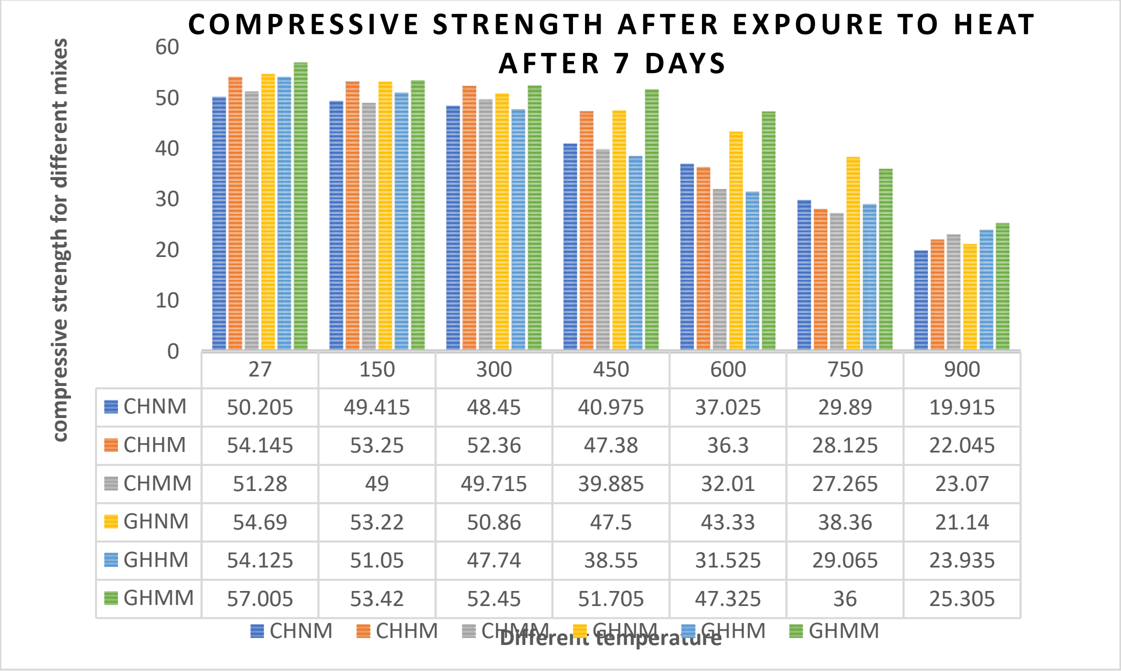


Figure 2 Compressive strength at 27 ºC

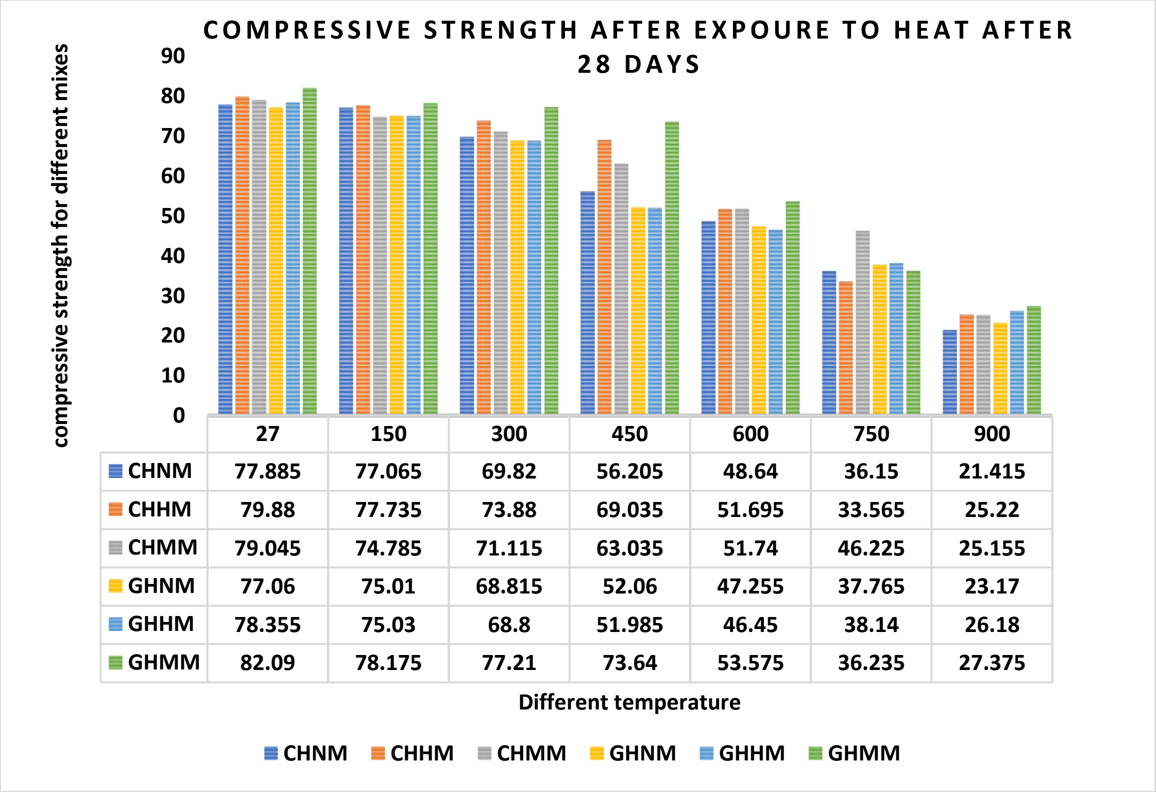
b. High Temperature Furnace

The compressive strength of GHMM mix subjected to 450 ^{0} C and 600^{0} C temperature was 89% and 62% more compare to all other mixes. The residual strength of CHNM mix rapidly decreases to 75.65% at 450 ^{0} C exposure and to 53.82% at 600^{0} C exposure where as CHHM and CHMM mix slightly decrease compare to CHNM mix after 7 days of curing. The residual strength of CHNM mix rapidly decreases to 68.63 % at 450 ^{0} C exposure and to 46.19% at 600^{0} C exposure where as CHHM and CHMM mix slightly decrease compare to CHNM mix after 28 days of curing. The residual strength of GHNM mix rapidly decreases to 86.85% at 450 ^{0} C exposure and to 55.96% at 600^{0} C exposure where as GHHM and GHMM mix slightly decrease compare to GHNM mix after 7 days of curing. The residual strength of GHNM mix rapidly decreases to 52.06% at 450 ^{0} C exposure and to 38.27% at 600^{0} C exposure where as GHHM and GHMM mix slightly decrease compare to GHNM mix after 28 days of curing. It shows that compressive strength after heating in high temperature furnace for 7 days of all the mixes. Figure 3 shows that the compressive strength after exposure to heat with different temperature with different mixes. In that the magnetite mix concrete samples shows the good strength compare to all other mixes of after curing of 7 days. Figure 4 shows that the compressive strength after exposure to heat with different temperature with different mixes. In that the magnetite mix concrete samples shows the good strength compare to all other mixes of after curing of 28 days.



	27	150	300	450	600	750	900
CHNM	50.205	49.415	48.45	40.975	37.025	29.89	19.915
CHHM	54.145	53.25	52.36	47.38	36.3	28.125	22.045
CHMM	51.28	49	49.715	39.885	32.01	27.265	23.07
GHNM	54.69	53.22	50.86	47.5	43.33	38.36	21.14
GHHM	54.125	51.05	47.74	38.55	31.525	29.065	23.935
GHMM	57.005	53.42	52.45	51.705	47.325	36	25.305

Figure 3 Comparison graph of compressive strength after exposure to heat for 7 days



	27	150	300	450	600	750	900
CHNM	77.885	77.065	69.82	56.205	48.64	36.15	21.415
CHHM	79.88	77.735	73.88	69.035	51.695	33.565	25.22
CHMM	79.045	74.785	71.115	63.035	51.74	46.225	25.155
GHNM	77.06	75.01	68.815	52.06	47.255	37.765	23.17
GHHM	78.355	75.03	68.8	51.985	46.45	38.14	26.18
GHMM	82.09	78.175	77.21	73.64	53.575	36.235	27.375

Figure 4 Comparison graph of compressive strength after exposure to heat for 28 days

Figure 5 Cubes kept in HTF in 900 °C

Figure 6 Cubes removed from HTF

Figure 7 Compression test after removed from HTF

V. CONCLUSION

From the experimental investigation and analysis in software, following conclusions are made for different types of Mixes:

Based on the fresh properties of concrete the slump test was conducted for all mixes and true slump was achieved. Compressive strength increases with replacement of normal aggregates by hematite and magnetite aggregates. The compressive strength of all the geopolymer mixes was high compared to conventional. Geopolymer concrete shows better strength in all the thermal properties compare to conventional concrete. The compressive strength of CHNM mix, CHHM mix, CHMM mix, GHNM mix, GHHM mix and GHMM mix was found to be same at temperature conditions. The compressive strength of GHMM mix subjected to 450 ^{0} C and 600^{0} C temperature was 89% and 62% more compare to all other mixes. The residual strength of CHNM mix rapidly decreases to 75.65% at 450 ^{0} C exposure and to 53.82% at 600^{0} C exposure where as CHHM and CHMM mix slightly decrease compare to CHNM mix after 7 days of curing. The residual strength of CHNM mix rapidly decreases to 68.63 % at 450 ^{0} C exposure and to 46.19% at 600^{0} C exposure where as CHHM and CHMM mix slightly decrease compare to CHNM mix after 28 days of curing. The residual strength of GHNM mix rapidly decreases to 86.85% at 450 ^{0} C exposure and to 55.96% at 600^{0} C exposure where as GHHM and GHMM mix slightly decrease compare to GHNM mix after 7 days of curing. The residual strength of GHNM mix rapidly decreases to 52.06% at 450 ^{0} C exposure and to 38.27% at 600^{0} C exposure where as GHHM and GHMM mix slightly decrease compare to GHNM mix after 28 days of curing. The further increment of temperature caused rapid decrement of strength in all the concrete mixes due to weight loss. The residual strength was found to be below 20% in all the samples.

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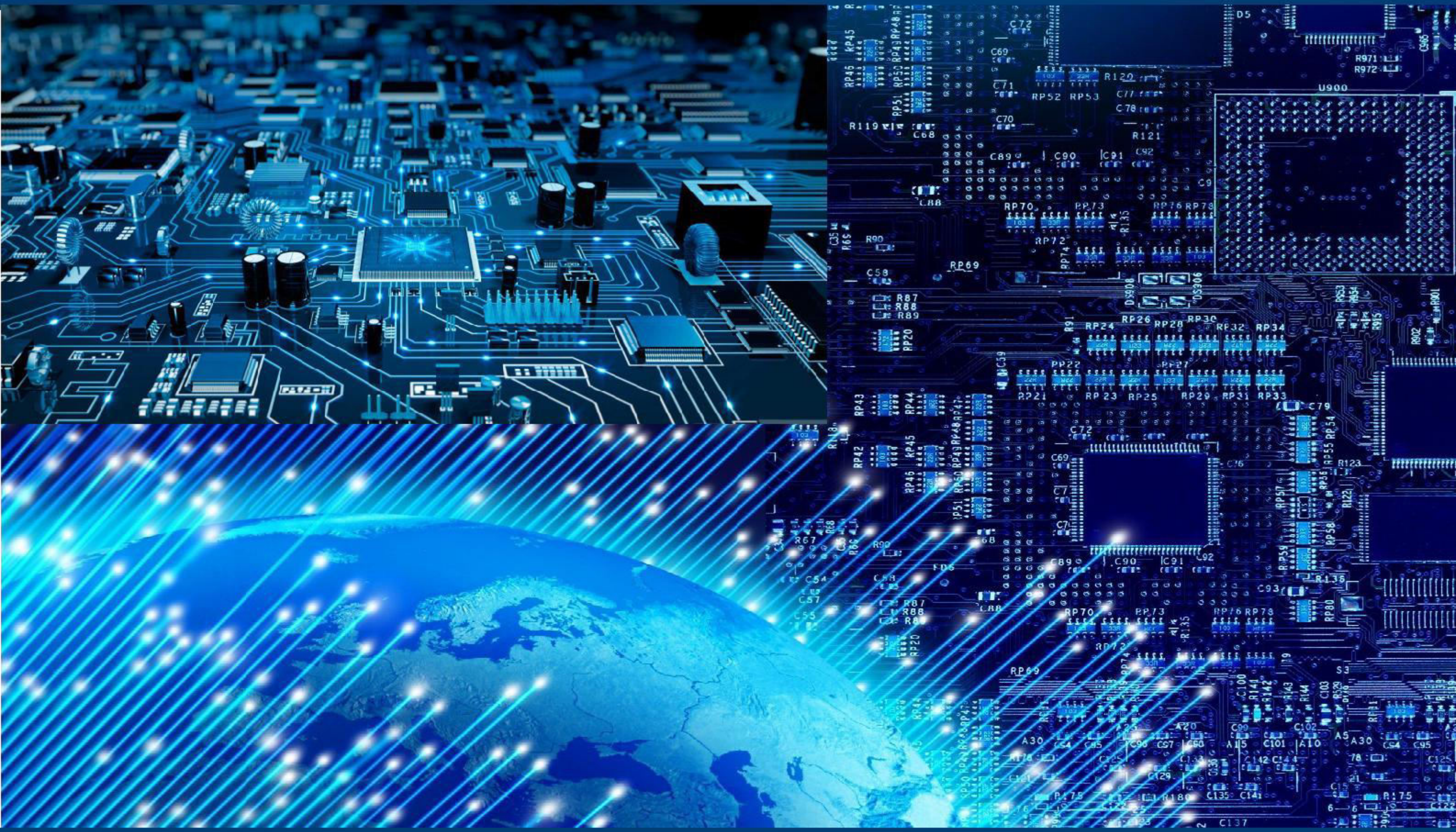

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