FORMULATION OF GEOPOLYMER CONCRETE USING LIGHTWEIGHT AGGREGATE

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A thesis submitted in partial fulfilllment of the requirements for the degree of Masters in Integrated Building Design

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ABSTRACT

Sustainable and greener production is the need of the hour due to abrupt demographic increase, depleting resources, ever increasing wastes and related environmental concerns. In this scenario, this study presents the formulation of cold bonded lightweight aggregates (LWA) based on industrial by products, which are coal fly ash (FA) and steel industry ground granulated blast furnace slag (GBFS). Two types of LWA were produced in this project; cement based aggregates (C_{ags}) and geopolymer aggregates (GP_{ags}), and were studied under varied curing conditions to produce optimized strength aggregates. Different tests were performed on LWA to investigate their physical properties, mechanical performance and durability characteristics. In the second part, lightweight concrete (LWC) were also manufactured using selected types of aggregates from those produced already and examined to investigate their suitable applications as a structural LWC. Results showed that produced aggregates were lighter than many aggregates from earlier studies and they also satisfied the ASTM standard because their density ranged between 764-878 kg/m^3. However, due to less density, they experienced comparatively higher water absorption value, but still they managed to comply with usual range for water absorption (<25%). Mechanical strength test results displayed that the strength of aggregates was improved with increasing binder percentage and C_{ags} proved to be stronger than GP_{ags}. Alkali silica reaction test results indicated that the 28 days expansion of specimens was well within limits and none of the aggregates presented deleterious characteristics, whereas, overall expansion was lesser for samples containing LWA than NWA samples. Petrographic analysis under thin sections study, XRD and FTIR, further confirmed the non-reactive nature of produced LWA with the absence of alkali silica reactive minerals. Regarding LWC formulated, results showed that density of concretes (1906-1965 kg/m^3) were within the limits of lightweight concrete; and also they presented water absorption values in the normal range for LWC (<10%). Compressive strength of geopolymer LWC produced was better than cement based concrete, and their values ranged between 17.43-29.66 MPa which confirmed their feasibility as structural LWC usage. Split tensile strength results were also in agreement to their compressive strength results and varied between 2.40-3.21 MPa. Concluding, results of this study confirm the successful production of LWA and their ability to manufacture LWC for more economical, technically sound, and environmental friendly concrete applications.

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LIST OF ABBREVIATIONS

HSC	High Strength Concrete	NWA	Normal Weight Aggregate
NWC	Normal Weight Concrete	AIV	Aggregate Impact Value
ITZ	Interfacial Transition Zone	TFV	Ten Percent Fines Value
LWA	Lightweight Aggregate	UPV	Ultrasonic Pulse Velocity
LWC	Lightweight Concrete	FTIR	Fourier Transform Infrared Spectroscopy
FA	Fly Ash	WA	Water Absorption
GBFS	Ground Granulated Blast Furnace Slag	CSH	Calcium Silicate Hydrate
GC	Geopolymer Concrete	CH	Calcium Hydroxide (Portlandite)
CA	Coarse Aggregates	C_{ags}	Cement Aggregates
PC	Portland Cement Concrete	GP_{ags}	Geopolymer Aggregates
ASR	Alkali Silica Reaction	XRD	X-Ray Diffraction Analysis

LIST OF NOTATIONS/SYMBOLS

m	Mass in “kg”
v	Velocity in “m/s”
w_a	Dry weight in “g”
w_b	Wet weight in “g”
x	Weight of sample taken prior to impact test in g
y	weight of fraction passing 2.36mm sieve at the end of impact test in g
P	Load at failure in “kN”
f_{10}	Load at maximum plunger penetration in TFV test noted in “kN”
A	Cross sectional area in “m^2”
L	Length of specimen in “m”
D	Diameter of specimen in “m”
T	Transit time in “s”
ΔL	Length change in “%”
L_t	Length of specimen after t days
L_i	Length of specimen initially

1. INTRODUCTION

1.1. GENERAL

With the abrupt demographic increase in recent times, the demand for construction materials is increasing and the resources are depleting at the same time. With incredible wave of technology and innovations, concrete still remains the highest utilized and in-demand construction material. Concrete is a composite material which consists of cement, aggregates and water. Environmental conditions now hinder the continuous and in-bulk supply of natural coarse aggregates due to emissions problems and sustainability issues [1]. Moreover, the higher unit weight of natural coarse aggregates is another problem for higher weight of concrete and resulting building loads. Therefore, in recent times, engineers are giving more importance to lightweight concrete formulation because of the disadvantages associated with the higher unit weights of concrete. Lightweight concrete have many advantages like; it reduces the overall building costs by reduced sizes of structural members and less reinforcement required because of lesser overall dead loads; it makes construction process relatively easier; and also considered as the green material relative to normal weight concrete [2]. Therefore, engineers are trying to produce lightweight aggregates artificially.

Lightweight aggregates can be developed from a variety of waste or raw materials. Due to increasing population, changing consumption patterns and increased leisure of life, heaps of waste are also piling day-by-day. Utilization of these wastes materials in construction material's production is the future of sustainability and safe environment. That is the reason many researchers and engineers have tried to produce aggregates with different waste materials [3-10]. Strength of concrete depends on its constituent and is determined by cement paste, aggregate and interface [11]. In high strength concrete (HSC), aggregate is the deciding factor for concrete strength whereas in normal weight concrete (NWC), cement paste or interface transition zone (ITZ) is the deciding factor [11]. In lightweight concrete, aggregate is the weakest link which decides the strength of concrete, therefore, it becomes necessary to carefully investigate the strength properties of lightweight aggregates.

Second most important component of concrete is the cement. Cement is a versatile construction material and is used in many civil engineering applications worldwide, however, carbon dioxide emissions related with its production process have real impacts on environment and cause climate change [12]. Geopolymers are latest research interest which has lesser carbon footprint. Geopolymers are developed up by alkaline activation of aluminosilicates materials like rice husk ash, fly ash, red mud, bentonite, metakaolin and steel slag. Using geopolymers in concrete formulation not only can reduce the emissions related problem; additionally it can also serve the purpose to reduce wastes. Therefore, engineers are working to develop geopolymer concrete and promote its use instead of cement: and many researchers have studied development of geopolymer concrete and pastes based on different waste materials like fly ash [12-19], blast furnace slag [20], palm oil fuel ash [21], metakaolin [22], rice husk and red mud [23].

The research programme under consideration accounts for the production of artificial lightweight aggregates (LWA) and subsequently the development of lightweight concrete LWC) using these aggregates. LWA were developed from different industrial by-products using cold bonded pelletization technique and applying two different binding mechanisms to ensure the formulation which includes cementing and geopolymerization. Different physical, mechanical and durability properties of LWAs were paid attention to confirm their suitability for use as coarse aggregate in concrete. Secondly, geopolymer LWC were developed using produced LWA which is a green material and will have many technical benefits. The properties of geopolymer were also compared with Portland cement LWC to further examine the ability of LWC to be used in structural material applications.

1.2. OBJECTIVE OF THE STUDY

The two part objective of this research work is as follows:

1. To develop LWA using fly-ash (FA) and granulated blast furnace slag (GBFS) by cold bonded pelletization method and to investigate their physical, mechanical and durability properties to assess possible use in structural LWC, which are sustainable and benign to environment..
2. To formulate the geopolymer LWC and study the properties of concrete for envisaged structural concrete applications; and to further verify applicability of LWA produced.

1.3. PRACTICAL APPLICATIONS

- Artificial LWA have excellent prospects to use in LWC construction both as structural and architectural elements. They will be prepared from industrial by-products through granulation process so waste reduction and low energy use will be their advantage.
- Geopolymer concrete (GC) are way towards sustainable production of future concrete structures. They have vast applications in all kind of concrete structures. Geopolymer

concrete is durable, environmental friendly and green material relative to energy intensive cement binder.

1.4. LIMITATIONS OF THE STUDY

Lightweight aggregate production through by-products or industrial/municipal waste is recommended due to many technical and environmental benefits; however the process should be supported by thorough investigations for their potential practical applications. This study, because of some time and technology driven setbacks, have some limitations which are highlighted as under:

- Any product generated from by products or waste materials should be investigated for metals leaching behaviour, which were not our scope of study.
- Freeze thaw resistance of concrete is very important property and for lightweight concrete it gains even more attention because of porous nature of aggregates which must be look upon. This aspect of the study was not investigated because of scope and technology limitations.
- Six different types of LWA were produced in this study, however only two selected types of aggregate were used to formulate concrete aiming at structural lightweight concrete formulation and to avoid extensive time dependant testing. Other low strength aggregates can further be investigated for low strength or medium strength lightweight concrete applications.

1.5. OVERVIEW OF CHAPTERS

Chapter 2: It includes the literature review of artificial LWA production through different techniques and binder applications. It also describes the development of geopolymerization, geopolymer concrete and geopolymer LWC theory with time.

Chapter 3: This chapter contains detail about material, methods and experimentation methodology adopted for this research work from start to the end till testing.

Chapter 4: This chapter throws light on all the outcomes of the study i.e. all the results are presented and discussed in this chapter.

Chapter 5: This chapter summarizes the final conclusions, practical applications of the study and some suggestions for future research works.

2. LITERATURE REVIEW

2.1. GENERAL

Demand of Construction materials is rapidly increasing with ever increasing population and development. Increasing waste generation from industrial processes and production units is another major concern for environment. Engineers and researchers are working to replace raw materials with waste materials and trying to develop new construction materials like bricks [24, 25], artificial aggregates [3, 6, 9, 26, 27], binders [28, 29], and glass ceramics etc. This approach can save raw materials and environment by serving as an effective waste disposal alternative.

Concrete is the most abundantly used construction material worldwide due to its fair strength, durability and superior performance. Coarse aggregates (CA) occupy about 60 to 70% of concrete volume, and therefore, greatly influence the strength of concrete and its unit weight. Normal weight concrete is tough, durable and has excellent strength; however, it adds significant weight to the structures. The self-weight of CA and ultimately that of concrete is the biggest contributor towards the load of concrete structures. Moreover, concrete industry consumes about 9 billion tons of aggregates annually which is a serious concern for their sustainable availability especially for countries which lack major natural aggregate resources. Therefore, future research trends in construction and civil engineering fields follow the artificial production of CA using different industrial and municipal by-products or wastes. This chapter throws light on related terms and definitions, research related to artificial production of lightweight aggregates and geopolymer lightweight concrete.

2.2. TYPES OF AGGREGATES

There are two broader classifications of aggregates that are being used in concrete namely fine aggregates (FA) and coarse aggregates (CA). FA are those aggregates which are finer than 4.75 mm and CA includes the fraction which is coarser than 4.75 mm. The discussion in this project will always be related to CA hereafter. CA can further be divided into different types as follows:

1. Normal weight aggregates
2. Lightweight aggregates

2.2.1. NORMAL WEIGHT AGGREGATES

Normal weight aggregates (NWA) are the type of CA which are formed either from natural disintegration of rocks or prepared in industries by crushing of rocks. NWA includes gravels and crushed stones. The density of NWA ranges between 1520-1680 kg/m^3 [30].

2.2.2. LIGHTWEIGHT AGGREGATES

Lightweight aggregates (LWA) are either natural or artificial. The density of LWA for structural concrete should be less than 880 kg/m^3 [31].

2.2.2.1. Natural LWA

There are many naturally available LWA. These are generally volcanic rocks which are formed due to high temperature volcanic eruptions and subsequent accelerated cooling of lavas. Natural LWA are highly porous due to sudden cooling of lavas and subsequently they are lighter in weight. Following are different types of natural LWA with their usual density range [32];

1. Perlite (120-192 kg/m^3)[1]
2. Vermiculite (88-160 kg/m^3)
3. Pumice (300-530 kg/m^3)
4. Scoria (400-650 kg/m^3)

2.2.2.2. Artificial LWA

LWA which are produced artificially using different industrial by-products or natural resources applying different techniques like sintering, autoclaving and cold bonded pelletization. Density of artificial LWA can vary greatly depending upon the technique through which they are manufactured.

Sintered LWA

These particular types of aggregate are produced though sintering process. In sintering process, a pre-treated and prepared mass is heated at around 600-800 ^{0}C for different time periods to produce hardened LWA. Depending upon primary material used in making aggregates, below are the different types of sintered LWA [33];

1. Expanded slag LWA (500-1000 kg/m^3)
2. Expanded clay, shale and slate LWA (500-1050 kg/m^3)

Cold Bonded LWA

[1] 1 kg/m^3 = 0.062 lb/ft^3

Aggregates made form cold bonded pelletization are relatively green material as cold bonding process takes place at room temperature which gets rid of high temperature process which is the requirement of sintering technique. In cold bonding, any binder like cement or lime is applied to produce aggregates.

2.3. TYPES OF CONCRETE

Concrete can be classified into different types based on weight of concrete, strength and binder used as follows;

Based on Weight of Concrete [32]

- Lightweight concrete (< 1920 kg/m^3)
- Normal weight concrete (2240-2480 kg/m^3)
- Heavy weight concrete (>3200 kg/m^3)

Based on Strength [34]

- Low strength concrete (<20 MPa)[2]
- Moderate strength concrete (20-55 MPa)
- High strength concrete (55 MPa)

Based on Binder

- Ordinary Portland cement concrete, PC (Cement based)
- Geopolymer concrete, GC (Geopolymerization)

2.3.1 LIGHTWEIGHT CONCRETE

Lightweight concrete (LWC) make use of LWA and has unit weight less than 1920 kg/m^3. LWC can be further divided into sub-types depending upon its strength performance.

2.3.1.1. Structural LWC

Structural LWC is the one which have minimum 28 days compressive strength not less than 17 MPa [34]. Its density ranges between 1120-1920 kg/m^3. It can be formulated either by incorporating LWA solely or by using combination of LWA and NWA in different ratios.

2.3.1.2. Non-Structural LWC

Non-structural LWC has 28 days compressive strength within 7-15 MPa. It can have densities somewhere between 800-1400 kg/m^3 [34].

[2] 1 MPa = 145 psi

2.3.2. GEOPOLYMER CONCRETE

Concrete which is made thorough geopolymerization is known as geopolymer concrete. It is considered to be a green material.

2.3.3. GEOPOLYMERIZATION

Geopolymerization is the phenomenon which produces geopolymers. Geopolymer is produced by alkaline activation of silica and alumina rich materials of geologic origin or by-product materials. Geopolymers are considered to be alternate binders to cement which is relatively green material due to less environmental impacts.

2.4. STUDIES ON ARTIFICIAL LWA PRODUCTION

LWA can be produced either by natural raw materials (expansive clays, slate, shale) or by secondary raw materials (sewage sludge, blast furnace slag, fly ash) [4]. However, waste based LWA formulations are latest research interests which have many technical, economic and environmental benefits. These secondary raw material (SRM) based aggregates can effectively mitigate the growing waste generation problems, alongwith the resuting releif to natural coarse aggregate resources rendeirng the concrete production more economical and bengin to the environment and sustaianble. Furthermore, LWA have many technical benefits as well like; lesser labour and transportation costs; lesser machinery and equipment efforts required for on-site transportation, pouring and handling of concrete; lesser self-weight of structures; significant reduction of section sizes and concrete volume required; reduced drift and seismic loads [32]. For these reasons there is growing demand for LWA these days.

There are two estensively applied techniques to produce LWA as discussed in previous chapter. Sintering is the most commonly adopted technique to convert different secondary materials into useful products. Many researchers have developed artificial LWA by high temperature sintering using alternate materials like metals sludge [35], mining residues [3], excavation soil [36], incinerator FA and bottom ashes [37], sewage sludge [26], fly ash [38] and waste glass [27]. However, high temperature requirements come up with the draw backs of CO_2 emissions, which is also not desirable as it carve the way to climate change and environment degradation along with high production costs.

Granulation or cold bonded pelletization is another approach through which LWA can be produced. It has certain advantages over sintering process which includes less process energy requirements. In granulation, materials are stabilized using any binder that is cement, lime, or alkali activation mechanisms like geopolymerization at ambient temperatures without any high temperature requirements. A study [7] focused on manufacturing of LWAs using fly ash (FA) and ground granulated blast furnace slag (GBFS) through cold bonding using cement as a binder. Another work [39] formulated cold bonded LWAs using municipal solid waste incinerator (MSWI) fly ash; authors applied second additional step of cold bonding to supplement the weak mechanical properties of pellets produced in first step. Most of the previous studies have used cement as binding material to develop LWA. Cement itself is a material which plays significant role in environmental degradation as production of cement causes CO_2 emissions in large quantities and consumption of natural resources. To reduce these disadvantages researchers are working over the years to produce alternate binding systems which can lead to more sustainable and greener materials. One such technique is geopolymerization which gave rise to geopolymer binding system. Davidovits in 1978 gave concept of Geopolymer (GP) for the first time [40]. Geopolymer makes use of materials containing alumina and silica in abundance and with alkaline activation of such materials a long chain polymer system is formed. Geopolymers have considerably less CO_2 emissions than Portland cement and describe extraordinary properties.

Sewage sludge ash aggregates [39]

Fly ash and Slag Aggregates [7]

Figure 1: Cold bonded lightweight aggregates produced from waste materials

LWA production using geopolymerization technique is another sustainable approach to realize waste management and resource conservation benefits. A research project [41] developed geopolymer aggregates from fluidized bed combustion (FBC) fly ash and mine tailings, and claimed their potential use for concrete by forming good strength concrete. Formulation of LWAs by alkaline activation of wood ash and different co-binders like, blast furnace slag, metakaolin and FA, was also reported [42]. This study provided the evidence of good strength concrete formulations using such aggregates Another study designed high performance concrete by adding geopolymer lightweight aggregates made by FA and GBFS [43].

Contrary to aforementioned advantages of LWA, compromised strength of aggregates is a very concerned disadvantage which depends on many factors. LWA strength performance depends on various factors like; density, water absorption, binder characteristics and curing conditions. When talking about LWA, density of aggregates as low as possible will be desirable to produce LWC. However, lower density of aggregates accompany with an obvious disadvantage of increased water absorptions. Lighter the density of aggregate is more porous it will be; and subsequently it will have more water absorption capacities. Such aggregates degrade the strength of concrete incorporating them [44].

Concrete is a three phase system. In concrete, failure and disruption can occur at; 1) cement paste, 2) through aggregate, 3) cement-paste interface/Interface transition zone (ITZ). In high strength concrete (HSC), aggregate is the deciding factor for concrete strength, whereas, in normal weight concrete (NWC), cement paste or interface transition zone (ITZ) is the deciding factor [9]. However in LWC, lightweight aggregate becomes the weakest part. However, this reduced strength can be marginalized to some extent by improved bond between cement paste and aggregate interface [45]. Cement paste enters into the pores of LWA and improves bond strength to ensure better strength of resulting concrete [44, 45].

Another most important characteristic of LWA is their strength which depends on binder type, their quantity and secondary materials applied. In addition to this, curing conditions also greatly influence the strength of cement composites. Suitable curing type and duration positively influence mechanical performance and durability of cement based composites [46].

The reaction of CA with cement matrix like alkali silica reaction (ASR) is another concern for aggregates and concrete durability. Reactive silica of aggregates react with alkalis of cement available in pore solution of matrix which results in formation of ASR gels. On absorbing water ASR gels expand which induce cracking and strength reduction in concrete [47]. In severe scenario ASR expansion can even cause failure of structures. It is interesting fact that LWA are less susceptible to ASR expansions and related deteriorations because pore structure of LWA can absorb ASR gels and can lessen the expansion [48]. In addition, apt use of GBFS and FA can inhibit the expansions resulting from ASR [49]. Different factors that influence the ASR and associated expansion are; (1) mineralogical composition of aggregates, (2) water absorption of aggregate, (3) aggregate’s porosity [48]. So it is necessary to evaluate the mineralogical composition and alkali silica reactivity of LWA to confirm their appropriate use in concretes.

2.5. STUDIES ON GEOPOLYMER CONCRETE PRODUCTION

Concrete is very important construction material in civil engineering applications due to its strength and durability performance as discussed before, and developing world greatly depends on concrete. As we know that concrete is a composite material consisting of cement, aggregates and water, and like other composite materials, its properties depend on its constituents. Larger fraction of concrete is occupied by aggregates which highly influence the strength and unit weight of aggregates. The second most important constituent of concrete is cement. Cement is energy intensive material and main contributor towards the global CO_2 and greenhouse gasses emissions. Production of 1 kg of Portland cement produces 1 kg of CO_2. [5]. Additionally, cement production also consumes large quantity of natural resources. Due to large quantities of CO_2 emissions from Portland cement production, researchers are thinking of new environmental friendly cementations materials. Green concrete production is the latest research interest. Many researchers have applied waste material as replacement of cement. Application of blast furnace slag [29, 50, 51], fly ash [52], paper mill sludge [28] have been studied.

Geopolymers are the way towards modern sustainable and environment friendly concrete solutions. Many Researchers have studied development of geopolymer concrete and geopolymer pastes based on different waste materials like fly ash [12-17], blast furnace slag [20], palm oil fuel ash [21], metakaolin [22], rice husk and red mud [23]. Apart from lesser energy intensive nature and carbon footprint, geopolymer concrete (GC) possess many advantages over Portland cement concrete (PC). GC can perform better than ordinary Portland cement at elevated temperature [13, 17], has better durability [20], good resistance against acids and sulphate attack [14, 53, 54]. They can better sustain marine environments as well [55, 56]. GC concrete also has benefit of developing high early strength in hot curing conditions which can suit many concrete applications like precast applications, hot weather concrete castings. Concrete gains approximately 70% strength within 3-4 hours of temperature curing which can speed up the project delivery time and can cut related time dependent costs [57]. Tensile and flexural strengths of concrete, and bond strengths of steel are more in GC concrete than PC which make them suitable for better cracking resistance and steel corrosion [14, 58]. Peak Load for crack development is more for GC than PC, but post peak relation between load and deflection is steeper, showing brittle failure after peak load [16]. GC having compressive strength more than 55 MPa can be obtained [14]. Davidovits also claimed that Egyptian pyramids were made by cast in place geopolymers [59]. Egyptian pyramids and Roman amphitheatres, when compared with the microstructure of modern days geopolymer, presented very similar microstructure as geopolymer [60].

GC concrete is more durable than PC against many aggressive environments. Alkali silica resistance of GC concrete is also more than PC. Experiments have proven that GC containing aggregates like sandstone and lime experienced lesser expansion than the corresponding control PC specimens [47, 61]. As geopolymer is made by pozzolans mostly (FA, GBFS, metakaolin, silica fume) and these materials can better resist ASR reactions [49, 62]. Fly ash reduces pore solution alkalinity and availability of calcium ions which are necessary for ASR gel formations [63]. Furthermore, mineral admixture refine pore structure of the pastes and improve permeability to further protect concretes from ASR [63]. Geopolymer concrete uses silica, alumina and alkalis for geopolymer formation and strength development mechanisms which are the necessary ingredient required for ASR reactions, therefore, GC are more resistant to ASR [47, 61].

3. METHODOLOGY

3.1. GENERAL

To meet the objectives of the research work, proper methodology plays a key role. This chapter describes the methodology adopted in this study. This research work can be broadly divided into two segments; in first part lightweight aggregates will be produced and will be paid attention to methods and procedures followed for assessing their properties like density, water absorption, strength of lightweight aggregates and their durability properties. The second half of this research project deals with the manufacturing of lightweight concrete using produced lightweight aggregates. Therefore, this chapter also describes the materials used for lightweight concrete production; and different tests and procedure followed to investigate the properties of concrete like slump value, density, water absorption, compressive strength, split tensile strength and ultrasonic pulse velocity to ensure the acceptable characteristics of concrete to be used as structural lightweight concrete afterwards.

3.2. EXPERIMENTAL WORK

3.2.1. MATERIALS

Two series of LWAs were produced in this study; cement aggregates (C_{ags}) and geopolymer aggregates (GP_{ags}). And similarly two different types of concrete were produced incorporating LWAs; Portland cement concrete (PC) and geopolymer concrete (GC). For C_{ags} and PC concrete production, ASTM Type I cement was applied as a binder. The fineness and specific gravity of cement were 3250 cm^2/g and 3.15, respectively. Primary materials applied in C_{ags} were two by-products from industrial process i.e. coal fly ash (FA) and ground granulated blast furnace slag (GBFS) (Figure 2). FA was obtained from DG Cement and its chemical composition suggested that it was ASTM C618 class F FA [64]. Considering particle size of FA, more than 90% of the particles were finer than 150µm. X-ray diffraction (XRD) analysis[3] showed minerals like quartz, mullite, anorthite, calcite, hematite and magnetite in FA as shown in **Figure 3**.

GBFS came from Dewan Cement Limited (Karachi, Pakistan) and showed the composition of Grade 80 slag of ASTM C989 [65] and its maximum particle size was 75µm. XRD

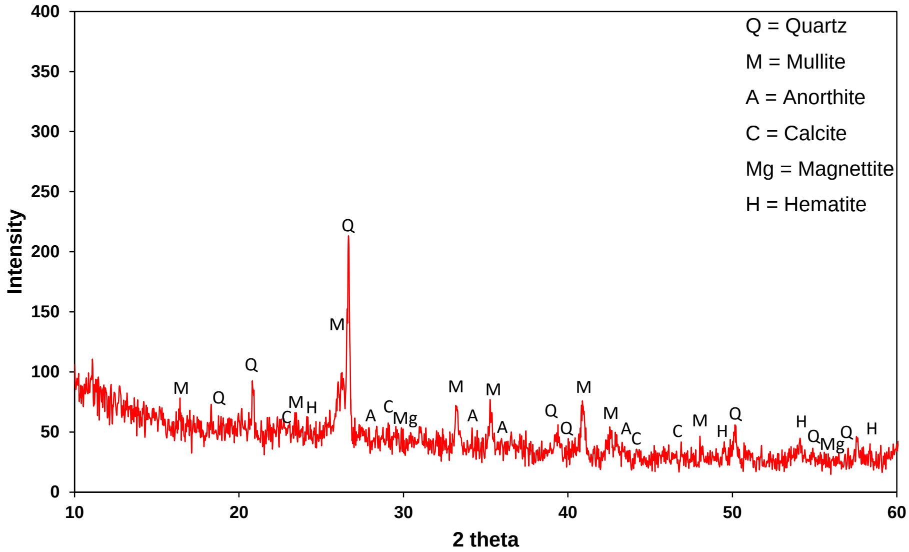
[3] XRD was performed in Chemical Engineering Department at COMSATS University Lahore campus

analysis of GBFS identified calcite as major phase along with akermanite, quartz and gehlenite. For GP_{ags} and GC concrete production, fly ash was applied as primary precursor material and GBFS was used as secondary precursor material, whereas, alkaline activators utilized were sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. NaOH flakes used to make NaOH solution had concentration of 98.0 ± 1% and came from SITARA Chemical industries (Sheikhupura, Punjab). Sodium silicate (possessed SiO_2/Na_2O ratio of 2.5 and its water content was 65% approximately.

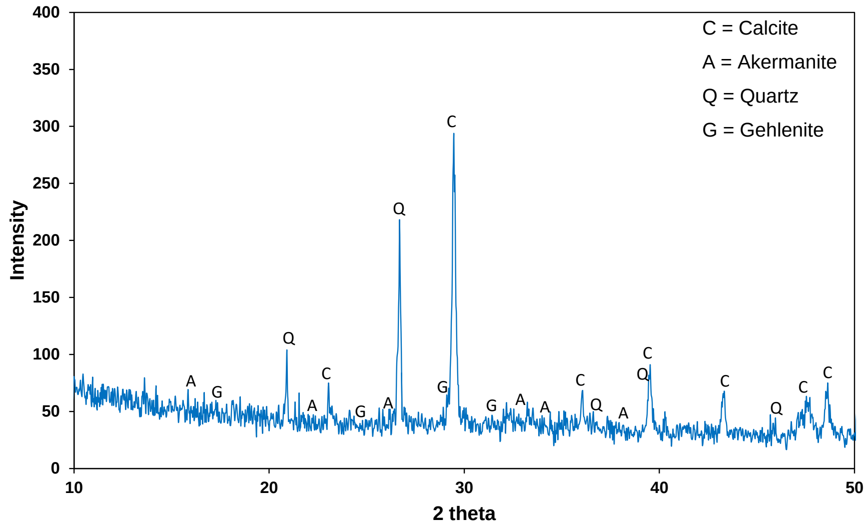
Table 1: Chemical Composition of different materials used; FA, cement and GBFS

Oxide (%)	Cement	Fly Ash	GBFS
CaO	63.6	9.02	40.85
MgO	2.2	1.70	1.63
SiO_2	20.3	56.34	37.42
SO_3	2.8	-	0.645
Al_2O_3	4.9	23.08	13.25
Fe_2O_3	2.8	6.43	1.29
K_2O	0.70	0.56	0.014
Na_2O	0.40	0.28	0.417
Cl	0.01	0.025	0.016
LOI	2.5	<3	2.30
Moisture Content	<1	<1	1.428

Figure 2. Different binder or precursor used in this work



(a)



(b)

Figure 3. XRD of: (a) FA, (b) GBFS

3.2.2 LWA PRODUCTION

Two different series of aggregates were created through cold bonded pelletization in this work: Series 1 aggregates contained cement as binder and are referred as C_{ags}; Series 2 aggregates are designed by alkaline activation of FA and GBFS (Geopolymer binder) and are termed as GP_{ags}. The Pelletizer machine used for formulation of LWAs is made up of a circular pan, a cylindrical shaft and an inclined platform as shown in **Figure 4**. The bottom plate of the pan has multiple 8.125 mm diameter holes punched in the plate. Shaft rotates within the pan about vertical axis of shaft, presses the material submitted in the pan and consequently pellets of cylindrical shape having fixed diameter of 8.125mm and varying length are punched out of the holes, which can be collected from inclined platform afterwards.

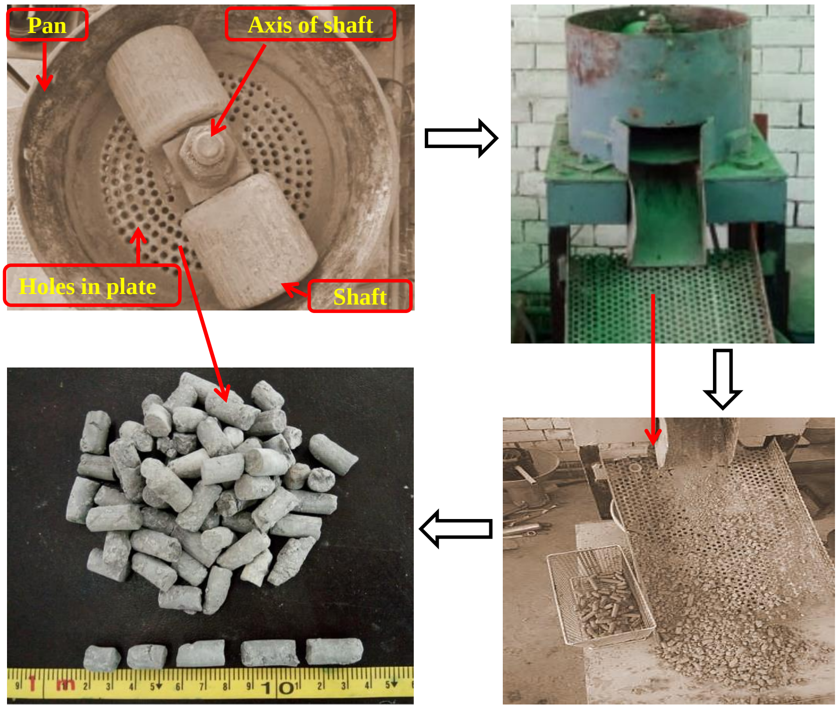


Figure 4. Pelletizer machine used in this study

In the production of Series 1 aggregates, cement was added in varying quantities (10-20%) and rest of the portion of mix contained equal proportions of FA and GBFS (40-45%). The water/solid ratio selected was between 0.25-0.30, which was selected for maximum pellets formation and efficiency. Calculated amounts of materials were dry mixed first for about 2-3 minutes; and then material was mixed for further 2-3 minutes after adding water. After formation of homogenous mixture, material was poured into the pelletizer for pellets formation.

For Series 2 aggregates, FA and GBFS were applied in varying percentages ranging from 80-90% and 10-20%, respectively. FA was major precursor and secondary precursor GBFS was added to study its effect on aggregates strength. Mixture of two alkaline solutions, 10 molar NaOH and Na_2SiO_3 having Na_2O/SiO_2 molar ratio of 2.5 was first mixed in selected proportions and then it was added in varied amounts of 25-30% of total weight of solid precursors. The ratio of the two solutions NaOH/ Na_2SiO_3 selected was 1.5 to gain better strength results [19].

3.2.3 CURING REGIMES

After formation, pellets were kept in laboratory as it is for about 24 hours to make them strong enough so that they can bear handling stress. After that, pellets were collected for different curing conditions applications. For C_{ags}, two different curing regimes were selected: (1) water curing at room temperature ($20^oC \pm 5$) till testing dates for various properties, named as 20W; (2) water curing at 70^oC in oven for 24 hours and ambient condition water curing at 20^oC after that till testing ages, denoted as 70W. GP_{ags} were studied under single curing regime that was dry curing condition. Aggregates were placed in oven at 70^oC, wrapped in plastic bags, for 24 hours, which hereafter were put in laboratory until they were being tested; this curing condition is denoted as “70D”. GP_{ags} were wrapped in plastic bags to avoid water loss for complete curing duration. **Table 2** provides the mix compositions used for LWA formulations with curing conditions adopted. **The pellets designation is explained as: first numeral tells the percentage of binder variable, after numeral, first alphabet is for type of binder, cement (C) or slag (S); second alphabet following a numeral denotes curing regime applied.**

Table 2. Batch compositions for LWA formulated

Pellets Name	Binder/Precursor (% by total solid)			Water/Alkaline Activator (% by total liquid/activator)			Curing Regime
	Cement	Slag	Fly Ash	Na_2SiO_3	NaOH	Water	
10C-20W	10	45	45	-	-	100	20W
20C-20W	20	40	40	-	-	100	20W
10C-70W	10	45	45	-	-	100	70W
20C-70W	20	40	40	-	-	100	70W
10S-70D	-	10	90	60	40	-	70D
20S-70D	-	20	80	60	40	-	70D

3.2.4 LWC PRODUCTION

Two distinct types of concrete were formulated in this study; Portland cement concrete (PC) and geopolymer concrete (GC). PC specimens were produced using ASTM type I cement as described in the previous section, and natural coarse aggregates were replaced by produced LWA in the batch formulations. Only C_{ags} were used for concrete production. **Table 3** shows the mixture proportions used for concrete production. Total of four batches were prepared; two PC batches containing C_{ags} (10C-20W and 20C-20W) and two batches of GC with same aggregates. Concrete mixes were designed for target strength of 30 MPa using fixed water to cement ratio of 0.465. Mixture proportions design and casting was done following ACI

Standard. For GC specimen's formulation, FA and GBFS precursors were used instead of cement and the selected ratio for FA and GBFS was 80/20. Alkaline activators used were solutions of 10 molar NaOH and Na_2SiO_3. The ratio of the two solutions NaOH/ Na_2SiO_3 selected was 1.5 to gain better strength results [19].

Concrete specimens were casted in steel cubes and cylinders of specified sizes. For compressive strength, water absorption and ultrasonic pulse velocity tests, cubes of 100 mm sizes were casted; whereas, for split tensile strength test, cylinders of 100 mm dia and 200 mm in length were casted. After 24 hours of casting, PC samples were de-moulded and placed in water tank for water curing at room temperature conditions. On the other hand, GC samples were kept in plastic bags and placed in oven at 70^{o}C for 24 hours and afterwards they were placed in laboratory conditions until testing at specified ages.

Table 3: Mixture proportions of concrete batches presented in mass (kg) per m^3

Mixture Designation	Binder/Precursor			Sand	LWA Aggregate	Water/Alkaline Activator		
	Cement	FA	GBFS			Na_2SiO_3	NaOH	Water
GC-10C-20W	-	388	96	939	436	135	90	-
GC-20C-20W	-	388	96	939	436	135	90	-
PC-10C-20W	484	-	-	939	436	-	-	225
PC-20C-20W	484	-	-	939	436	-	-	225

3.2.5 SPECIMEN FORMULATION FOR ALKALI SILICA REACTION

To determine alkali silica reaction potential of produced aggregates, prisms of 40mm x 40mm cross section and 160mm in length were manufactured. Binder, aggregate gradation and amounts were adjusted on the basis of different densities of LWAs according to ASTM C-1260 recommendations [66]. Water or alkaline to binder ratio adopted was 0.47. Prisms were prepared both with cement and geopolymerization separately. Maximum strength LWA from each series was selected to manufacture prism to conduct ASR tests. Specimens were also made incorporating normal weight aggregate (NWA) for comparison purposes to compare expansion results with that of LWA. Mix compositions designed for specimen preparation are shown in **Table 4**. Six specimens were manufactured for each combination; three of them were prepared for immersion in sodium hydroxide solution to analyze expansion of specimens, and other three were prepared to keep at room temperature conditions without any exposure to alkaline solution to compare compressive strength and water absorption of exposed and un-exposed specimens. **The specimens designation is explained as: first letter tells the type of binder adopted such that "C" denotes cement and "G" means**

geopolymer; after dashed line, numeral followed by an alphabet represents type of aggregate used, where, 20C means maximum strength LWA from Series 1 containing 20% cement, and 20S shows LWA from Series 2 having 20% slag.

Table 4. Designed mixture compositions for ASR test

Specimen Type	Specimen Designation	Mass of binder (g)			Mass of liquid applied (g)			Mass of LWA (g)
		Cement	Fly Ash	Slag	Water	Na_2SiO_3	NaOH	
C-specimens	C-20C	440	-	-	207	-	-	660
	C-20S	440	-	-	207	-	-	616
	C-NWA	440	-	-	207	-	-	990
G-specimens	G-20C	-	280	70	-	124	83	660
	G-20S	-	280	70	-	124	83	616
	G-NWA	-	280	70	-	124	83	990

3.3. TESTING

Different tests were performed on LWA and concrete to examine their physical properties, mechanical performance and durability characteristics. **Figure 5** shows the summary of research methodology adopted for production and experimentation of LWA.

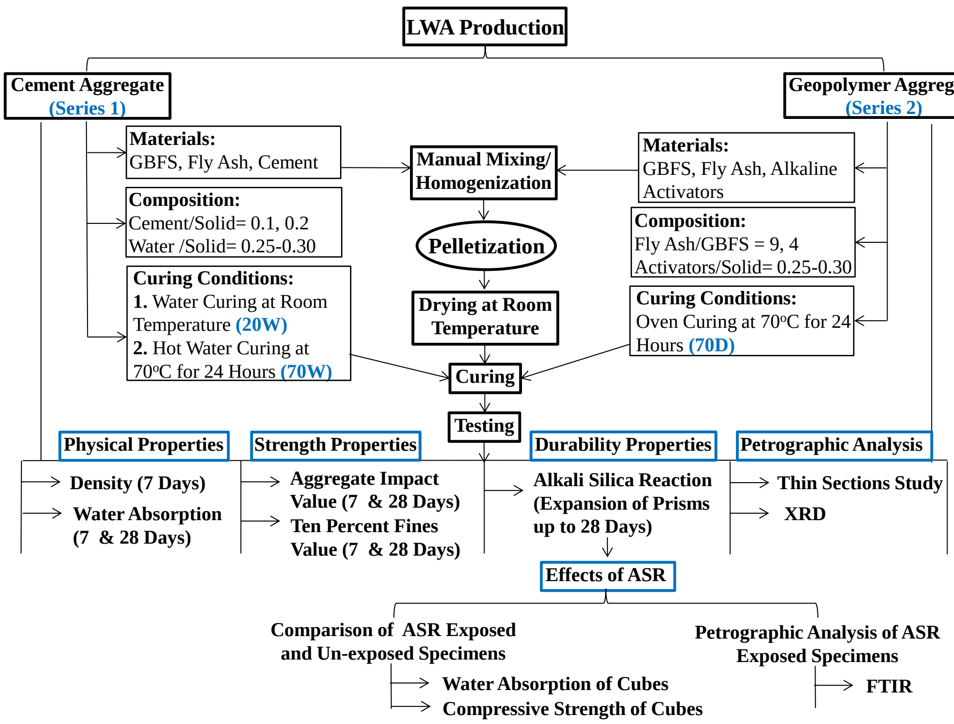


Figure 5. Summary of experimental methodology for LWA study

3.3.1. PHYSICAL PROPERTIES

3.3.1.1. Density

Density of aggregates is very important property which decides the strength of concrete. Density of LWA was obtained by a simple approach. A cylinder of known volume was filled with aggregates and then it was weighed on electric balance. Density of aggregates was then evaluated using Eq. **(1)**.

$$\text{Density} = \frac{m}{v} \tag{1}$$

Where

m = mass of aggregates (kg);

v = volume of measuring cylinder (m^3)

Concrete density is decisive factor which decides the strength of concrete. More the density of concrete is, more will be strength of concrete. To determine the density of concrete, cube specimens of 100 mm were first oven dried at 50^{o}C for 3 days then their weight was recorded. Dimensions of concrete cube was verified by vernier callipers and by using simple relationship of mass and volume, oven dry density of concrete was determined.

3.3.1.2. Water Absorption

Water absorption of LWA was measured by adopting procedure of ASTM C127 [67]. A little change in the procedure was observed. LWA were soaked in water for 3 days instead of single day as directed by this standard, because LWA cannot be fully saturated within 24 hours, instead they continue to absorb water for few days depending upon the pore structure of aggregates. At the end of 3 days, water absorption was calculated from Eq. (2).

$$\text{Water Absorption} = \frac{w_b - w_a}{w_a} \times 100 \tag{2}$$

Where,

w_a = dry weight (g),

w_b = wet weight, in air (g),

To estimate the water absorption capacity of concrete, cube specimens of 100 mm size were first oven dried at 50^{o}C and then they were placed in water tank for 3 days, fully immersed. Weight of the cubes after every 24 hours was measured. After 3 days soaking, cubes were placed in oven for drying at 50^{o}C for 3 days. After 3 days, oven dry weight of the cubes was measured. And then by using Eq. (2) the water absorption capacity of concrete specimens was measured.

3.3.1.3. Workability of Concrete

Workability of the concrete is the ease with which concrete can be handled and worked with. It is very important property of concrete, which determines the concrete pouring methods, compaction effort and mechanical equipment required for proper compaction. It is that property of fresh concrete which highly influence the hardened concrete properties. Slump test was performed to measure the workability of fresh concrete as per ASTM C-143 [68]. There are different types of slump; true slump, shear slump and collapse slump. For workable and good quality concrete true slump is the desirable type of slump. Figure 6 shows the setup for slump test on concrete.

(a) Concrete filled slump cone (b) Slump value of concrete

Figure 6 : Slump test on fresh concrete

3.3.2. STRENGTH PROPERTIES

3.3.2.1. Aggregate Impact Value (AIV)

Aggregate Impact value test is conducted to assess the strength of aggregates against impact loads. Impact value test was performed according BS 812 part 112 [69] test procedure. Aggregate impact value (AIV) was calculated using Eq. **Error! Reference source not found.**.

(a) Cup filled with aggregates (b) Impact value apparatus (c) Sample after impact blows (d) Sieving of sample after test

Figure 7 : Test procedure for aggregate impact value test

3.3.2.2. Ten Percent Fines Value (TFV)

Another most important property for which concretes are often designed is compressive forces. So it is extremely important to determine how much compressive forces LWA can take. LWA ability to take compressive forces is often examined by a test known as Aggregate Crushing Value test following BS 812-110 [70]. This test suggests that loads up to 400 KN should be applied on aggregates and corresponding degradation in aggregates is determined under these loads. LWA are quite weaker than natural gravels or crushed stone aggregates, therefore they cannot take that much load. For this reason, aggregate crushing value test cannot be performed on LWA. An alternate test was used to evaluate the compressive strength of LWA, Ten Percent fines value test, as per BS-812-111 [71]. Ten Percent fines value (TFV) test was applied on both artificial aggregates produced and reference normal weight aggregate sample. Load was applied to produce ten Percent fines (m) and actual load (P) was noted. Controlling plunger penetrations were set as 24 mm and 20 mm for LWA and NWA, respectively. At the end, TFV of different aggregates were calculated using Eq. **(3)** and Eq. **(4)**.

$$\mathrm{TFV} = \frac{14\times P}{f_{10}+4} \tag{3}$$

$$f_{10} = \frac{w_2}{w_1}\times 100 \tag{4}$$

Where,

w_1 = initial weight of sample (g),

w_2 = weight fraction passing 2.36mm sieve (g),

f_{10} = load at maximum plunger penetration (KN),

3.3.2.3. Compressive Strength of Concrete

The most important property for which concrete is designed is compressive strength. For compressive strength measurements cubes specimen of 100 mm sizes were casted. Measurements were taken after 7 and 28 days of curing of concrete specimens after de-moulding. For every condition and reading three cube specimens were casted. Cubes specimens were tested following the test procedure of BS 1881, Part 116. Cube specimens were taken out of water tank and placed in lab for drying for 24 hours, prior to testing. Then specimens were tested by universal testing machine under compressive loads at loading rate of 1 kN/s ± 0.2 kN. Compressive strength of each specimen was then calculated using Eq. **(5)**

$$\text{Compressive strength} = \frac{P}{A} \tag{5}$$

Where,

P = Maximum load at failure (N)

A = Cross-sectional area (m^2)

(a) Cube sample placed in UTM

(b) Specimen at first crack

(c) Fully cracked specimen

Figure 8: Test setup for compressive strength test on cube samples

3.3.2.4. Split Tensile Strength of Concrete

For split tensile measurements cylindrical specimens of 100 diameter and 200 mm in length were casted. Test was performed following the test procedure of ASTM C-496M. Specimens were tested under universal testing machine with loading rate of 800 N/s ± 200 N **(Figure 9)**. The strength of specimens was calculated from Eq. **(6)**.

$$\text{Split tensile strength} = \frac{2P}{\pi LD} \tag{6}$$

Where,

P = failure load (N),

L= length of specimen (m),

D = diameter of specimen (m)

(a) Specimens placed in UTM (b) Specimen at failure (c) Specimen after failure

Figure 9. Split tensile strength of concrete cylindrical specimens

3.3.2.5. Ultrasonic Pulse Velocity Test

Ultrasonic pulse velocity test is a non-destructive test method through which different properties of concrete can be analysed like; dynamic modulus of elasticity, compressive strength of concrete and internal structure of concrete like, uniformity, presence of voids, cracks etc. The test was performed to assess the compressive strength and relative percentage of voids in LWC in this study. Test was performed as per ASTM C-597. Ultrasonic pulses were generated through a pulse generator and were received by a pulse receiver. Time required to travel the waves through the specimens determines the degree of homogeneity of concrete internal structure. More the velocity the pulse trough the concrete is better will be the quality of concrete. Ultrasonic pulse velocity through the concrete was obtained by using Eq. **(7)**.

$$V = \frac{L}{T} \tag{7}$$

Where,
V = Velocity (m/s),
L = Distance between centre of transmitter and receiver (m)
T = transit time (s)

3.3.3. DURABILITY PROPERTIES

After casting, specimens were de-molded after 24 hours. Prior to test, G-specimens were first cured at 70^{o}C for duration of 24 hours. Because G-specimens were quite fragile and without curing they could not bear handling stress and immersion in water. Then all the specimens were immersed in sodium hydroxide solution (1 molar) in a bucket, and bucket was placed in oven with temperature set at 80^{o}C (**Figure 10**). Expansion of specimens was studied after 3, 7, 14, 21 and 28 days. Following equation was used to find expansion of specimens;

$$\Delta L = \frac{L_t - L_i}{L_i} \times 100 \tag{8}$$

Where,

ΔL = length change (expansion %),

Lt = length of specimen after t days,

Li = length of specimen initially

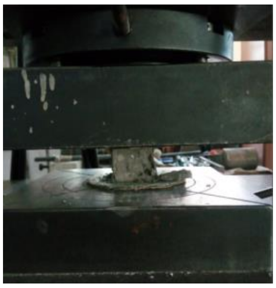
Specimens were brought out of the oven after 28 days and final reading was noted. Prisms were then cut into 40mm cubes and tested under UTM to find compressive strength of cubes. Un-exposed prisms were also cut into 40mm cubes and tested for compressive strength measurement after same age to find the difference in compressive strength of exposed and un-exposed samples. Water absorption of both types of cube specimens was also measured to examine the porosity change due to sodium hydroxide exposure and ASR.

(a) Specimens in NaOH solution

(b) Bucket placed in oven

(c) Length change measurements

(d) cubes of exposed specimens



(e) cube specimen after crushing

Figure 10. Different steps of alkalis silica reaction durability test

3.3.4. PETROGRAPHIC ANALYSIS

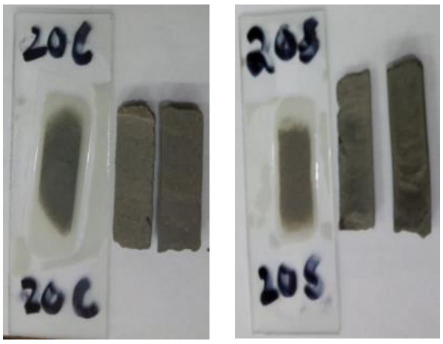
Petrographic analysis for LWA and NWA was performed as per ASTM C295 to check the presence of minerals which may cause alkali silica reaction, and to compare the results of specimen expansion accordingly. Thin sections of standard thickness were prepared[4] using thin section making system (metkon GEOFORM) and were examined under petrographic microscope (OLYMPUS BX51), under magnification of 4x-6x. Thin sections of different

[4] Thin sections were prepared in petrography lab of Geology Department at University of Punjab

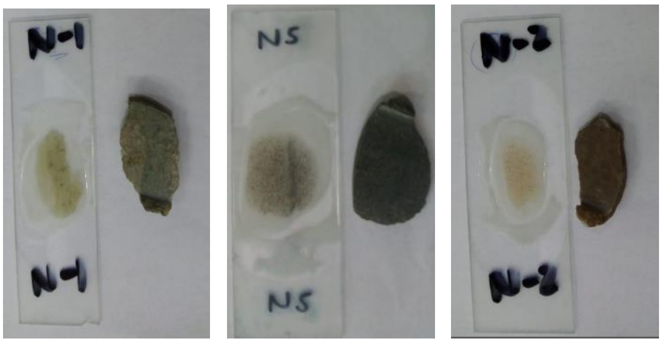
aggreagtes are shown in **Figure 11**. X-ray diffraction (XRD) analysis was also performed on LWA and NWA. Aggregates were grounded to make powder of standard size, and thereafter, were examined through diffractrometer (X'Pert Pro DY 3805) using Cu-Kα radiations at 10^{o}/min scanning rates. Exposed and un-exposed ASR tests specimens were also analysed under Fourier transform infrared spectroscopy (FTIR)[5] by a spectrometer (ATR 6700 Thermo Nicolet) to witness various chemical species present in the specimens and to confirm the possible onset of ASR reaction.

(a) Petrographic microscope

(b) Thin sectioning system



Thin sections of LWA



Thin sections of NWA

Figure 11. Thin sections study of different LWA and NWA

[5] FTIR analysis was conducted by Chemical Engineering Department of COMSATS University Lahore Campus

4. RESULTS AND DISCUSSIONS

4.1 GENERAL

This chapter encompasses the different results of tests that have been carried out on produced LWA and LWC. Overall the results section is sub-divided into two sub-sections. In the first section, discussion will be made on different tests results and properties of LWA developed like; density, water absorption, strength of aggregates and durability of aggregates under ASR. In the second part, LWC formulated by incorporating LWA will be considered for results analysis and discussions. Different test performed on LWC include; slump test, density and water absorption of concrete, compressive strength, split tensile strength and ultrasonic pulse velocity test.

4.2. EXPERIMENTAL RESULTS AND DISCUSSION

4.3. LWA RESULTS

4.3.1. DENSITY

Density of aggregates is a crucial factor which determines the weight of concrete and strength properties. Physical properties of LWA aggregates studied after 7 days curing are displayed in **Table 5**. Density of C_{ags} varied between 867-878 kg/m^3. Higher density of the aggregates was observed containing higher percentage of cement in the mix. Higher unit weight of cement than other components of the mix i.e. FA and GBFS could be responsible for this effect. Similar findings have also been quoted by another study [7]. Density of 10C-20W was 867 kg/m^3 and that of 20C-20W was 872 kg/m^3. Increasing cement percentage, the aggregate particles had been getting heavier and more compact structure could be observed. However, the difference of densities with increasing cement content was not very prominent as density changed from 867 kg/m^3 to 872 kg/m^3 (0.57% increase) by increasing cement from 10% to 20%. This could be for two reasons; (1) aggregate particles are cylindrical in shape and rodded bulk density may vary greatly depending upon difference in compaction and existence of voids, (2) particle size of the aggregates greatly affect the density. Nonetheless, density of LWA aggregates from in this study was lesser than arterial LWA produced by other researchers [7, 39, 72], but they were denser as compared to natural LWA like vermiculite (88-160 kg/m^3), perlite (120-192 kg/m^3) [32], palm shell and boiler clinker aggregates (610-810 kg/m^3) [73].

Table 5. Density and water absorption of aggregates

Sample Name	Density (kg/m^3)	Water Absorption (%)
10C-20W	867	21.92
20C-20W	872	18.73
10C-70W	876	23.10
20C-70W	878	20.25
10S-70D	764	30.09
20S-70D	809	28.30
NWA	1602	0.14

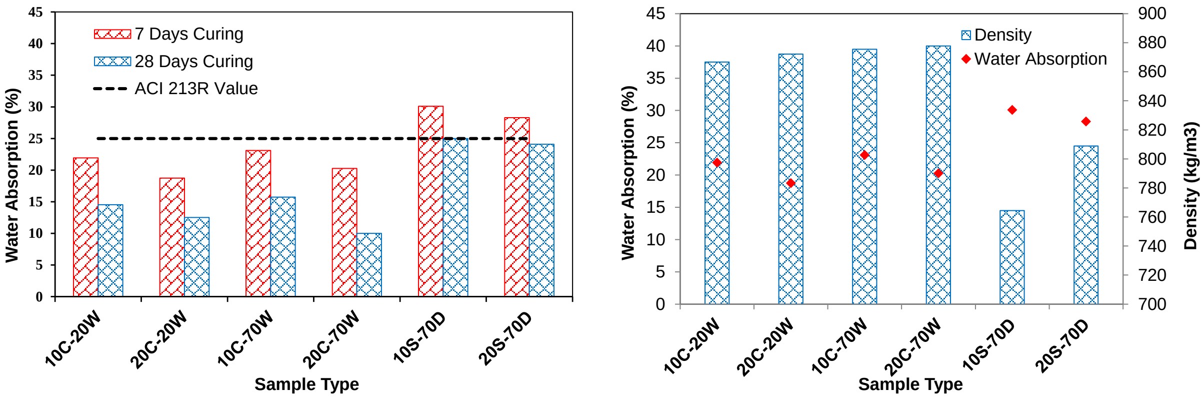
GP_{ags} were even lighter than C_{ags} as shown in **Table 5**. Density of GP_{ags} was lesser for low replacement ratio of GBFS and the difference was more significant as compare to cement aggregates. Increasing slag quantity by 10%, density was increased by 13.72% in 20S-70D as compared to 10S-70D; because GBFS is heavier than FA. GP_{ags} produced were lesser in weight than GBFS, rice husk and FA based geopolymer based aggregates (769-1060 kg/m^3) and mined tailings based pellets (900-1000 kg/m^3) [41, 43].

Cold bonded LWA from this study showed densities lesser than the sintered LWA which normally have densities in the range (1100-1500 kg/m^3) [39]. They also satisfied the density requirement of ACI 213R [32] according to which, density for LWA for structural concrete should not be more than 880 kg/m^3. LWA produced presented significantly lesser densities than normal weight aggregate as well. Highest and least density was presented by 20C-70W and 10S-70D, and they were 45.26% and 56.48% lighter than control normal weight aggregate sample used respectively.

4.3.2. WATER ABSORPTION

Water absorption (WA) of different aggregates is presented in Table 1. WA of lightweight aggregates depended on three main factors; (1) binder percentage in the mixture, (2) curing conditions, (3) curing time. WA of aggregates having 10% and 20% cement as binder was 21.92% and 18.73% respectively, after 7 days curing. Adding 10% more cement, reduced the water absorption by 14.5%. Increasing water absorption results for increased cement content are in accordance with density results. More cement content produces more hydration reaction and less pores [7]. Similarly, two curing regimes for LWA caused different results.

C_{ags} cured in water at room temperature conditions observed lesser water absorption than water cured aggregates at elevated temperature. Aggregates containing 10% cement as binder showed W.A values of 21.92% and 23.10% when water cured and hot water cured curing respectively. Elevated temperature cured aggregates showed 5.4% more water absorption than water cured sample at room temperature conditions. Similarly the difference in water absorption for aggregates containing 20% cement was 8.1%. This shows that, with hot water curing, WA showed increasing trend and this increment was increasing with higher percentage of cement content. All four type of C_{ags} had WA within normal range for LWA (<25%) according to ACI-213R. However, most of the commercial artificial LWA exhibit WA within 10-18% [39]. Water absorption values of produced LWA after 7 days curing were little higher than previously reported results i.e. 8.7-15.5% [39] and <20% [7]. More water absorption of aggregates is associated to lesser density of aggregates, which is an indication of porous microstructure. WA values of aggregates reduced considerable with curing days as shown in **Figure 12(a),** which shows the comparison of water absorption after 7 and 28 days curing. W.A observed 33.7% and 33.3% reduction after 28 days curing as compare to 7 days, in aggregates containing 10% and 20% cement, respectively.



(a) (b)

Figure 12. Water absorption value of LWA produced, after 7 and 28 days of curing

Water absorption values for GP_{ags} were quite higher than C_{ags}. After 7 days of curing, GP_{ags} with 10% and 20% slag showed WA of 42.52% and 28.30% respectively. These values made it clear that GP_{ags} were more porous as compared to C_{ags}, which was the reason, they showed low densities as illustrated in **Figure 12(b)**. GP aggregates presented higher water absorption than usual range for commercial LWA (10-18%). However, W.A showed decreasing trend as curing days were increasing. After 28 days curing, W.A of 10S-D70 decreased from 42.5% (7 days) to 25% (28 days) and showed 41.17% reduction whereas, 20S-D-70 showed W.A value of 24.09% with reduction of 14.87% as compare to 7 days curing results. After 28 days curing, all the aggregates presented W.A within usual range (<25%) as reported in ACI-213R [32].

4.3.3. AGGREGATE IMPACT VALUE

Aggregate impact value (AIV) results for different aggregates are presented in **Table 6**. The lower the aggregate impact value is, better will be the resistance of aggregates against impact loads. Strength of aggregates was considered for three variables, binder content, curing regime and curing time. It is clear from tabulated results that impact resistance of C_{ags} was increasing for increasing cement percentage in the aggregates and it was due to improvement of C-S-H formation as well as more portlandite (CH) formation owing to the increased hydration reaction. Mineral admixtures like FA and GBFS also react with CH and further increase strength [7]. Also, cement interacts with calcium oxide of GBFS to produce better and denser microstructure [74, 75]. After 7 days curing, AIV for 10C-W20 and 20C-W20 was 32.34%, 27.78% and 28.24%, 21% for water curing and hot water curing conditions respectively. Aggregate impact resistance was better for hot water cured samples. Changing curing conditions from water curing to hot water curing, aggregates containing 10% and 20% cement observed 14.1 and 25.6% betterment in impact resistance. This result was contrasting to WA results, as WA observed more values with hot water curing regime. This is because , more penetration of hot water through the pores causes hydration reaction for un-reacted particles; in addition, GBFS due to elevated temperature water curing can initiate early and expedited formation of ettringite that plays its role in strength improvement [50, 76]. **Figure 13** shows the relationship of WA and the AIV. As it is evident from **Figure 13**, all other aggregates observer good correspondence between WA and AIV results i.e. aggregates with lower WA were more resistant against impact loads.

Similarly, GP_{ags} containing more percentage of GBFS offered better resistance. Impact values of 10S-D70 and 20S-D70 were 43.4% and 28.53% respectively. For 10% more addition of GBFS, impact resistance increased by 34.26% which shows that GBFS addition support the better strength and reduced porosity in the matrix [77]. Furthermore, GBFS addition improves microstructure by formation of calcium based polymer structure [56, 78]. In contrast, AIV for NWA was 10.08% which is significantly lesser than produced LWAs.

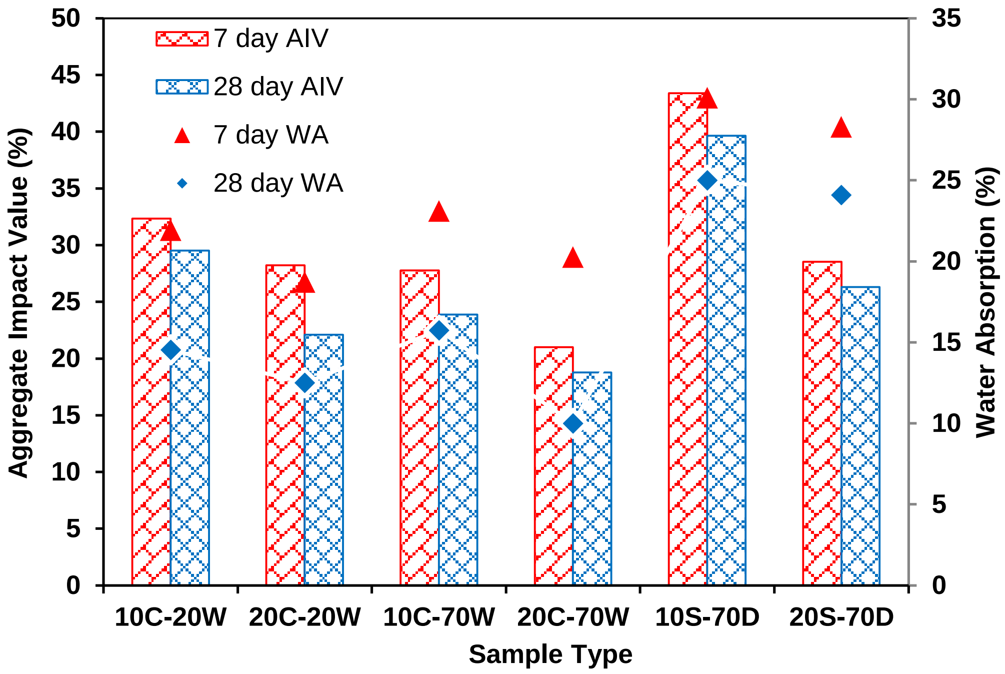


Figure 13: Relation between aggregate impact value and water absorption of aggregates

Resistance of aggregates against impact loads was increasing with curing days. Water cured aggregates containing 10% and 20% cement binder presented impact values of 29.52% and 22.12% respectively after 28 days; and corresponding hot water cured aggregates had impact values of 23.89% and 18.77% respectively. AIV's for 10S-D70 and 20S-D70 after 28 days curing were 39.64% and 10.8% respectively. Highest and least improvement in impact resistance was observed by 20C-W2 (21.67%) and 20S-D70 (7.82%) after 28 days, as compared to 7 days. It shows that C_{ags} continued to gain strength with time, whereas, GP_{ags} acquired maximum strength within early 7 days curing. This is so, because geopolymer usually attain high early strength (92-96%) within early 7 days, and then it gain slow or negligible strength [12]. Hot water cured aggregate containing 20% cement was best to perform after 28 days which presented AIV of 18.77%. This aggregate was approximately ½ time as strong against impact loads as natural aggregate was. Aggregate for use in concrete must have AIV less than 30% as per BS-812-12. All the LWA produced met this criterion after 28 days curing except 10S-D70.

Table 6. AIV and TFV of aggregates after 7 and 28 days of curing

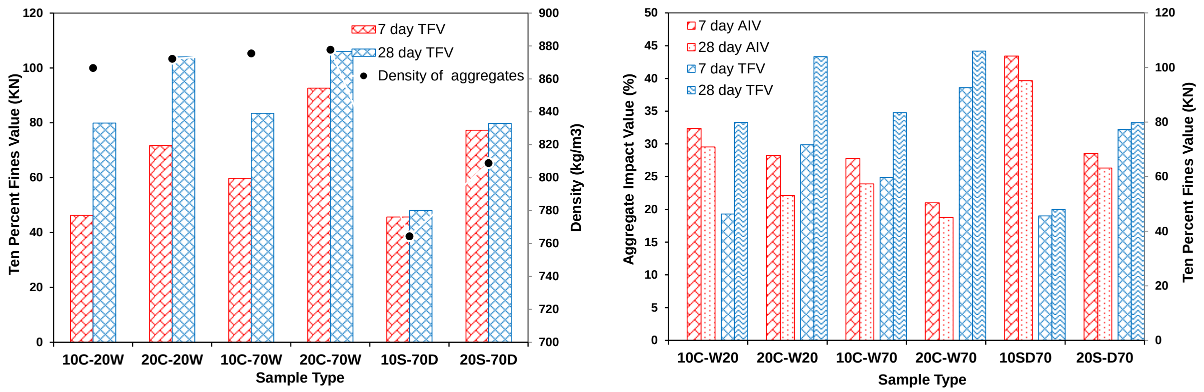
Sample Name	Aggregate Impact Value (%)		Ten Percent Fines Value (KN)	
	7 Days	28 Days	7 Days	28 Days
10C-20W	32.34	29.52	46.27	79.84

20C-20W	28.24	22.12	71.64	103.95
10C-70W	27.78	23.89	59.74	83.44
20C-70W	21.00	18.77	92.59	105.99
10S-70D	43.4	39.64	45.61	48.00
10S-70D	28.53	26.30	77.26	79.75
NWA	10.08	10.08	183.83	183.83

4.3.4. TEN PERCENT FINES VALUE

Ten Percent fines value (TFV) of different aggregates is presented in **Table 6**. Results for ten TFV were in accordance with density and impact value test as shown in **Figure 14**. Aggregates with higher density showed better performance both in impact loads as well as against compressive loads. Strength was increasing both for C_{ags} and GP_{ags} with increasing binder content and curing time. C_{ags} offered more resistance against crushing than GP_{ags}. Higher ten Percent fines value shows better resistance of aggregates against compressive loads. Adding 10% more cement, TFV of 46.27 KN for 10C-W20 was changed to 71.64 KN for 20C-W20 with an improvement of 54.8%. Similarly for hot water curing regime, the improvement in TFV for 10% cement increment was 55% approximately. TFV of aggregates containing 10% cement after 7 days curing was 46.27 KN and 59.74 KN respectively for water cured and hot water cured conditions. This shows that hot water cured aggregates were stronger than water cured ones. On the other hand, 20C aggregates also showed 29.2% improvement of resistance against compressive loads by changing curing regime from water curing to hot water curing.

GP_{ags} observed strength improvement with rising percentage of GBFS in aggregates mixture composition. TFV of aggregates was 45.61 KN and 77.26 KN for 10S-D70 and 20S-D70 respectively. Strength of aggregates also improved with curing time. Compressive strength improvement of 72.55% and 45.1% after 28 days curing was observed for 10C and 20C water cured aggregates respectively as compare to 7 days curing; and for hot water cured pellets, corresponding gain in strength was 39.6% and 14.4%. The difference in TFV of aggregates at 7 and 28 days curing was more prominent than impact resistance improvement which implied that, aggregates offered better resistance to compressive loads than impact loads. Maximum improvement of 72.55% in TFV from produced aggregates was observed by 10C-W20; and maximum improvement of 21.67% in AIV was observed for 20C-W20. It was interesting to note that C_{ags} showed better improvement of strength with time as compare to GP_{ags}. Ten percent fines value of normal weight aggregate considered was 183.83 KN. From results it was evident, that C_{ags} (20C-70W) can take about half of the loads that NWA can take.



(a) (b)

Figure 14. Relationship between: (a) TFV and Density of aggregates, (b) TFV and Aggregate AIV

4.3.5. EXPANSION DUE TO ALKALI SILICA REACTION

Expansion of various specimens measured after different time is illustrated in **Figure 15**. Expansions measurements were recorded up to 28 days. Geopolymer-based-specimens (G-specimens) made with LWA, 20C-70W and 20S-70D, and NWA experienced expansions of 0.07%, 0.06% and 0.066% respectively after 14 days. The expansions of same specimens after 28 days exposure were 0.074%, 0.064% and 0.072%. Expansion of cement-based-specimens (C-specimens) after 14 days exposure was 0.07%, 0.12% and 0.1% for C-20C, C-20S and C-NWA specimens respectively. Length change for all specimens was within acceptable range according to ASTM standard (C1260); that is highest expansion for specimens with deleteriously aggregates should not be more than 0.2% [66]. G-specimens performed better than C-specimens, and none of the G-specimens developed cracks even after 28 days exposure. Similar results have also been reported in previous work that geopolymer specimens are more resistant against alkali silica reaction [47, 61]. Few G-specimens observed white leaching material on surface of specimens, which can be due to calcium and sodium ion leaching onto surface [47]. While micro-cracks were evident in few C-specimens like, C-20S and C-NWA. **Figure 16** shows specimens which experienced leaching and cracks formation due to ASR. It is important to note that, in C-specimens, maximum expansion with micro-cracks was observed for specimen which was made with GP_{ags}. Likewise, in G-specimens, highest expansion was observed by a specimen which was made with C_{ags}. This implies that, there is compatibility issue between different binder and aggregates, which can be associated with various reasons like; (1) geopolymers may acquire further strength when dipped in alkaline solutions because of reaction of un-reacted particles of matrix and alkaline solution, which can promote matrix densification and porosity reduction consequently [47], 2) re-adjustments and densification in matrix may cause micro-cracks.

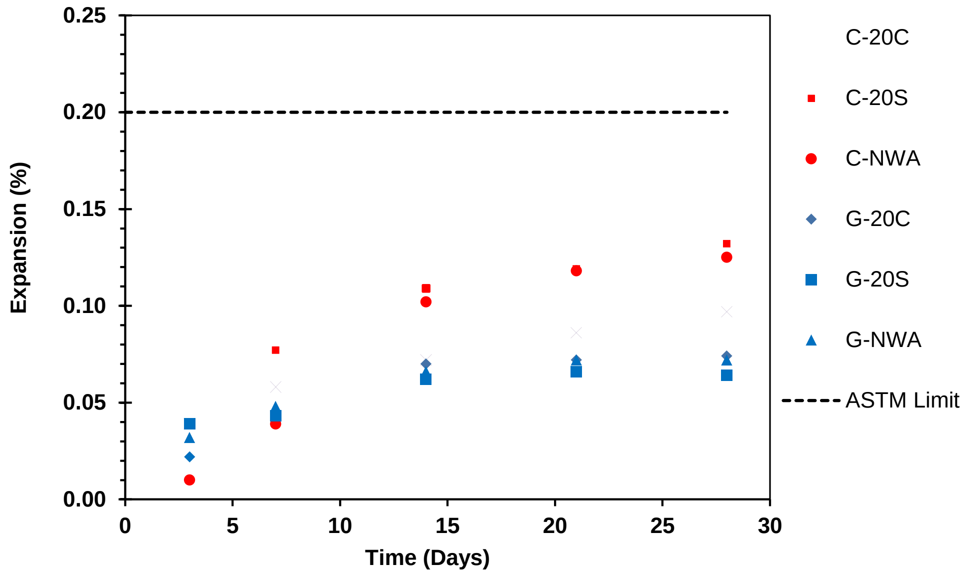
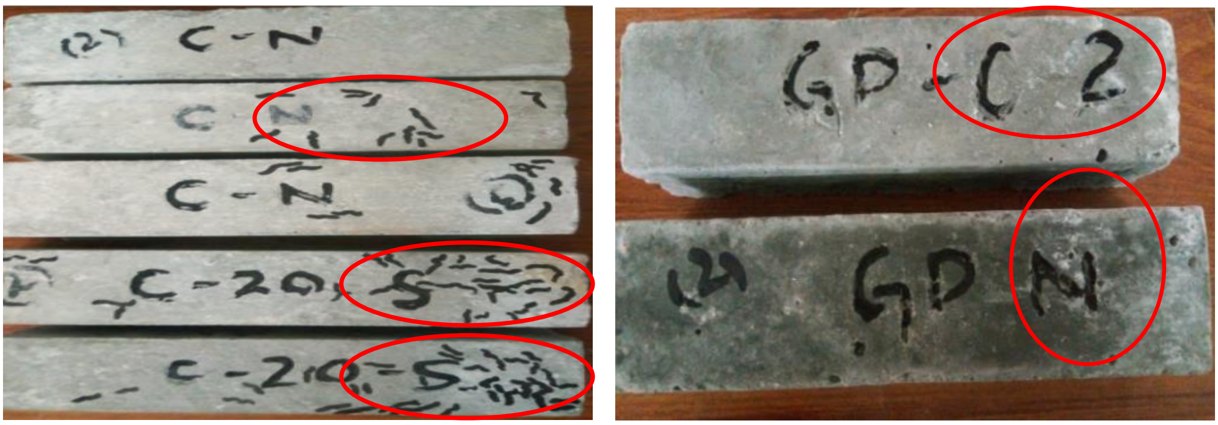


Figure 15. Expansion of different specimens after 28 days exposure to alkaline solution



(a) (b)

Figure 16. NaOH exposed specimens: (a) C-specimens exhibiting cracks, (b) G-specimens displaying leaching

4.3.5.1. Water Absorption of ASR Test Specimens

On completion of alkali silica reaction test and observation of expansion of specimens, they were reduced to 40 mm cube sizes to conduct water absorption and compressive strength tests on them. WA values of NaOH exposed and un-exposed cubes are shown in **Figure 17**.

Almost all the cubes which were exposed to sodium hydroxide solution for ASR test showed more water absorption values than that of un-exposed samples. Cement based specimens observed increase in the water absorption in the range of 16-34% while geopolymer specimens experienced lesser increase ranging between 14-18%. Expansion during alkali silica reaction test produced cracks which ultimately allowed more penetration of water into those cracks. Only specimen from exposed cubes which showed less water absorption as compared to un-exposed samples was one, which was made with geopolymer aggregate and geopolymer binder (GP-20S). This shows that geopolymer mortar and geopolymer aggregate were not affected by alkali silica reaction; rather exposure to sodium hydroxide solution may have caused improvement in binder reaction products which ultimately caused reduction in porosity of samples. Porosity of cement based samples was increased with exposure of NaOH solution during alkali silica reaction test, whereas, porosity of geopolymer based specimens showed decreasing trend after exposure [47].

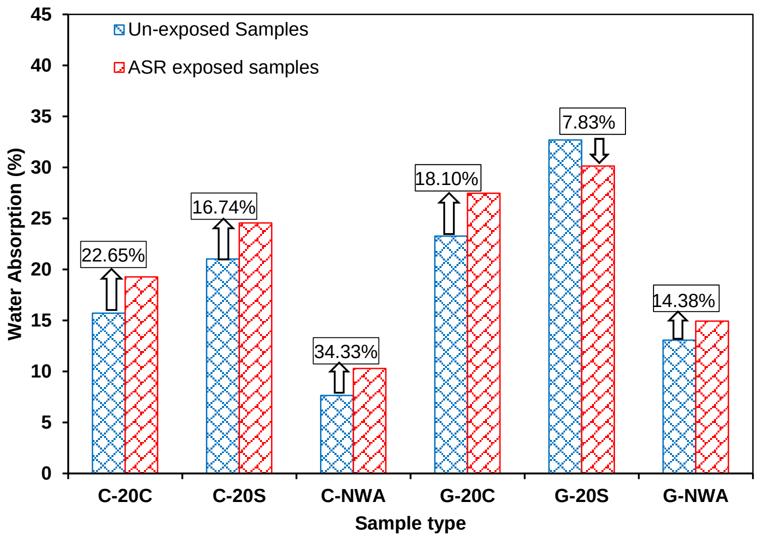


Figure 17: 28 day water absorption of NaOH exposed and un-exposed specimens

4.3.5.2. Compressive Strength of ASR Test Specimens

Sodium hydroxide solution application impacted C-specimens and G-specimens differently. **Figure 18** shows results for compressive strength of cube specimens for both exposed and un-exposed conditions. C-specimens showed strength deterioration after exposure; which is obvious because of crack formations. Cement cubes presented 5.49-9.27% decline in the compressive strength due to 28 days NaOH exposure as compared to strength of un-exposed specimens. All the G-specimens showed betterment in compressive strength after exposure.

G-specimens experience extraordinary rise in strength of 42-87% relative to un-exposed specimen's strength. Although expansion of specimens induced cracks in G-specimens, yet, penetration of NaOH solution via these cracks may have caused polymerization of un-reacted slag and FA particles, which introduced matrix densification and subsequent strength development [47]. GP-20S specimen presented compressive strength of 16.27 MPa for 28 days ASR exposed samples as compared to the compressive strength of 8.70 MPa for un-exposed samples and observed maximum strength improvement of 87% as compared to strength of un-exposed samples. This sample also showed improvement of porosity with exposure which confirms the theory of strength improvement for geopolymer matrix with exposure to sodium hydroxide solution and temperature. Concluding, geopolymer aggregates and geopolymer cube samples showed improvement in strength with exposure to sodium hydroxide solution.

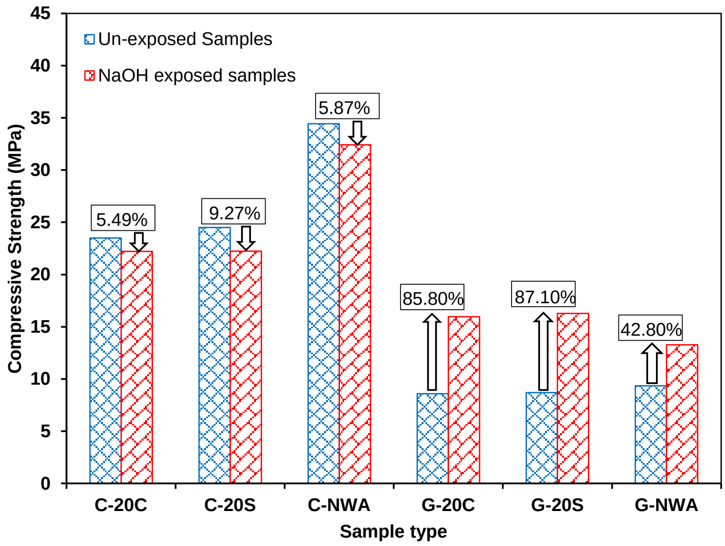


Figure 18. 28 day water absorption of NaOH exposed and un-exposed specimens

4.3.6. PETROGRAPHIC ANALYSIS

4.3.6.1. Thin Sections Study

Thin sections of LWA and NWA were examined through petrographic microscope to recognize minerals available in these aggregates. Seven sections were fabricated overall; two thin sections of LWA which presented maximum strength, 20C-70W and 20S-70D, and five thin sections represented five different rocks which were present in NWA sample. Thin sections analysis showed that, most of the portion of lightweight aggregates was composed of very fine grain sizes reaction products which could not relate to any minerals and hardly be identified by petrographic microscope. Only 5-25% presence of quartz was revealed. For NWA sample, particles of different rocks were counted to find the relative proportions of different rocks present in NWA as per ASTM C295 [79]. **Table 7** provides information regarding different rock types, relative percentages of different rocks in the crushed stone sample, minerals and their relative percentages identified in thin sections. Thin sections analysis found different minerals like of quartz, plagioclase, hematite, feldspars, ilmenite, altered chlorite, pyroxene, epidote, and altered sericite in various rocks. Neither NWA nor LWA contained ASR minerals like, cristobalite, trydymite, cryptocrystalline quartz and opal. The only concern for ASR was 60% share of sandstone in NWA, which displayed presence of considerable amount of crystalline and polycrystalline quartz, 70-90%. However, this polycrystalline form was un-strained and less reactive. Photographs of thin sections taken by petrographic microscope under plane-polarized light are shown in **Figure 19**.

Table 7. Minerals identified in thin sections of LWAs and NWA sample

Aggregate Type	Aggregate Designation/ Rock Name	Relative Percentage in Sample	Minerals Identified
LWA	20C-W70	-	Quartz (15-25%), clay size fraction/reaction products (80-85%)
	20S-D70	-	Quartz (5-15%), clay size fraction/reaction products (90-95%)
NWA	Meta-dolerite (greenish grey,)	8.9%	Pyroxene (10-15%), altered chlorite (10-15%), plagioclase and altered sericite (35-40%), polycrystalline quartz (10%), epidote (3-5%)
	Meta-dolerite (blackish grey)	20.9%	Pyroxene (30-35%), plagioclase (40-45%), quartz (5%), ilmenite (3-5%), altered chlorite (5-10%)
	Sandstone (brown)	23.1%	Quartz, crystalline to polycrystalline (85-90%), hematite (5%), feldspars (2-5%)
	Sandstone (dark grey)	37.7%	Quartz (70-75%), feldspars (3-5%), argillaceous rock fragments (15-20%)
	Granite (white)	9.5%	Quartz, crystalline to polycrystalline (30-35%), feldspars (60-65%), magnetite (1-2%)

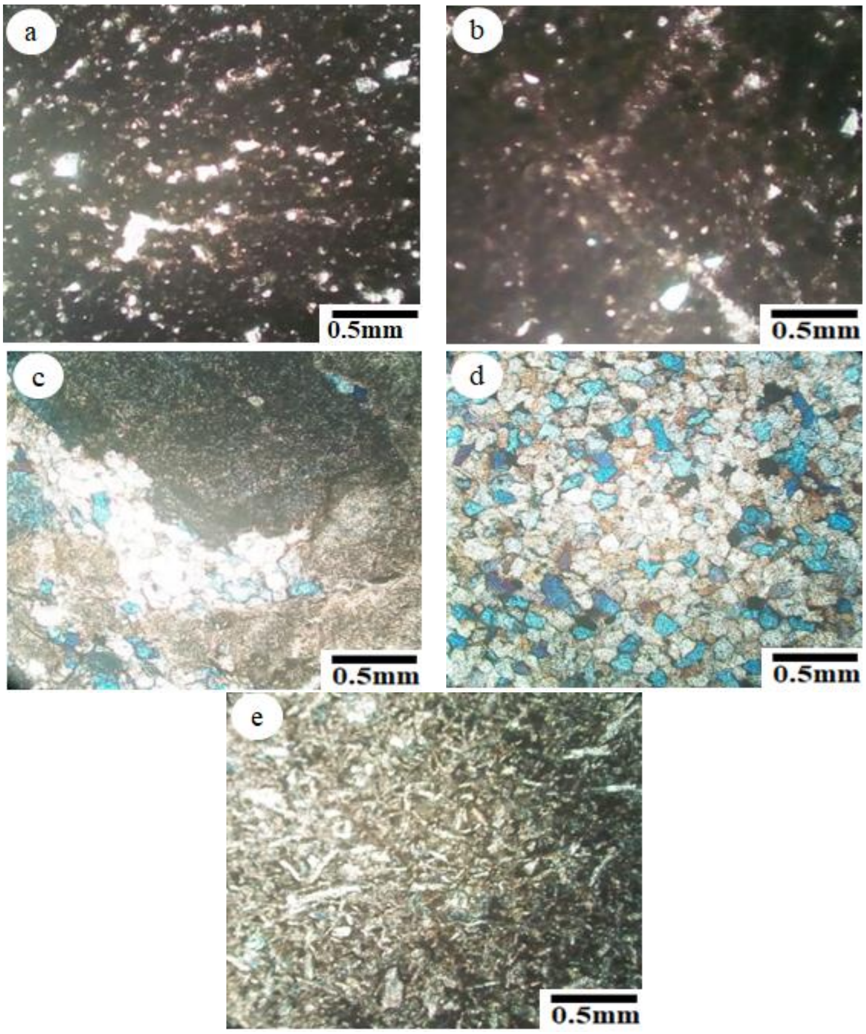
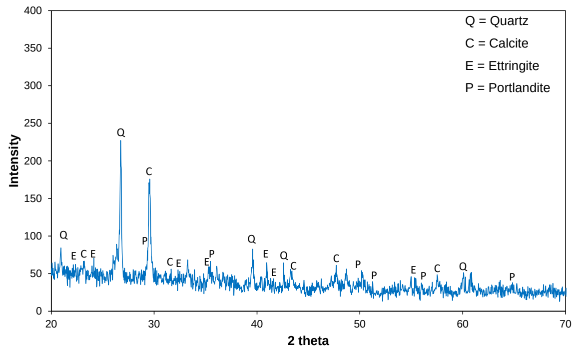


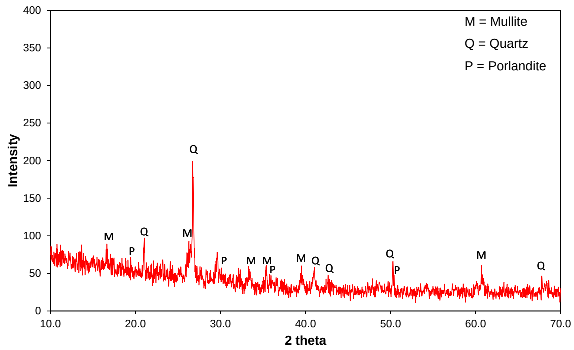
Figure 19. Thin section images of different aggregates: (a) 20C-70W, (b) 20S-70D; (c) black grey metadolerite; (d) brown sandstone; (e) white granite

4.3.6.2. X-ray Diffraction Analysis

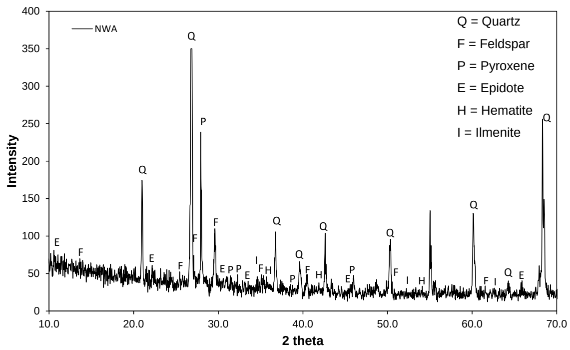
XRD analysis on powdered form of aggregates was performed to find mineralogical composition and the analysis results are displayed in **Figure 20**. Main hydration reaction species in cement based mortars and pastes are generally C-S-H (calcium silicate hydrates) and CH (portlandite). XRD analysis does not identify C-S-H phases because of their amorphous or poorly crystalline nature. Ettringite and portlandite peaks can be clearly seen from **Figure 20(a)**, which are generated by the reactions of aluminate, silicate, and ferrite phases in cements on hydration [80]. Some other minerals were also present in 20C-70W aggregates like, calcite and quartz, which were related to the unreacted fly ash and GBFS [15]. On the other hand, As 20S-D70 also observed peaks related to portlandite which is the reaction product normally generated due to GBFS present in the mixture [81]. The same aggregate also presented mullite and quartz peaks from fly ash particles which probably failed to contribute in geopolymerization [15]. XRD also does not show any peaks associated with geopolymerization reaction products because they are mostly amorphous. NWA sample presented minerals of quartz, pyroxene, feldspar, epidote, ilmenite and hematite. XRD results were in close agreement with thin sections analysis results and observed similar kind of minerals.



(a) 20C-70W



(b) 20S-70D

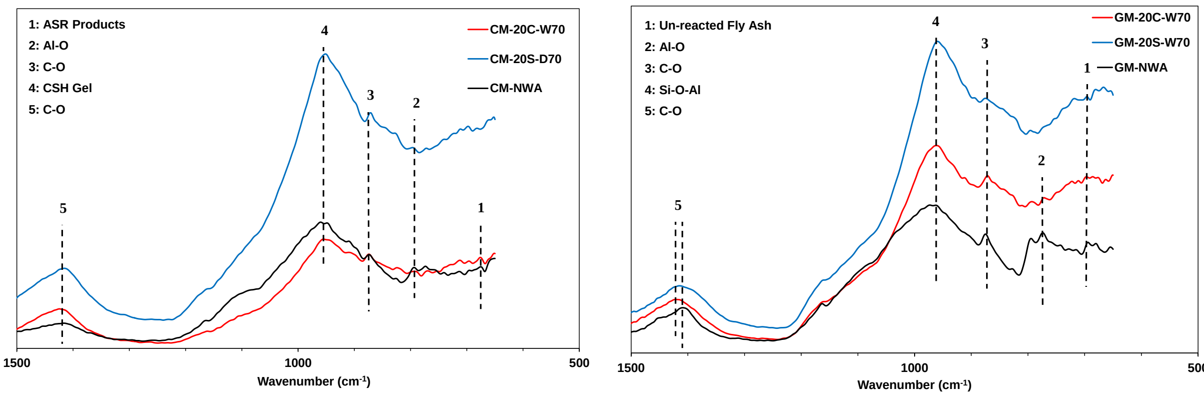


(c) NWA

Figure 20. XRD results of different aggregates

4.3.6.3. Fourier Transform Infrared Spectroscopy (FTIR)

Results of FTIR analysis for cement and geopolymer based prisms are shown in Figure 21. C-specimens (Figure 21a) displayed a band vibration related to Si-O-Si for ASR products at about 667 cm^{-1} [82], which supported the expansion test results and described that ASR occurred in C-specimens. Interesting observation is that cement prisms containing GP_{ags} and NWA showed this vibration, and these specimens also observed higher expansions. C-specimens also observed vibrations for Al-O and C-O bond at approximately 785 cm^{-1} and 873 cm^{-1} respectively. Al-O bond indicates un-reacted aluminosilicates; whereas, C-O bond shows carbonation reaction, which can take place with the availability of CO_2 in water or available atmospheric CO_2 [82, 83]. Strong band vibration at 967 cm^{-1} was also observed for all C-specimens that shows formation of C-S-H gel [83]. C-S-H gel is major phase that is produced during hydration reaction of cement.



(a) C-specimens (b) G-specimens

Figure 21. FTIR test results of NaOH exposed samples

In G-specimens no band vibrations associated with ASR reaction products were observed, (Figure 21b) which verifies that G-specimens as well as GP_{ags} were less reactive in alkaline environments. G-specimens also observed similar band vibrations corresponding to C-O and Al-O at same wavenumber as C-specimens experienced. All the G-specimens showed a minor peak at 698 cm^{-1} which was associated with un-reacted FA particles [47]. Major band vibration for geopolymer gel (Si-O-Al) was observed at 960 cm^{-1} in all the G-specimens and these gels denote the major geopolymer hydration products [82].

4.4. CONCRETE RESULTS

4.4.1. WORKABILITY OF CONCRETE

Slump test was performed on all the concrete mixtures immediately after concrete manufacturing as a measure of workability and the results of slump tests are reported in **Table 8.** Slump value for geopolymer concrete (GC) lightweight concrete mixtures varied between 28-30 mm, although they were designed for slump value of 50-100 mm. The low slump value was due to the alkaline solutions, which were quite stickier and tend to reduce workability of concrete [84]. On the other hand, Portland cement concrete (PC) mixtures observed considerable higher and acceptable slump value between (65-70 mm). It is interesting to note that, slump value was little higher for concrete mixtures containing higher density aggregates. Increasing size and ultimately weight of aggregates the slump value increases [85].

Table 8. Workability, physical and mechanical properties of different LWC after 7 days of curing

Mixture	Slump Value	Dry Density	Water Absorption	Compressive Strength	Split Tensile Strength	Ultrasonic Pulse Velocity
	(mm)	(kg/m^3)	(%)	(MPa)	(MPa)	(m/s)
GC-10C-20W	28	1906	5.20	24.97	2.44	2936
GC-20C-20W	30	1965	4.82	29.66	3.21	2988
PC-10C-20W	65	1945	6.27	17.43	2.40	2601
PC-20C-20W	70	1956	5.54	23.45	2.46	2835

4.4.2. DENSITY OF CONCRETE

Density of concrete is very important factor which decides the unit weight of concrete and dead loads of concrete structure, which ultimately decide the behaviours of structure under seismic loads. Oven dry density of different concrete samples is shown in **Table 8**. Concrete density is greatly affected by the unit weight of aggregates [73]. Density of concrete was increased with higher density of aggregates containing higher percentage of cement in their mix composition. For GC concrete mixtures density ranged between 1906-1965 kg/m^3 and for PC specimens the density of concrete varied within 1945-1956 kg/m^3. All types of concrete mixture fall in the category of LWC because density of structural LWC should be less than 2000 kg/m^3 [73]. According to Euro code 2: Part 1-1, the density of lightweight concrete should not be more than <2200 kg/m^3 [84]. The density of concrete produced in this study were less than previously produced oil palm clinker based lightweight concrete, where density of concrete was in the range 1955-2172 kg/m^3, and are comparable to the densities of another study (1850-2050 kg/m^3). Comparative relation of density of different mixtures is shown in **Figure 22** .

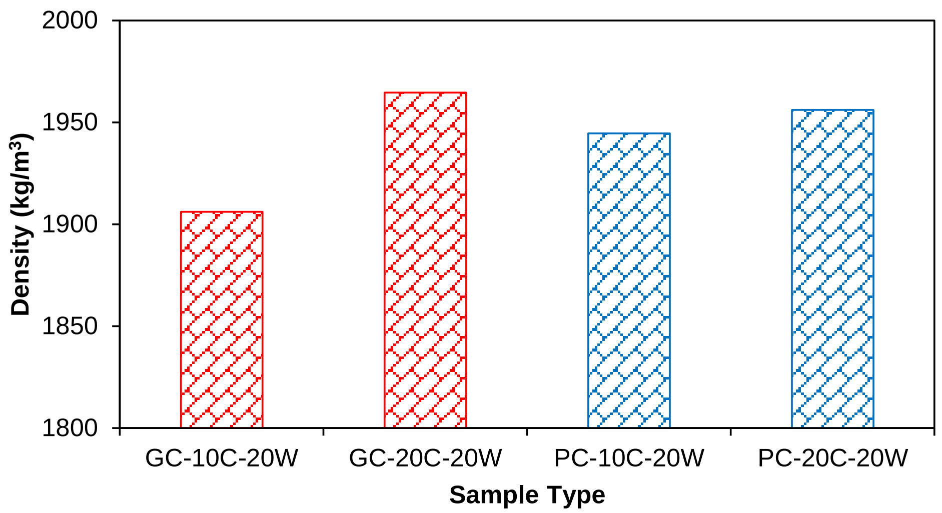


Figure 22. Density variation of different concrete mixtures after 7 days of curing

4.4.3. WATER ABSORPTION OF CONCRETE

Water absorption of concrete is an important measure to estimate the quality of concrete and expected durability of concrete in its service life. WA value of concrete cubes of various mixtures was measured after 7 days of curing and presented in **Table 8.** It can be observed from the results that water absorption for GC specimens was only between 4.80-5.20%. Water absorption capacity of concrete greatly depends on porosity of matrix and aggregates used. Good quality concrete normally present water absorption values less than 10%. And high quality concretes observe water absorption values within 5% [73]. PC specimens showed water absorption values between 5.54-6.27%. Geopolymer concrete cubes presented even lesser water absorption than cement based concrete cubes. GBFS addition shows improvement in microstructure and water absorption reduces , that could be the reason behind lesser water absorption of GC specimens [84]. Density of aggregates also has influence on concrete water absorption such that concrete specimens having heavier aggregates showed lesser water absorption. Furthermore, water absorption results were in accordance with density of concrete **Figure 23**. Denser concrete specimens experienced lesser water absorption.

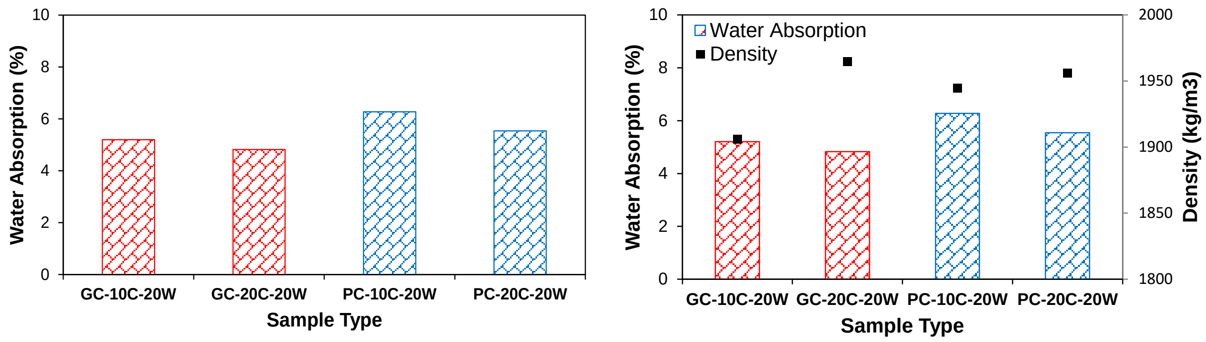


Figure 23. Relation between water absorption and density of concrete mixtures

4.4.4. COMPRESSIVE STRENGTH OF CONCRETE

Compressive strength test was performed on cube specimens for all the mixtures; for every condition three cube specimens were tested and average strength results after 7 days curing are quoted in **Table 8.** It is clear from tabulated results that geopolymer concrete specimens showed more strength than cement based concrete specimens. This is so, because geopolymer usually attain high early strength (92-96%) within early 7 days, and then it gain slow or negligible strength [12]. Whereas, Portland cement concrete usually acquire 70-80% of 28 days compressive strength after 7 days of curing [45]. The compressive strength value for GC specimens ranged between 24.97-29.66 MPa, and PC specimens presented corresponding value within 17.43-23.45 MPa. The maximum strength attained after 7 days curing was 29.66 MPa of GC-20C-20W specimen which was higher than corresponding PC specimen by 26.58%. Moreover, compressive strength results were in agreement with density results as shown in **Figure 24**; concrete specimens having higher density presented more compressive strength in their respective categories.

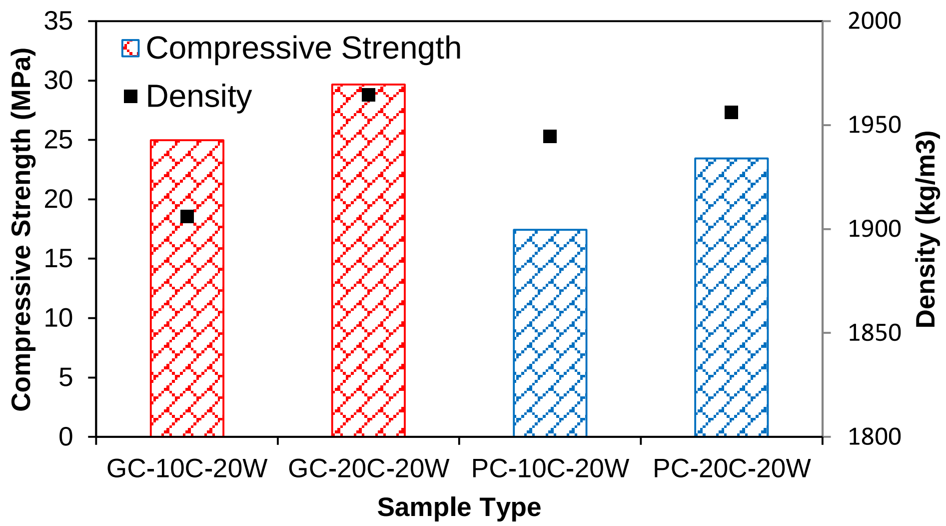


Figure 24. Relation between compressive strength and density of concrete

Furthermore, compressive strength was also increasing with increasing curing days **Figure 25**. From figure it can be observed that geopolymer specimens observed negligible gain in strength with increase in curing time. Geopolymer specimen containing 10C-20W showed about 2.64% strength gain as compared to 7 days compressive strength. Whereas, for GC-20C-20W, the strength improvement was ignorable (0.81%). On the other hand, PC specimen (PC-10C-20W) showed considerable improvement in compressive strength (15.89%) relative to 7 days compressive strength value, where compressive strength changed from 17.43 MPa to 20.2 MPa. PC-20C-20W showed 5.33% improvement in compressive strength as well. It can be deduced from results that concrete specimens made with high strength aggregate (20C-20W) showed lesser strength gain with curing age both in geopolymer and cement concrete specimens. In addition, results also confirmed the theory of early strength gain of geopolymer concrete.

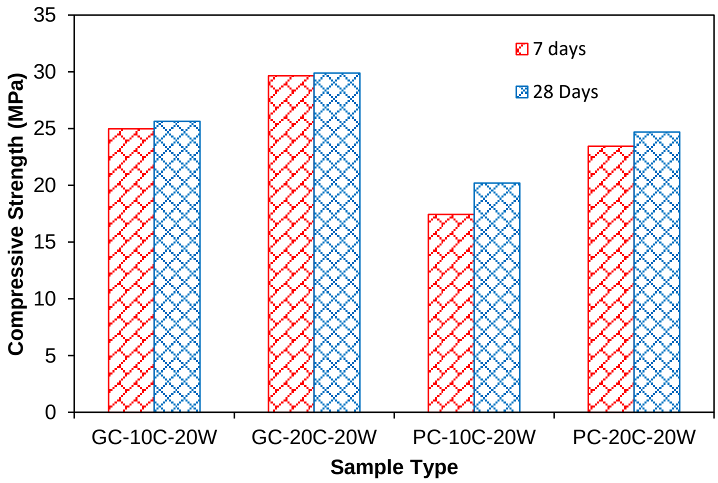


Figure 25: Comparison of compressive strength of concrete specimens after 7 and 28 days curing

4.4.5. SPLIT TENSILE STRENGTH OF CONCRETE

Normally concrete is designed for compressive forces because its tensile strength is low and often neglected and alternatively steel reinforcements are provided to take tension forces. However, in some cases like highway bridges, dams and pavements it is advisable to carefully consider the tensile strength of concrete [73]. Splitting tensile strength is relevant measure which gives an appropriate idea about the susceptibility of concrete to possible cracking in concrete due to flexural or tensile loading [84]. So with this background and objective, split tensile strength test was performed on concrete cylindrical specimens and results are displayed in **Table 8**. Like compressive strength results, GC specimens observed higher split tensile strength than PC specimens and values ranged between 2.44-3.21 MPa. Concrete specimen GP-20C-20W presented quite remarkable strength of 3.21 MPa after 7 days of curing, which was the highest value among all specimens. PC specimens showed strength values between 2.40-2.46 MPa. It was reported that, minimum split tensile strength required for structural lightweight concrete after 28 days of curing is 2 MPa [73]. Strength was also increasing with curing time as illustrated in **Figure 26**. GC specimens observed little betterment in strength, on the other hand, PC specimens presented about 5.42-19.11% improvement in strength. Maximum gin in strength was observed for PC-20C-20W specimen whose strength was increased by 19.11% with increasing curing days. Split tensile strength results also verified the compressive strength results and they presented similar trends as shown in **Figure 27**. Overall, Both GC and PC specimens presented values above this requirement and therefore produced LWC can be considered for structural LWC applications.

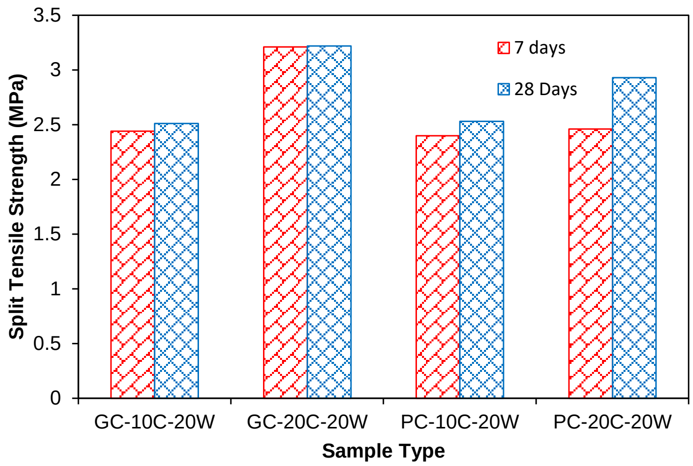


Figure 26: Comparison of split tensile strength of concrete specimens after 7 and 28 days curing

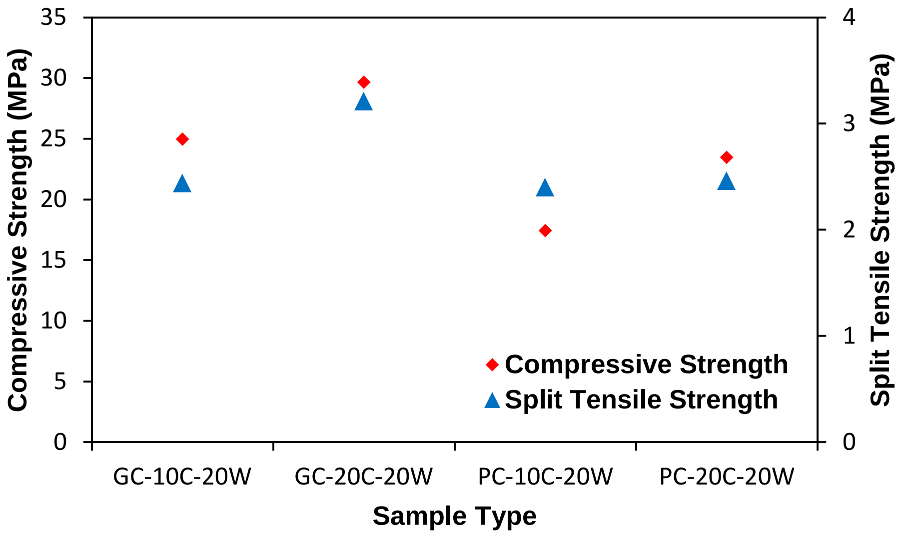
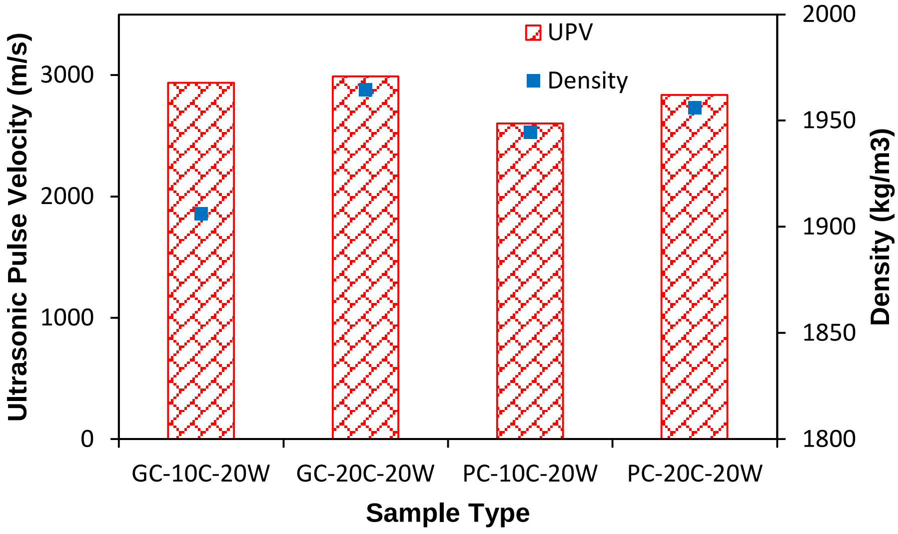


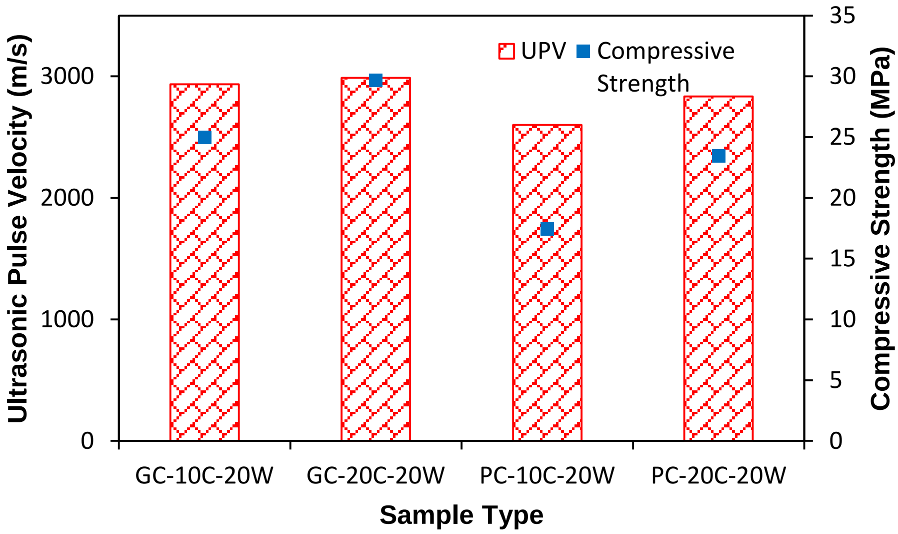
Figure 27. Relation between split tensile strength and compressive strength of concrete

4.4.6. ULTRASONIC PULSE VELOCITY TEST

Ultrasonic pulse velocity (UPV) test is an effective way to assess the quality of concrete [86]. It appropriately tells about the flaws in concrete and can serve as a way to guess concrete compressive strength. UPV test results on different concrete samples are presented in **Table 8.** This test measures the transit time of pulse generated to pass through the concrete samples. Speed of the passing pulse will be more if the concrete internal structure is more compact and denser which is an indication of better quality and strength of concrete. UPV value for GC concrete observed to range between 2936-2988 m/s, whereas, PC concrete presented values between 2601-2845 m/s. UPV test results further verified the compressive strength and split tensile strength results. Concrete specimens having more density and compressive strength observed higher UPV values **Figure 28**. Overall, UPV value of all types of concrete fall in the range of 2000-3000 m/s, another study reported UPV values in the same range for oil palm clinker based lightweight concrete specimens [84].



(a)



(b)

Figure 28. Relation between; (a) ultrasonic pulse velocity and density of concrete, (b) ultrasonic pulse velocity and compressive strength of concrete

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSION

This study was designed to make artificial LWA using industrial by-products with different binding systems and under diverse curing conditions to assess the feasibility of good performance and sustainable LWA for economic and environmental friendly construction works ultimately. Two different kinds of LWA were produced based on cement as binder and process of geopolymerization. Their physical properties, mechanical strength and durability characteristics were examined and compared with some previously produced LWA and standard guidelines. For a second step, LWC was formulated with some of selected LWA to confirm the LWC production and present the properties for economical and better structural concrete applications for many technical advantages. Some of the related findings and key results of this project are:

Oven dry density of C_{ags} ranged between 867-878 kg/m^3 and that of GP_{ags} varied between 764-809 kg/m^3. Density of both types of aggregates was increasing with increasing amounts of binder (cement or GBFS). LWA produced in this study were lighter than many previously developed cold bonded and sintered LWA.

Water absorption of LWA was reducing with rising proportions of cement or GBFS in the mixture for C_{ags} and GP_{ags} respectively. C_{ags} possessed lesser WA as compared to GP_{ags} which were in agreement with density results. WA of aggregates was improving with curing days and all the aggregates presented WA values within usual range i.e less than 25%, after 28 days curing.

To assess the mechanical performance of aggregates two different strength tests were performed; aggregate impact value (AIV) test and ten percent fines value (TFV) test. Strength test results infer that, performance of aggregates was improving with higher percentage of binder and curing duration. C_{ags} could bear more loads than GP aggregates. C_{ags} and GP_{ags} presented AIV’s within 18.77-29.52% and 26.30-39.64% respectively, after 28 days curing, whereas, NWAs exhibited AIV of 10.08%. Most of the aggregates met the criteria of BS-812 for concrete aggregates (AIV should be less than <30%), except GP_{ags} containing 10% GBFS share. Similar results were observed for TFV. Regarding different curing conditions, C_{ags} cured with hot water experienced better strength, both against impact and compressive loads, as compared to water cured aggregates. It was observed that, hot water cured aggregates containing 20% cement possessed half the strength of NWA under compressive loads (TFV of 106 KN) which can be withstood by NWA (TFV of 184 KN), that confirm their possible use in structural lightweight concrete formulations.

To check the durability of LWA in concrete, ASR test was performed both on cement and geopolymer specimens and expansion was recorded. Results revealed that G-specimens experienced less expansion than C-specimens. Specimens containing LWA displayed lesser expansion relative to NWA specimens, and they also satisfied the criteria of ASTM standard. Which further suggest that these aggregates can be used without any harmful effects to concrete under alkaline environments. Water absorption and compressive strength test results on ASR exposed and un-exposed cube specimens depicted that: (1) WA of C-specimens was increasing after exposure to alkaline solution, and compressive strength was reducing, which confirm the onset of ASR reaction and associated micro cracking; (2) WA was increasing for G-specimens as well, however, detrimental effect was less than C-specimens, on the other hand, their compressive strength was enhanced after ASR exposure which dictate the strength improvement of geopolymer binders under alkaline environment.

Petrographic analysis was also conducted on LWA and ASR exposed specimens to investigate the validity of expansion results. Thin sections study of aggregates reported the absence of any alkali silica reactive minerals in LWA formulated, whereas, NWA was composed of major proportions of sandstone aggregates which can cause alkali-silica reaction. FTIR test exhibited small vibrations related to alkali silica reaction products in cement based and NWA specimens; however, most of the LWA based specimens, both with geopolymer and cement, did not exhibit these bands. This confirms the possible incorporation of LWA for concrete formulations.

LWC designed by using LWA produced, exhibited density between 1906-1965 kg/m^3 and 1945-1956 kg/m^3 for geopolymer and cement based concrete respectively. Results also confirmed that concrete were lightweight concrete. Water absorption for LWC designed were within limits and varied between 4.82-6.27% overall for both cement and geopolymer concretes.

Compressive strength of geopolymer concrete from this study was higher than cement concrete. Strength of concrete specimens was increased with curing age and PC specimens observed this improvement with considerable effect. Overall, the compressive strength values ranged between 20.2-29.9 MPa for all types of concrete and satisfied the criteria for structural LWC. Similar results for split tensile strength were observed, which were in agreement with compressive strength results. Split tensile strength of manufactured concretes from current study was within 2.51-3.21 MPa. Ultrasonic pulse velocity test further confirmed the previous strength test results. Concretes with higher density and more compressive strength presented higher velocity and vice versa. The UPV values for all types of concrete fall between 2000-3000 m/s.

Concluding, when we look at the physical, mechanical and durability properties, LWA produced in this study have excellent feasibility to formulate lightweight concretes. Additionally, they can carve the way towards NWA resource conservation, technical benefits of lightweight construction and waste management.

5.2. RECOMMENDATIONS

LWA and LWC were produced in this study successfully having good performance in all respect within the defined domain and objectives. However, there are many other properties of LWA and LWC that should be examined for future works like;

1. Freeze thaw resistance of LWA can also be explored for better performance because LWA contain considerable amount of water permeable pores.
2. Many other agro-industrial and municipal wastes can be tried for aggregates manufacturing for sustainability and to tackle the burden on environment related to wastes.
3. Strength of LWA need more consideration and efforts for betterment in future by using different additives and binding systems
4. Bond between LWA and cement or geopolymer matrix and similarly bond between steel reinforcement and matrix need to be considered for a better performance of respective composites.
5. LWC performance under fire and aggressive environments need to be further studied carefully.

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