STUDIES ON BEHAVIOR OF TIE-CONFINED FLY ASH AND GGBS BASED GEOPOLYMER CONCRETE UNDER AXIAL COMPRESSION

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CERTIFICATE

This is to certify that the thesis titled **"STUDIES ON BEHAVIOR OF TIE-CONFINED FLY ASH AND GGBS BASED GEOPOLYMER CONCRETE UNDER AXIAL COMPRESSION"** by M VENU is a bonafide research work carried out under my supervision and submitted to the department of civil engineering, National Institute of Technology, Warangal for the award of degree of Doctor of Philosophy in civil engineering and has not been submitted elsewhere for the award of any degree or diploma.

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APPROVAL SHEET

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DECLARATION

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M VENU

Dedicated to
My
Beloved Parents

ABSTRACT

Production of Ordinary Portland Cement (OPC) leads to huge emission of carbon dioxide into atmosphere contributing to greenhouse effect. To reduce the negative impacts on atmosphere, sustainable construction materials are being developed to over use of virgin materials used to produce concrete. In such context, the geological origin materials or industrial by-product materials rich in silica and alumina can be used in producing concrete. Many efforts are being conducted to reuse waste industrial processes (such as fly ash, blast furnace slags, etc.) in the manufacture of concrete.

In this study fly ash and GGBS are used as binders instead of ordinary Portland cement in the preparation of Geopolymer concrete. A suitable combination of fly ash and GGBS as binders in geopolymer concrete (GPC) results in high compressive strength even under ambient curing conditions. Many researchers reported the mechanical and durability aspects of GPC, but very few research works are focused on confinement effect of GPC. Though several investigators have proposed mix design for fly ash and GGBS based GPC but there is a less research work reporting the stress-strain behaviour of plain and tie-confined Geopolymer concrete. The confinement of GPC is very essential parameter as it improves the flexural strength, toughness and ductility as well as change the failure mode of concrete under flexural loading**.** The techniques of reinforcing and/or pre-stressing of concrete take care of its tensile capacity. However, these techniques improve the ductility of concrete. Thus, the present study is aimed to investigate the confinement effect of GPC by

considering the parameters viz. tie reinforcement, alkaline/binder ratio, compressive strength of concrete. An experimental program was carried out to evaluate the confinement effect of geopolymer concrete prisms (200 mm * 100 mm * 100 mm) by varying the parameters like confinement index, compressive strength of GPC (20 MPa, 40 MPa, 60 MPa) and tie-configuration (6 mm, 8 mm).

The obtained results conclude that the modulus of elasticity increases with an increase in the compressive strength of concrete, and an equation is proposed for calculating the modulus of elasticity based on the compressive strength of the GPC. It is also found that the modulus of elasticity of fly ash and GGBS based geopolymer concrete is lower that of conventional concrete obtained based on the formula given in IS456-2006 (5000√fck). Equations are proposed to determine the ultimate strength and strain at ultimate stress of Geopolymer concrete in terms of confinement index. A non-dimensionalised stress-strain equation was developed adopting Sargin's model to predict stress-strain behaviour of tie-confined geopolymer concrete under axial compression.

To validate the proposed semi-empirical equation and also to predict the moment-curvature (M-Ø) relationship, under and over reinforced beams (1800 mm * 200 mm * 120 mm) were cast by varying compressive strength of geopolymer concrete (20 MPa, 40 MPa, 60 MPa). The experimental M-Ø results were compared with analytical M-Ø relation developed using MATLAB programming. The results indicated an error less than 15% by comparing experimental and predicted moments and its corresponding curvatures. Increase in strength of concrete increases the ultimate moment carrying capacity but decreases the curvature marginally.

However, the predicted analytical value is only slightly lower than that of the obtained experimental values. Hence the M-Ø relationship of the geopolymer concrete beam at ambient temperature is found to be satisfactory and it could be predicted well by adopting strain compatibility criteria.

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INTRODUCTION

CHAPTER 1
INTRODUCTION

1.1 GENERAL:

Nowadays concrete plays a major role in the human life. It is the prominent material to the construction industry and also usage of concrete became second only to water around the world. In this, cement is the most commonly used as a binding material in the concrete industry. But usage of concrete is enormously increased to produce structural elements. In this, cement is the most promising binding material to produce conventional concrete. But there are many environmental issues are associated with producing cement. Portland cement (PC) production has resulted in high amount of CO_2 emissions into the atmosphere and PC is one of the major energy-intensive material and it requires huge amount of natural resources i.e; limestone. In the present scenario emission of greenhouse gas contributes about 1.5 billion tons annually or about 7% of the total greenhouse gas emissions to the earth's atmosphere due to PC production. However, many efforts have been started in the construction industry to overcome this by utilizing industrial by products and developing substitute binders in concrete. To preventing this there must be study needs to focus to develop alternative and sustainable material towards cement free concrete. Which can be replaced by supplementary binder materials in the form of silica fume, metkaolin, rice-husk ash, GGBS and fly ash. Geopolymer concrete is an inorganic polymer aluminium silicon Acid material and it was introduced by the French chemist J. Davidovits in the last century in the late 1970. Geopolymer generated at the same time as excited by alkaline substances, while consuming one of these various industrial wastes have the characteristics of low energy consumption and low resource consumption. Geopolymer has received much attention in recent years as an environmentally friendly material. Geopolymer materials needs a broad range of naturally available industrial bi-products. Geopolymer concrete has advantages like; simple process, Inexpensive, low energy consumption, high mechanical performance and durability, etc. The broad application development prospect has always been an internationally active research material.

Fly ash and GGBS materials are the industrial by-products from the thermal and iron industries. Which are successfully converts a left-over material into a useful material in concrete industry and also offers possible solution to overcome the several environmental issues such as Co_2 emission. However, GPC technology could also be an alternative and eco-friendly to the conventional concrete.

1.2 GEOPOLYMER CONCRETE

Geopolymer is a mixture of concrete in which the use of Portland cement material as the binder is replaced by other materials such as fly ash, rice husk ash and many others containing silica and aluminium (**Davidovits**, **1996).** Replacement of Portland cement base material considered more environmentally friendly and more effective by utilizing materials waste industrial plant waste to be more environmentally concerned. Geopolymer is a geosynthetic concrete product in which the binding reaction occurs as polymerization reaction. In polymerization reactions, silica (Si) and aluminium (Al) has an important role in the polymerization bonds aluminium with alkaline will produce SiO and AlO_4 as that shown in the following Figure 1.1.

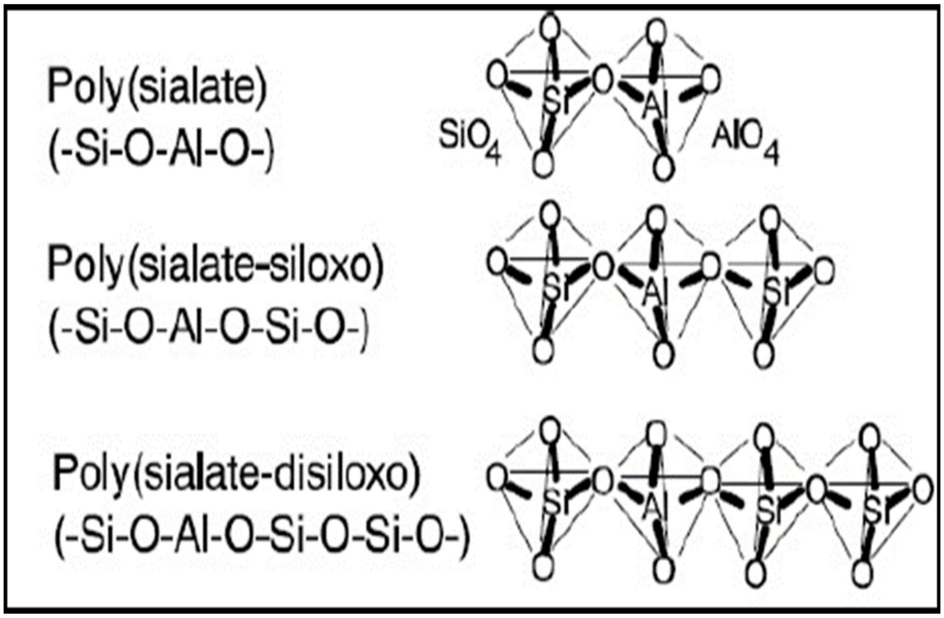

Figure 1.1: Basic forms of geopolymer (Davidovits, 1999)

1.3 BACKGROUND

Portland cement as binder is the one of the most important material used in conventional concrete manufacturing. Nowadays, rapid development of infrastructure is increasingly day by day resulting in demand for cement. However, in the case of cement production process, CO_2 emissions into the atmosphere is very high **(Davidovits, 1994),** so it leads to air pollution. This is one factor incentive for the discovery of other alternative materials that can replace position the cement in the concrete mixture to get the friendly concrete environment. To minimise the cost, it requires waste alternative materials for replace the use of cement. In this study, the authors do experiment with making geopolymer concrete. Geopolymer is a mixture of concrete in which the use of cement material Portland as a binder is replaced by other materials such as fly ash (fly ash), ash husk ash (rise husk ash), and many others contain silica and aluminium **(Davidovits, 1996).** In this study fly ash and GGBS is used as binder instead of PC. The composition of geopolymer concrete material is still widely performed. Thereafter, several authors were experimented on strength, durability and workability properties of GPC (**Wang et al., 1995)**. The results shown that GPC producing by fly ash having satisfactory strength. The GPC achieved about 50 MPa strength at higher concentration of alkaline solution and high temperatures (**Puertas et al.,** 2000**)**. Thus, fly ash based GPC have good strength, it has few drawbacks i.e., flash set,curing period, curing regime (ambient curing) and low workability (**Fernandez-Jimenez et al., 2002**). Generally, fly ash-based GPC needs high temperatures (60-90℃) to achieve early strength. GPC is feasible to cast in laboratory by applying heat curing condition but it is very difficult to cast in situ condition for the full-scale projects. So, in order to overcome the drawbacks, alkali activated slag (GGBS) was used as a binder in GPC. The addition of slag to GPC has negative impact on setting behaviour and workability (**Nath et al., 2014**). To prevent the flash setting, superplasticizer is suggested to achieve required workability of fly ash-based GPC's (**Hardjito et al., 2004**). Subsequently to utilize GPC for common practice as that of conventional concrete, researchers proposed various mix design methodologies (**VijayaRangan, 2008**). In the present scenario, the requirement of high-performance concrete is increased. For this reason, research moved towards utilisation of fly ash and GGBS in concrete making. Though the several studies reported by authors emphasise the applicability of GPC with combination of fly ash and GGBS to replace high strength OPC concrete (**Manjunatha et al., 2014**) but still there is a less attention paid on confined geopolymer concrete. Thus, several authors developed mix design for fly ash and GGBS based GPC but there is a less research on stress-strain behaviour of tie-confined concrete **(and Rangan et al.2008).** With this background, an experimental investigation is proposed in this research work to assess the effect of parameters viz. tie reinforcement, alkaline/binder ratio, grade of concrete on the behaviour of geopolymer concrete under axial compression. The aim of the investigation is to propose a stress-strain model for tie confined geopolymer concrete and use it for assessing the moment curvature response of GPC beams subjected to flexural loading.

1.4 CONSTITUENTS OF GEOPOLYMER CONCRETE

Nowadays, geopolymer concrete gaining attention of researchers and industries as it can totally replace cement in PC concrete. Thus, substituent to the cement "new material by" geopolymer material is reducing air pollution by two ways- Less emission of CO_2 into atmosphere by less utilization of cement; and consumption of fly ash in huge quantity, which is a waste product from thermal industries. The fly ash being dumped by the thermal power stations is occupying large cultivable area too. Geopolymer concrete contains the main binder ingredients as metakaolin, rice husk ash, pumice, fly ash, ferro chrome slag, redmud, GGBS etc. along with activator solution such as Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3). The selection of silica and alumina rich raw materials mostly depends on type, local availability, applicability of the materials hereafter called as source material. The activation process of source materials can be accelerated by the use of alkaline activator such as "sodium hydroxide or potassium hydroxide and; sodium silicate or potassium silicate".

1.5 BASIC CONCEPT OF POLYMERIZATION PROCESS

The alkaline activation of aluminosilicate materials is a complex process that isn't still completely explained. The reaction of aluminosilicate materials in a strong alkaline environment results in the rupture of Si-O-Si bonds, Si-O-Al and Al-O-Al;

and in the next stage, the formation of two new phases whose mechanism seems to be a process that requires an alkaline activator ("synthesis through the solution"). The orientation of Al ions into the structure of Si-O-Si, represents a characteristic important part of this reaction. Aluminosilicate gels are essentially formed. Their composition can be characterized by the Mn + [- (Si-O 2) LCA-O] n • w H_2O, where z and M + represent, respectively, the Si / Al molar ratio and a cat ion monovalent and where n is assimilated to the degree of polymerization. Figures 1.1 and 1.2 show the elementary chains or basic forms of geopolymer according to the Si / Al ratio **(Davidovits, 1999)** and a model of geopolymer structure **(Davidovits, 1999).**

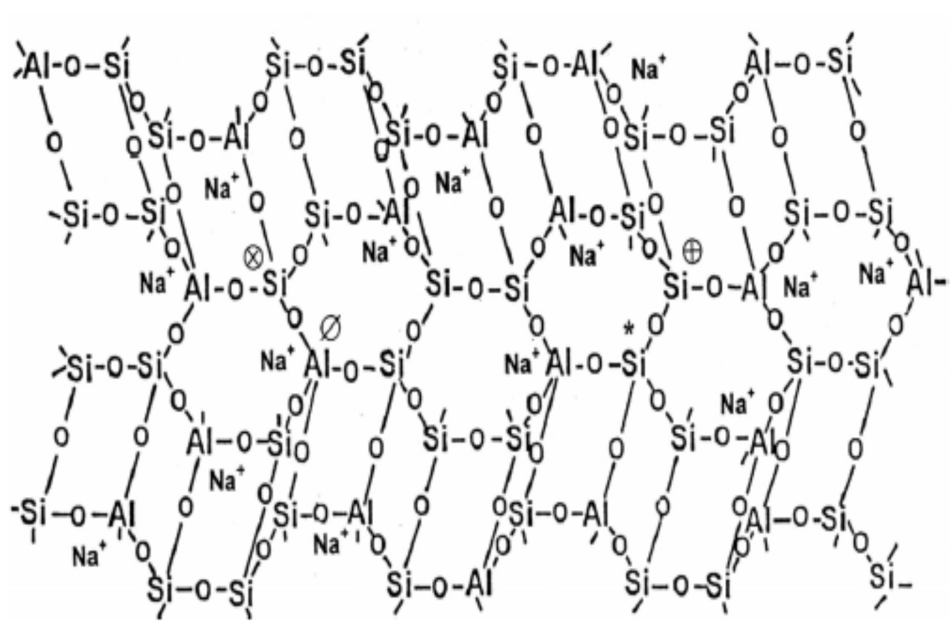

Figure 1. 2: Davidovits model of the geopolymer structure (Davidovits, 1999)

CSH gels and CAH phases can also be formed according to the composition of starting raw materials and reaction conditions. Molecules of water or secondary H_2O may also be formed during these reactions (Poly condensation).

Depending on the nature of the raw materials and the reaction conditions, substances amorphous (gel) or partially amorphous or crystalline may be formed. There are many variables that influence the alkaline activation process: the type and composition of the raw materials, the nature and concentration of the activator, the solids concentration, curing temperature and time, etc. Regarding the effect of the nature of the activator on the chemical training process alkaline inorganic polymers, it is worth mentioning both the role of the cations alkalis that are incorporated into the system as that of anions such as silicates present in the activation solution. The size of the cations also affects the morphology of the structure. Thus, K^+ ions appear to be responsible for a higher degree of condensation and mechanical strength of the final product with respect to Na^+ ions, when incorporated in the same conditions. The metal ion K^+ has a higher basicity and is larger, which allows a better rate of dissolution and thus more effectively promotes the reaction of poly condensation to obtain stronger and denser structures some researchers **(Van Jarsveld and Van Deventer, 1999; Cyr et al., 2012)** have also observed that geopolymers based on activated glass powder with KOH give better mechanical performance in terms of compressive strength. The same results were observed by others **(Xie and Xi, 2002** activated various alumina and silica-based minerals. On the other hand, these authors have stated that NaOH allows a better dissolution of minerals compared to KOH**)**. Similarly, the use of alkaline solutions with solutions of sodium silicates or potassium generate higher reaction kinetics than hydroxide solutions alkaline

(Caijun Shi et al., 2006). The various steps involved in the formation of geo polymer are as shown in **Figure 1.3**

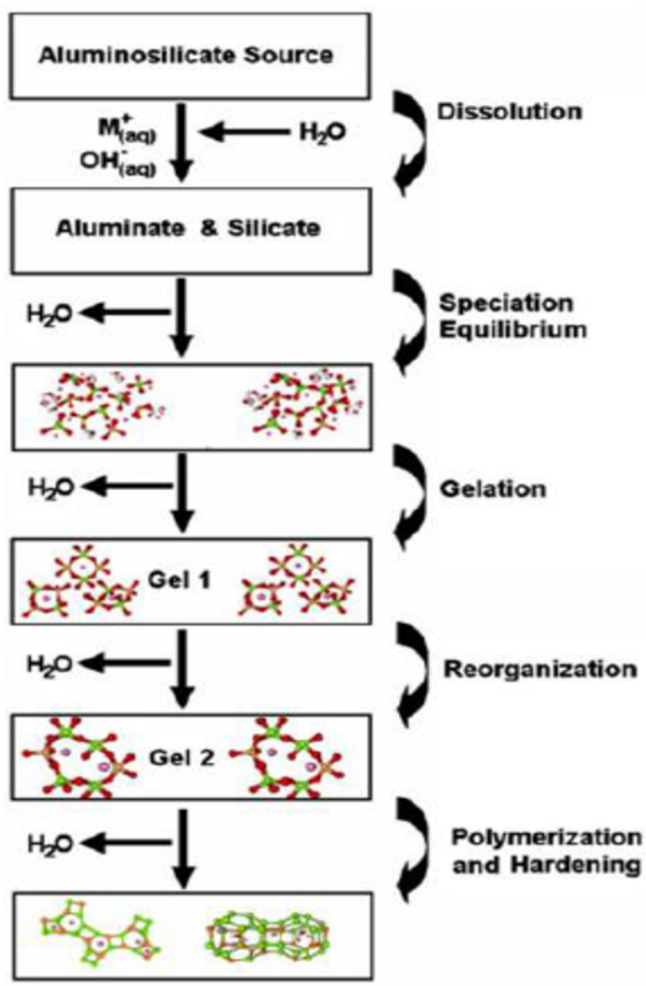

Figure 1.2: Various Steps involved in the formation of Geopolymer (Caijun Shi et al., 2006).

1.6 ADVANTAGES OF GEOPOLYMER CONCRETE

From the literature it has been found that GPC has many advantages over OPC concrete.

1. The high early strength gain and high strength
2. Good resistance to aggressive chemicals (sulphate attack)

3. Insignificant drying shrinkage and very low creep **(Song et al., 2007; Swanepoel et al., 2002).**
4. Good resistance to hot and cold weather
5. Better suitable material for infrastructure application
6. Sound in fire resistance (Duxson et al., 2007; Kong and Sanjayan et al., 2010; Zhu and Jay, 2010 GMR THESIS)
7. The ability to productively utilise large quantity of waste materials
8. Reduction in curing time

Hence an alternative and sustainable material for the concrete sector to limit the CO_2 emission into atmosphere by providing ecological and eco-friendly materials like geopolymer concrete.

1.7 DISADVANTAGES OF GEOPOLYMER CONCRETE

1. In spite of the many advantages of GPC and also it carries few disadvantages that must be rectified before implementing GPC can be used widely.
2. Preparation of sodium hydroxide solution evolves huge amount of heat. So, it requires skilled labour and care must be taken during preparation of solution.
3. A conflict conclusion has arrived on factors affecting strength and workability of GPC by many authors
4. Cost of production is little higher than OPC.

Hence GPC needs to focuses on further research in the field of concrete industry.

1.8 APPLICATIONS OF GEOPOLYMER CONCRETE

Geopolymer concrete is a high strength inorganic polymer with good mechanical properties and superior durability performance. It has high resistance and enhanced durability to ingress of aggressive chemicals and elevated temperatures. However, GPC has world wide applications in the field of construction.

These materials nevertheless have applications on a smaller scale. Indeed, having bought from Davidovits' patent, the Texas Company Lone Star has developed the PYRAMENT able to gain a very high resistance quickly. This white cement composed of 80% of Portland cement and 20% geopolymer was used by the U.S Air Force to build temporary airports during the Gulf War. Although, this application was successful, the Lone Star Company closed a few years later due to their financial reasons. They are also used in structural renovation in the form of fibre composites. Geopolymer base **(Davidovits, 2002b).** Geopolymers find their applications in the prefabrication industry, in particular in Australia, where Queensland University has developed geopolymer concrete beams prefabricated.
Geopolymer technology is more advanced in prefabricated applications because of the relative ease of handling sensitive materials (eg alkaline activation solutions) and the need for a controlled environment of hardening to relatively high temperature. Australia is one of the pioneers in the use of geopolymers. An example of Commercialization of geopolymer concrete in Australia by **Palomo et.al** used geopolymers based on fly ash for the manufacture of materials with special properties mainly for: monobloc of iron sights, light dies to replace traditional hearts in the sandwich panels and fire-resistant coverings. These application examples show that activated materials have enormous potential for their use in the field of building materials.

1.9 CONFINEMENT

The techniques of reinforcing and/or pre-stressing of concrete take care of its tensile capacity. However, these techniques improve the ductility of concrete. Efforts have been made to improve ductility of concrete by confining using ties/stirrups. The major deficiency i.e., ductility of concrete can be overcome by providing suitable confinement to the concrete in compression zone. A method of confining concrete in structural members is by providing spirals, ties, fibres, FRP, Ferro cement etc. Circular binding is more efficient than rectangular binding in confining the concrete, because in this case the confinement effect is developed by hoop tension. Confinement produces a tri-axial state of stress, due to which the strength and deformability increases, the later increasing to a greater degree. As the flexural members are rectangular in shape, a rectangular tie is preferred. When confined with such spirals/ties, the deformable capacity of the section is improved and hence the moment-curvature characteristics of such a cross section tend to be similar to that of steel section.

To achieve a ductile behavior, the structural members should also be carefully detailed. A careful detailing of transverse reinforcement is very important as the confining action it provides to the brittle concrete, enhances its strength as well as ductility.

The various methods available to confine the concrete are

i. By providing lateral ties, spirals

ii. Inclusion of steel fibres, carbon fibres

iii. Jacketing through ferro cement & fibre reinforced polymers

The Confinement Index **(S.R Reddy et al 1974)** is defined as

C_i = $(P_b - P_{bb})(\frac{f_v}{f_c})(\sqrt{\frac{b}{s}})$ -------------- Eq (1.1)

Where 'b' is the breadth of the prism and 's' is the spacing of ties, 'P_{bb}' is the ratio of the volume of ties to the volume of concrete corresponding to a limiting pitch (1.5 times the least lateral dimension), 'P_b' is the ratio of the volume of ties to the volume of concrete, 'f_v' is the yield stress of steel and 'f_c' is the compressive strength of concrete.

1.10 LATERAL TIES IN CONCRETE

It is known that the ductility can be improved by confining action of lateral ties in concrete**. As per IS: 13920 – 1993** the ties have to place in the concrete with 135^0 hooks to meet the requirements of seismic design. The beam-column joints are the places where high congestion of reinforcement exists, due to which the 135^0 hooks may create obstruction for placing the concrete. Thus, an alternative way of placing the ties is with welded ends with proper lap length.

1.11 NEED FOR STRESS-STRAIN BEHAVIOR OF GPC

Generally, stress-strain behavior of a concrete provides insight in to its ability to ensure adequate degree of safety and serviceability in structural applications and also, it is required to obtain the design curves. Hence Stress-strain behavior is obtained by using lateral ties as confinement. Then tie-confined geopolymer concrete can be used in the construction field.

Generally, the stress-strain behavior of structural R.C.C members can be analyzed theoretically. Stress-strain behavior of steel is as there is very less material variation than the concrete. Concrete prepared at in-situ conditions is not homogeneous and has uncertainties. However, a slight variation in the behavior of GPC and conventional concrete exists. Also, it is well known that the there is significant variation in the behavior of both unconfined and confined concrete. Now, as the improvement in construction industry has been supporting the use of modern concretes like GPC by using waste blended materials and the stress-strain relation for GPC is to be used in design provisions. The lateral ties are most commonly used for confinement effect in concrete. In the present study, an investigation on tie confined geopolymer concrete was conducted. Usually, to predict the confined stress-strain behavior of PC concrete with lateral ties, there are various empirical confinement models that have been stated in the literature during last three decades. But it is very important to predict a similar confinement model for tie confined geopolymer concrete also.

In the present investigation the main objective is to develop stress-strain behavior of tie confined fly ash and GGBS based GPC. In order to understand the behavior of such a material, it is essential to do a detailed literature survey on the different constituents of this material and about the behavior of individual elements.

1.12 TIE-CONFINED GEOPOLYMER CONCRETE

Most of the studies have been focused on strength and durability aspects of GPC, rather than stress-strain, ductility, shrinkage and creep. It is observed from the literature that the deformation capacity or stiffness of geopolymer concrete is quite low compared to conventional concrete. The stiffness and deformability can be improved by various methods like wrapping laminates, fibre reinforcement, confinement, etc. Of all these methods, confinement is one of the most effective way to improve the ductility of concrete and also it improves the compressive strength of the member. Studies on confined geopolymer concrete have been receiving much attention recently.

A lot of research has been reported on confined stress-strain behaviour of conventional concrete but literature on confined GPC is scantly available. Therefore, similar tests can be conducted on GPC to evaluate the strength and deformability characteristic similar to OPC concrete. Tests on confined concrete has proved that suitable arrangements of transverse reinforcement had a significant improvement in both strength and ductility. Also, the strength improvement from confinement and descending portion slope of stress-strain curve had a significant influence on flexural strength and ductility of reinforced concrete members. Stress-strain behaviour of confined GPC concrete is very crucial to obtain moment-curvature relationship and to evaluate the deformability and ductility of R.C. members. The parameters affecting the stress-strain behaviour of confined concrete are longitudinal reinforcement (its diameter, position and amount), spacing of bars, active reinforcement (circular, square ties), pseudo-active reinforcement (ferro mesh), passive reinforcement (viz. steel, glass fibres), diameter and yield strength of confining reinforcement, strength of concrete, confining reinforcement/concrete core (volumetric ratio), size and shape of tested specimen.

1.13 NEED FOR THE STUDY ON TIE- CONFINEMENT ASPECTS OF FLY ASH AND GGBS BASED GEOPOLYMER CONCRETE

The main fundamental option in predicting the response of Tie-confined aspects of fly ash and GGBS based geopolymer concrete (TCGPC) is essential to study the stress-strain behaviour of the constituent materials.

As concrete is basically designed to resist much in compression, and the knowledge of concretes behaviour in compression is essential. Usually, the behaviour of confined and unconfined concrete in uni-axial compression is understood, obviously its flexural behaviour can be probably predicted. Due to the confinement of concrete by lateral ties enhanced ductility of RCC. The provision of lateral ties in concrete ties resist the stresses perpendicular to axial compressive loads, restrict the development of early crack propagation and ensures transferring the brittle behaviour of concrete to a ductile behaviour. The active confinement due to lateral ties in the core concrete results in a good adhere with core and concrete cover **[Ramesh. K et.al, 2000].** Spalling of cover takes place before the initiation of confinement. The tie-confinement by lateral ties had significant results in deformation and integrity of core concrete.

Therefore, over the years, a considerable volume of studies have been focused towards developing stress-strain behaviour of concrete in both unconfined and confined conditions. Tie-confined GPC beams may exhibit a distinct in respect of moment curvature response. The moment-curvature curve in the descending branch is mainly affecting by the rotation capacity of concrete beam. However, the superior performance of a structure during seismic loading, blast and dynamic forces are the energy absorption capacity, governing by the area under the load-deflection curve. The presence of tie-confinement in fly ash and GGBS based GPC indicates that the area under load-deflection curve can be higher than that of unconfined concrete. Hence, TCGPC structures should be efficient to resist dynamic loads. From the foregoing discussion on many aspects it can be mentioned that there is a necessity for studying such type of confinement effect in Geopolymer concrete members also. Meanwhile, it is very important to consider in terms of serviceability of concrete structures. Hence, the present research is more focused on all types of concrete, which is made by blending different materials. Tie-confinement of fly ash and GGBS based GPC is one such material. So far, the behaviour of such a concrete is not much established, the utilization of such a concrete by design engineers, should be question. Therefore, there is an investigation to develop a model for such an emerging and advanced building material in concrete industry. With this idea in mind, an elaborated literature survey was taken up as reported in Chapter 2 on the state of art on GPC, fly ash and GGBS based concrete mechanical properties and the tie-confinement effect on GPC, under compression and flexure.

1.14 THESIS ORGANIZATION

The thesis titled "A Study on Tie-Confinement Effect on Fly ash and GGBS Based Geopolymer Concrete "is framed in the following way.

i. First chapter of the thesis deals with the introduction to Portland cement concrete, fly ash and GGBS based GPC along with its advantages, disadvantages and applications in the present scenario.
ii. Second chapter describes the literature on fly ash and GGBS based GPC, Tie-confinement of conventional concrete and GPC.
iii. Third chapter describes the scope and objectives of the study.
iv. Fourth chapter describes the experimental study on mechanical properties and young's modulus of GPC.
v. Fifth chapter describes the stress-strain behaviour of Tie-Confined fly ash and GGBS based geopolymer concrete and developed semi-empirical formulae.

vi. Sixth chapter describes the moment-curvature relationship and validation of proposed Analytical Model.
vii. Seventh chapter describes the conclusions and the scope for further investigations are presented.

The literature review of the present study is explained in Chapter 2.

LITERATURE REVIEW

CHAPTER 2
LITERATURE REVIEW

2.1 GENERAL

Chapter 1 gave introduction to geopolymer concrete, factors affecting geopolymer concrete, advantages, applications, constituent materials of GPC, confinement, lateral ties in concrete, need for stress-strain behaviour of GPC and difference between OPC and geopolymer concrete. Hence it is necessary to have a literature review on terminology and chemistry, source materials and alkaline liquids, field applications and durability aspects of geopolymer concrete, high-strength concretes confined with ties, stress-strain behaviour of different models, stress-block parameters and tie-confined geopolymer concrete which is dealt from chapters 2.

2.2 LITERATURE REVIEW ON GEOPOLYMER CONCRETE

Purdon (1940), was probably the principal investigator to study the alkaline activated slag-based concrete. Subsequent to this, several authors performed studies on alkali activated slag to find that it is an alternative and sustainable binder to cement based concrete**.**

Rattanasak et al. (2011), conducted the experiments on setting time and strength of the geopolymer pastes by using high calcium fly ash. To investigate this sucrose and calcium chloride admixtures were used. These were considered as by weight of the fly ash as 1% and 2% and obtained results reported that the due to presence of calcium chloride reduced initial setting time and whereas delay in final setting time due to sucrose effect. The optimum dosage of 1% shows the good results over the 2% dosage according to this study.

Kumar et al. (2017), carried work on behaviour of fly ash based geopolymer concrete. The parameters varied in this study such as fly ash to alkaline solution ratio, geopolymer solids to water ratio and concentration of sodium hydroxide and sodium silicate also, to attain the maximum compressive strength. From the results it was concluded the optimum proportions of variables are NaOH concentration as 12M, $Na_2 SiO_3$ concentration as 2M, fly ash: alkaline solution as 60:40, geopolymer solids to water ratio as 2.15 and $Na_2SiO_3$to NaOH ratio as 2.5.

Morsy et al. (2014), conducted studies on behaviour of fly ash based geopolymers by varied were: the ratio of $Na_2 SiO_3$ to NaOH ratios such as 0.5, 1, 1.5, 2 and 2.5 and these specimens cured in hot air oven at 800C for 1 day. In this, at sodium silicate to sodium hydroxide ratio of 1, the maximum compressive strength was obtained, this is due to its homogenous and less porous matrix and another observation was that strength is increased with an increase in curing age.

Debabrata Dutta and Somnath Gosh (2014), investigated the influence of the percentage of Na_2O content (6% and 8%), silicate modulus (0.5, 1 and 1.5) and different curing temperatures (55℃, 65℃, 75℃ and 85℃) on fly ash and GGBS based GPC. It has been found that percentage of Na_2O content must be lower in the presence of the GGBS and with an increase in percentage of Na_2O increases the strength.

Gunneswara Rao et al. (2014), experimented on normal consistency and setting times of fly ash based geopolymer pastes varying by NaOH concentration 8M to 16M, the ratio of Na_2SiO_3 to NaOH (1.5, 2.0, 2.5 and 3) and different curing temperatures (30℃, 60℃ and 90℃). It has been reported that as there was increase in concentration of the sodium hydroxide increases were observed in the setting time for alkaline solution ratio 1.5 and 2. Even after increase in NaOH concentration results in decreases in setting time, it was also observed that the temperature curing contributes a significant role in decreasing the setting time and slight reduce in setting time till 60℃.

Rao et al. (2015), investigated fly ash and GGBS based geopolymer pastes and mortars. In this, different parameters by varying of NaOH concentration (8M, 12M and 16M) and also two curing regimes were adopted such as ambient and hot air curing at 60℃ for 1 day. It was concluded that inclusion of GGBS resulted in delay of setting time and also avoid the oven curing for polymerisation and gaining strength can be easily achieved under ambient curing.

2.3 LITERATURE REVIEW ON TYPE OF ALKALINE LIQUIDS

Pinto et al. (2004), stated that the molar ratio of sodium silicate to sodium hydroxide ratio plays a vital role in the gepolymerisation process. Subsequently, authors recommended that the sodium silicate to sodium hydroxide ratio 2.5 gains the maximum compressive strength with no variation in binder content.

Bakharev (2005), reported that fly ash-based GPC needs pre-curing before application of heat at room temperature condition for long time helps to improve strength. It has been found that the geopolymers activated with NaOH had much better results compared to sodium silicate solution.

Parthiban et al. (2013), have experimented that fly ash and GGBS combination effect varied from 0-100% and also sodium silicate to sodium hydroxide ratio effect varied 1 to 1.5 by keeping the sodium hydroxide concentration as constant 10M. As there was increase in GGBS content and alkaline content increase in compressive strength of the geopolymer concrete.

2.4 LITERATURE REVIEW ON CURING REGIME OF GEOPOLYMER CONCRETE

Glukhovsky (1959), study reported that curing temperature significantly influences the polymerization process of geopolymer concrete. They observed that rate of gain in strength is higher at temperature curing (60℃ to 90℃).

Palomo (1999), studied the fly ash based geopolymer pastes mechanism at high alkaline environment. In this study varied parameters are such as cured at hot air oven 65℃ and 85℃ about 2h 5h and 24 hours, alkaline to fly ash ratio and concentration of sodium silicate to sodium hydroxide was 12M and 18M respectively. In this strength contribution mainly due to its formation of reaction product of alumino silicate hydrate gel was found to be mainly responsible. For fly ash based geopolymer pastes curing can be restricted to 2 to 5h only.

Hardjito et al. (2004), stated that the making of fly ash-based GPC by considering different parameters influencing the compressive strength of GPC. It has been found that concentration of NaOH solution range from 8M to 16M, curing temperature range from 30°-90℃, curing time duration is from 6 hours to 96 hours and low water to geopolymer solids ratio lead to enhanced compressive strength of fly ash-based GPC. The compressive strength of GPC is increased with an increase of Na_2SiO_3 to NaOH ratio.

Chindaprasirt et al. (2007), reported fly ash (class C) based geopolymer mortars. In this, different parameters varying such as hot air oven curing (1, 2, 3 and 4) days, delay time (0, 1, 3 and 6) hours, curing temperatures (30℃, 45℃, 60℃, 75℃ and 90℃), the ratio of Na_2SiO_3 to NaOH (0.67, 1, 1.5 and 3) and concentration of NaOH (10, 15 and 20M). The obtained results concluded that the compressive strength was increased when Na_2SiO_3 to NaOH ratio 0.67 and 1, at 1 h of heat curing at 75° C for 2 days was used.

2.5 LITERATURE REVIEW ON MECHANICAL PROPERTIES OF GEOPOLYMER CONCRETE

Somna et al. (2011), have conducted study of ground fly ash that means 10.5 mm size and regularly available fly ash varied in concentration of NaOH (4.5, 7, 9.5, 12, 14 and 16.5M) cured at ambient temperature condition. From this experimental study, it has been revealed that there was an enhancement in compressive strength with an increase in the concentration of NaOH (8-14M) and even after increase in the concentration of NaOH, the compressive strength was found to be decreased. This can be due to formation of early precipitation of the aluminosilicate products in geopolymers.

Joseph et al. (2012), experimented on the behaviour of fly ash-based GPC by varying parameters. The parameters considered for study are total aggregate content (60%, 65%, 70% and 75%), Na_2SiO_3 to NaOH ratio (1.5, 2.2, 2.5 and 3.0), external curing condition (30℃ to 120℃) up to 24 hours and the alkaline solution to fly ash ratio (0.35, 0.45, 0.55 and 0.65). It was observed that, the maximum compressive strength, poisons ratio, modulus of elasticity was achieved at total aggregate content 70%, Na_2SiO_3 to NaOH ratio 2.5, 10M NaOH (concentration) at 100℃ for 24 hours.

Balakrishnan et al. (2013), has experimented on fly ash-based GPC. The mechanical properties varied are Na_2SiO_3 to NaOH ratio 2.5, binder content as 395 kg/m^3, 410 kg/m^3 and 450 kg/m^3, fine aggregate content (100% sand, sand and sand stone: 50% each and; 100% sand stone) and curing temperature (outdoor and heat 72hrs). From this study, it was observed that the binder content of 410 kg/m^3

showed the maximum compressive strength. The compressive strength achieved was 60% in 90 days over 28 days of curing time.

Deb et al. (2014), has done research on fly ash and GGBS based GPC. The influence of GGBS on the setting time and compressive strength was studied for different percentage replacements of GGBS contents are: 0%, 10% and 20% and the influence of Na_2SiO_3 to NaOH ratio - (1.5-2.5) on GPC was also evaluated. From the results, it was found that an increase in the addition of GGBS resulted in increased mechanical properties of GPC, besides its low workability and it can be due to reducing ratio of alkaline activator to binder content.

Jawahar et al. (2016), has summarized that the addition of GGBS content to GPC enhanced the mechanical properties of fly ash and GGBS under ambient curing conditions. Hence, curing can be avoided with the inclusion GGBS to fly ash-based GPC.

2.6 LITERATURE REVIEW ON CONCRETES CONFINED WITH TIES

Generally, confinement effect on concrete grab the attention around the globe in the field of construction. So, there is a good amount of information available on the use of confinement in concrete.

J.B Mander, M.J.N Priestley and R Park [1988] have proposed a theoretical stress-strain model for confined concrete. This model subjected to uniaxial compressive loading and it is confined by transverse reinforcement and also a single equation is considered for the stress-strain equation. The developed model allows for cyclic loading and includes the effect of strain rate and the effect of different types of confinement is taken into account by providing an effective lateral confining stress, which can be depend on the configuration of the transverse and longitudinal reinforcement. Popovics (Thomas A. Hales et. al) suggested a simple uniaxial relation of confined concrete model, this requires three control parameters (f'_{cc},e_{cc} and E_c). The cyclic loading response of curves was observed by Unloading and reloading. An allowance for the dynamic response in stress-strain modelling may be incorporated by modifying the quasi-static concrete parameters (f'_{cc}, e_{cc}, and E_c) by dynamic magnification factors which are used in the stress-strain model**.** The complete stress-strain behaviour of unconfined and confined concrete is shown in Figure 2.1.

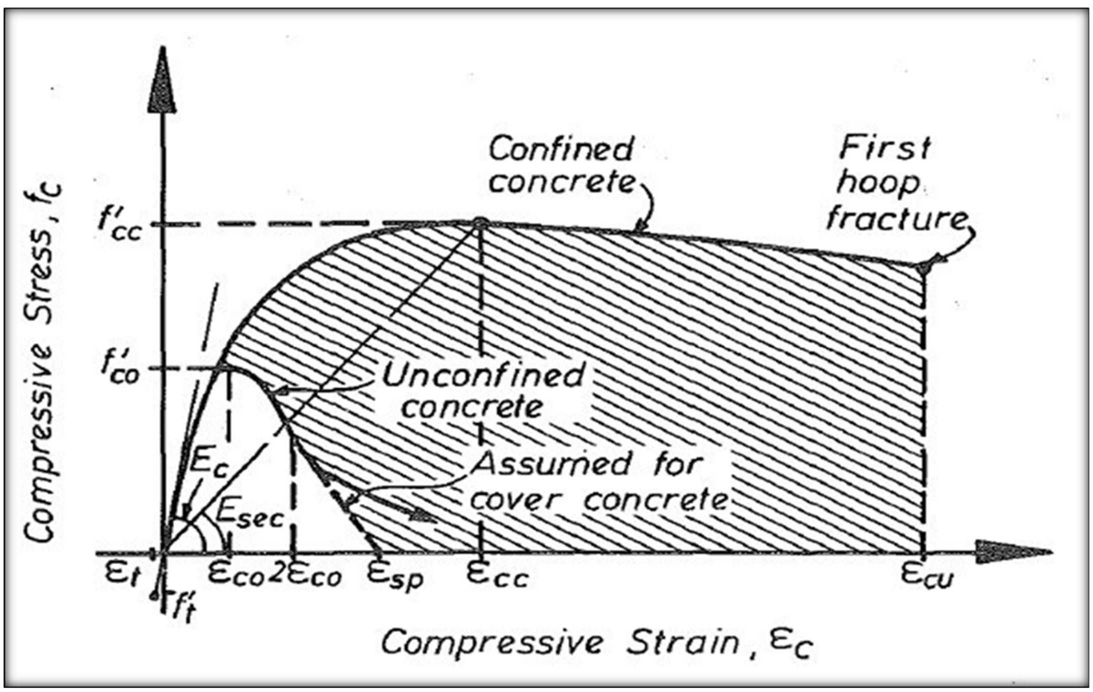

Figure 2.1: Stress-strain model proposed for monotonic loading of confined and unconfined concrete (Park and Paulay).

Daniel Cusson et al [1995] have experimented stress-strain model for confined high-strength concrete and developed the model. The various parameters varied were: tie yield strength, transverse reinforcement ratio, tie configuration, concrete compressive strength, tie spacing and longitudinal reinforcement ratio are accounted for the developed stress-strain model. The strength and ductility of confined concrete can be obtained based on the computation of the effective level of confinement pressure, which depends on the stress in the transverse reinforcement at maximum strength of confined concrete, and on the effectively confined concrete area. The confined concrete of strength and ductility represents strong correlation with the effective confinement index, f_{ce}/f_{co}. This confinement index allows a classification of high strength concrete columns and divided into three types: low, medium, and high confinement. From the results it was demonstrated that a significant improvement in strength and toughness due to its increase in tie yield strength of confined concrete columns. Generally, the failure of HSC columns is differentiated by the formation of an inclined shear failure plane, separating the concrete core into two wedges laterally restrained by the reinforcement cage. In this case, the inclination of the shear failure plane shows good agreement with the effective confinement index. In post-peak region, confined high strength concrete columns show a stress-strain relationship with a flat top and very ductile response. The Proposed stress-strain curve for confined high-strength concrete is shown in Figure 2.2.

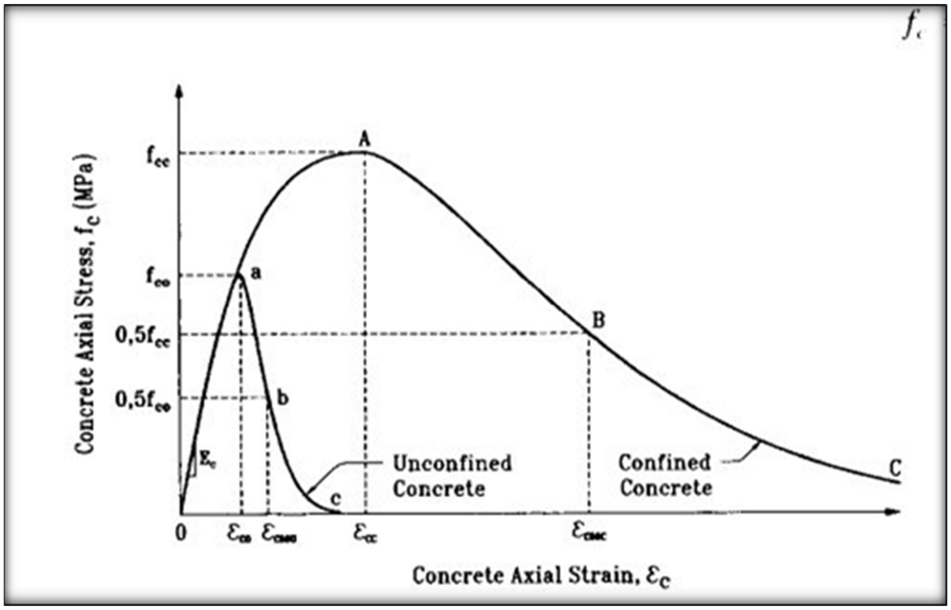

Figure 2.1: Proposed stress-strain curve for confined high-strength concrete

Weena P. Lokuge et al [2005] have demonstrated a study on the stress-strain model for laterally confined concrete. It is well recognized that the ductility of HSC columns can be increased by providing lateral steel reinforcement as confinement to the core of concrete columns. The applied confining pressure by the reinforcement is governing from the lateral strain of concrete. Based on shear failure of concrete, a simple strain-based model is proposed, which was developed by using prevailing test results for high strength columns provided with active confinement. The proposed stress-strain model based on strain is a new approach in predicting the response of HSC in the presence of active lateral confinement. The developed model can be used for concrete for active and similarly for passive confinement.

B. Bousalem, N. Chikh [2007], developed a stress-strain model for confined ordinary concrete strength by providing rectangular transverse reinforcement on the basis of the observations from the previous studies conducted. The developed model was governed by incorporating the confinement's parameters like the gain in strain, the gain in strength and the slope of the descending branch.

Kumar, G.R. [1998], conducted a study on a confinement model for high strength concrete. The model developed by using test results of 126 prisms (size 150 x150 x 300 mm) tested through strain control under concentric load. The parameters varied in the proposed study were: tie configuration, (6 and 8 mm), spacing between ties N (225, 150, 100, 75, 50 and 25 mm) and grade of concrete (30 to 50 MPa). From the experimental results, a stress– strain model and the rectangular stress block was developed for high strength concrete with tie confinement.

Custom and Paultre [1994 carried out on tie-confined high strength concrete by testing 27 large scale high strength concrete columns (235 x 235 x 1400 mm), confined by rectangular ties under concentric loading. Study was varying with tie yield strength, its configuration, spacing between ties, lateral reinforcement ratio, longitudinal reinforcement ratio, the grade of concrete and effect of concrete cover. Their outcomes suggest that merely the core concrete area should be taking into account in assessing the axial compressive strength of high strength concrete columns. They also reported that reduction in tie spacing can also cause an increase in strength and toughness of high strength columns.

Reddy, S. R [1974], performed tests on 432 prisms of size 100 x 100 x 200 mm and 150 x 150 x 300 mm to examine the ties and helices confining effect of rectangular binders on concrete. Half of these specimens were confined by rectangular ties and in these specimens no cover is present. Through this experimentation, proposed a general equation for stress-strain curve for confined concrete. In this study, the developed stress block was validated by predicting the moments and curvatures of R.C beams conducting a flexural study on 56 simply supported beams.

Muguruma et al. [1993], have developed a three-part stress strain model for confined concrete based on earlier investigations. By considering a wide range of grade of concrete ranging from 40 to 130 MPa was covered. They conducted tests on small size square specimens laterally confined with square helix hoops of various yield strengths and with different volumetric ratios. In this, the yield strengths of the hoops ranged from 161 to 1353 MPa was used.

Nagashima et al. [1992], have proposed a two-part stress-strain relationship for confined high-strength concrete columns. In this study, casted and tested, 26 prisms of size specimens (225 x 716 mm) of high strength concrete of strengths 59 and 118 MPa and these were reinforced with lateral ties of yield strengths 784 and 1374 MPa. To obtain this, the different parameters taken into account were lateral steel yield strength, tie configuration, spacing between lateral ties and grade of concrete.

A. Sofi, B.R. Phanikumar et al (2015):

Studies reported that flexural behaviour of plane and fibre reinforced concrete beams were tested by varying dosage of fibre and concluded that inclusive of fibres increased the failure load and also more ductile behaviour. The correlation of predicted crack width and measured crack width was found to be satisfactory.

Chris G. Karayannis, Constantin E. Chalioris (2013):

Carried the experimental investigation on shear critical beams behaviour of RCC beams by varying reinforcement were tested. The results indicated that rectangular spiral reinforcement beams were shown enhanced bearing capacity and increase in shear capacity.

Magda I. Mousa (2015):

A study has been carried out on flexural response of RCC beams of size (2200x150x200) mm with variables are considered as length of tension reinforcement lap splice, concrete cover and grade of concrete. The obtained results show that increase in cracking load, ultimate capacity and delay of crack propagation were observed.

K. J. H. ZHOU et al (2011):

They examined the study of flexural and deformability characteristics of RCC beams. In this study, the variable parameters are reinforcement area, grade of concrete, yield strength of steel, confining pressure and steel ratio in compression zone and, are studied based on theoretical method. Furthermore, A "concurrent flexural strength and deformability design" was developed considering both strength and deformability requirements based on empirical formula. However, study revealed that the adding confinement to compression in high strength concrete can increase the deformability of RCC beams.

M. Srikanth et al (2007):

A study carried out on moment curvature relationship of RCC beams using several confinement models. Confinement to concrete in the compression zone was provided. However, from the inferred results experimental results on par with obtained analytical results using Mendis and Cusson model when compared to other models.

M.L.V. Prasad and P.R. Kumar (2015):

They experimented on moment–curvature of confined fibre reinforced self-compacting concrete. Based on study, the predicted analytical moment –curvature was developed. The similar behaviour in experimental and analytical moment curvature was observed.

S. Annamalai et al [2017]:

Have done work on flexural response of GPC simply supported beams cured under ambient temperature. A comparison made between GPC and OPC concrete by casting of 2 RCC and 2 GPC beams was done. In this study M60 grade of concrete was used and results summarised that flexural capacity of GPC beams is marginally higher than to that of RCC beams.

2.7 LITERATURE REVIEW ON CONFINED-GEOPOLYMER CONCRETE

Aamer Bhutta et al [2017]:

This study describes the flexural response of GPC composites reinforced with steel and polypropylene macro fibers based on beams under flexure loading. These varied parameters include different types (length-deformed, end-deformed and straight) of macro steel and polypropylene fibers with higher aspect ratio and two different curing regimes curing regimes (ambient, heat curing). The results also inferred that End- deformed steel fibers shown the better ductile flexural response compared to other steel fibers in both curing regimes.

Xiaochun Fan and Mingzhong Zhang [2016]:

There was a study on flexural response of GPC beams reinforced with basalt rebar that was tested and compared with RCC beams. It was reported that flexural response of GPC beams was different than RCC beams due to contrast in mechanical behavior between GPC and OPC concrete. In the case of reinforced basalt rebar GPC beams under flexure loading indicates that maximum crack width is two times to that of RCC beams.

Faiz Uddin Ahmed Shaikh and Aditya Patel [2018]:

This paper presents the flexural response of hybrid PVA fibre and AR-Glass textile Reinforced GPC Composites of three plate simply supported specimens' size of 15x40x400 mm for three-point bending were evaluated. The parameters varied in textile reinforced concrete and glass fibre reinforced concrete. In GPC one is fly ash and slag based under ambient air cured and another one is fly ash-based heat cured specimens were determined. The significant conclusion from this was an increase in PVA fibre volume fraction from 1% to 1.5% did not show any improvement in flexural strength of both TRC and TRG.

C. K. Madheswaran [2015]:

They have conducted experimental studies on response of 12 GPC RC and four OPCC beams under mono static loading and these are designed to be critical in shear according to IS: 456:2000. This Study includes shear span to depth ratio and 40 MPa compressive strength. The results attributed the crack propagation, failure pattern and load deflection characteristics are similar to that of OPCC beams. However, the analytical results and experimental results shows a good prediction.

Mohana Rajendran and Nagan Soundarapandian [2013]:

A study carried out on flexural response of 30 GPC Ferro cement slabs were tested by varying number of chickens meshes and alkali activated solution concentration (8, 10, 12 and 14) molarity for the investigation. The results proved that the load carrying capacities, deflection at ultimate load and energy absorption are improved in GPC Ferro cement slabs. Also, there is increase in initial cracking load and ultimate load with an increase in alkaline solution molarity. Further, it is noticed that there is a decrease in crack width and increase in number of cracks. Generally, ferro cement mainly resists in crack growth during loading.

Dawid Pawłowskia and Maciej Szumigałaa (2015):

They studied that the flexural behaviour of Basalt fibre-reinforced polymer based concrete beams under short -term static loading was investigated by varying area of reinforcement. The FEM was used to analyse the members and results represented that there is an increase in area of reinforcement and there is an increase in the peak loads and also stiffness of the beams. From the results, there is a good agreement between the both experimental &numerical results.

G.B. Maranan et al (2015):

Studied the flexural strength and serviceable characteristics of GPC beams provided with glass-fibre-reinforced polymer tested under a four-point static bending test. The varied parameters were diameter of bars, percentage of reinforcement, and anchorage system. The exhibited results show that serviceability performance of a beam was improved but no significant effect was observed flexural performance when varying bar diameter of the beams.

G.B. Maranan et al (2018):

Recent study conducted on Shear behaviour of GFRP geopolymer concrete beams were cast and tested by varied parameters of area of web reinforcement, spiral pitch, area of longitudinal reinforcement and shear span to effective depth ratio. The results revealed that the spirally-reinforced beam performed increase in shear strength and deflection than the conventionally reinforced beam.

Khoa Tan Nguyen et al (2016):

Reported that the mechanical properties and flexural response of reinforced GPC beams were determined under four-point bending, elastic theory and finite element model by using ABAQUS. A similar behaviour was concluded on GPC and OPC. The experimental results have shown better correlation with developed ANSYS model than the elastic theory. The stiffness of geopolymer beam is slightly higher than the theoretical analysis model.

Mohammed Haloob Al-Majidi et al (2017):

Evaluated the tensile properties of fibre reinforced geopolymer composites under ambient temperature. However, results stated that addition of steel and PVA fibres in the GPC can significantly improve the strain hardening characteristics, flexural and tensile strength, it represents that fibre reinforced GPC potentially viable for in-situ applications.

Piti Sukontasukkul et al (2018):

Performed on flexural capacity and toughness of fibre reinforced GPC. A comparison was made by hybrid steel and polypropylene fibres in the GPC, results indicated that inclusion of steel fibres with hybrid system is potentially alternative to enhance the toughness, flexural capacity and post –peak response of GPC. An increase in fibre dosage, which results in increase in residual strength of GPC specimens.

George Mathew et al (2018):

Performed tests on reinforced geopolymer concrete beams of size 150mmx200mmx1800mm under elevated temperature by varying in concrete cover. However, ductility of the geopolymer concrete beams reduces continuously when it exposed to elevated temperature. An equation was proposed to predict the service load crack width of GPC beams under elevated temperature.

Sumajouw et al.

Concluded that the deformation and crack propagation of reinforced geopolymer concrete is shown similar behaviour to that of reinforced cement concrete.

M. Albitar et al:

They performed tests on fly ash and lead smelter slag-based GPC columns and beams under concentric and eccentric loading. This study mainly focused on slenderness effect of GPC and axial load moment was studied. The analytical interaction diagrams were compared with experimental results. The results highlighted that the analytical interaction diagrams overestimated the test results and this can be due to difference in material properties.

N.Ganesan et al [2014] authors performed tests on the stress-strain behavior of confined geopolymer concrete. Their study intended to examine the influence of confinement on the behavior of both fly ash-based GPC and conventional concrete. The volumetric ratio of confinement is the main variable was considered. Based on this, an analytical model was proposed for the stress-strain behavior of confined GPC. From their findings, it was found that the confinement is greatly influencing to increase the strength and ductility of GPC rather than the conventional concrete.

N. Ganesan, Ruby Abraham et.al [2015] have presented a paper on establishment of stress block parameters for geopolymer concrete. Their study designed to study the mechanical properties as well as stress block parameters of GPC. From their investigation, it has been found that GPC possesses enhanced mechanical properties to that of conventional concrete. However, the stress block parameters obtained for GPC were found to be good correlation with those given in IS456:2000 for conventional concrete.

From the foregoing research on the various construction materials used in confinement studies on GPC, it was evident that the literature available very scantly, on the development of GPC using fly ash and GGBS. Also, the behavior of Tie Confined GPC made by using fly ash and GGBS has not been investigated by any earlier researchers. In order to implement this study by design experts, the behavior of this new concrete need to be investigated. Hence, an experimental program was intended to know the behavior of this material and a model was proposed for the same. A detailed experimentation performed as described in further Chapter. Chapter 3 show the scope and aim of the investigation under taken.

2.8 HIGHILITHS FROM THE LITERATURE

From the literature survey, it is concluded that, few researches have been reported on confined geopolymer concrete. Hence, an attempt has been made for understanding stress-strain behaviour of "Tie-confined fly ash and GGBS based geopolymer concrete".

i. The combination of sodium hydroxide and sodium silicate alkaline activator can be most suitable for producing GPC rather than the other alkaline activators.

ii. In GPC, higher amount of dissolution of silicon and aluminium shows increase in the compressive strength of geopolymer concrete.

iii. Increase of NaOH concentration leads to an increase in the compressive strength.

iv. The authors concluding as ideal ratio of sodium silicate to sodium hydroxide as 2.5 for fast polymerisation process.

v. Geopolymerization rate may be accelerated by addition of GGBS in the presence of alkaline activators.

vi. A high replacement of fly ash with GGBS in GPC can produce high strength GPC and it can eliminate oven curing.

vii. Numerous confined stress-strain models was proposed for conventional concrete. Stress block parameters were established for confined conventional concrete. Tie-confinement significantly enhanced the strength, ductility and toughness of concrete.

viii. Ties and helices confining is an effective method greatly enhance ductility of concrete.

ix. The developed confined stress-strain models have been validated with flexural study on simply supported beams.

x. By using confined stress-strain model, moment-curvature relationship was predicted.

Chapter 3 deals with the scope and objective the present investigation.

CHAPTER 3
AIM AND SCOPE OF THE WORK

From the literature survey, it is clear that, there is a few researches available that has attempted to develop “Tie- confinement aspects of fly ash and GGBS based geopolymer concrete”. TCGPC is equally able to withstand with the conventional concrete in construction. Hence, it was clearly understood that, there a need to understand the complete behaviour of TCGPC to know the stress-strain behaviour

So, a separate analytical model is required to predict the stress-strain behaviour of TCGPC is available very scantly. This will help the designer to understand the behaviour and propose the same for field work.

The performance of plain GPC will differ from the performance of reinforced GPC. To know the reinforced GPC behaviour, first we need to have a clear idea on the mechanical properties of plain GPC. In this study mechanical properties of plain GPC were investigated and also elastic modulus, stress-strain behaviour and moment-curvature of confined GPC were studied. The elastic modulus stress-strain behaviour and moment-curvature will effect the maximum strain and design stress of a structural member. The results from this study will be helpful to establish the stress block for geopolymer concrete. The use of industrial bi-product materials like; fly ash and GGBS in the concrete industry will be helpful in conserving the natural resources and also to reduce environmental impacts.

3.1 LITERATURE FROM SO FAR RESEARCH, THE FOLLOWING POINTS ARE HIGHLIGHTED

i) Sustainability is very important in view of the depleting natural resources for construction materials. Among the other methods, use of fly ash and GGBS from the industrial wastes in new concrete can able to solve this some extent.

ii) Use of fly ash and GGBS based geopolymer concrete has many advantages, including concreting in harsh environments and water scarcity cities. This concrete has much attention in the future.

iii) GGBS inclusion can significantly improve the performance characteristics of GPC.

Keeping in view the above factors an analytical and experimental programme is planned with the following objectives.

1. Evaluate the Mechanical properties of plane geopolymer concrete with fly ash and GGBS as source material. Three different mixes are aimed in this study, are being selected as lowest structural concrete GPC20. Medium Strength Concrete GPC40 and high Strength concrete GPC60.
2. Response of Tie- confined fly ash and GGBS based geopolymer concrete (TCGPC) under uni axial compressive loading and develop stress–strain model for Tie-Confined Geopolymer Concrete of three different mixes by varying confinement.
3. The developed semi-empirical formulae is validated with suitable experimentation, based on flexural studies with the simple supported R.C beams.

An experimental program was carried out to develop a semi-empirical formula by casting and testing plain and tie-confined geopolymer concrete prisms are incorporating parameters such as confinement index, concrete strength. Thus, the study involves confirming the verifying the fresh and hardened properties of GPC in the initial phase. In the next phases were taken up for the developing the analytical model (semi-empirical formulae) of Tie-Confined Geopolymer Concrete and this was validated by conducting suitable flexural study on simple supported beams.

To obtain the objectives mentioned above, a suitable experimentation has been designed and the entire work was divided into four phases such as given below.

1. Phase-I: Determination of the mechanical properties of plain Geopolymer concrete of three different mixes.
2. Phase-II: Developing the Stress-Strain Curve for Tie-Confined geopolymer concrete and semi-empirical formulae for predicting the Moment Curvature behaviour of the same.
3. Phase-III: The prediction of Moment Curvature behaviour of the Tie-Confined geopolymer reinforced concrete and validation of the proposed semi-empirical formulae proposed in Phase-III by conducting flexure test on simply supported geopolymer based R.C beams.

In all the phases, throughout the study the proportion of fly ash and GGBS was selected as 70:30 for TCGPC 20, 60:40 for TCGPC 40 and 50:50 for TCGPC 60 respectively. NaOH solution with a concentration of 8 M and the combination of sodium silicate (Na_2SiO_3) and sodium hydroxide solutions (NaOH) in the mass ratio of 2.5 were used in this complete research.

3.1.1 PHASE-I

The phase-I investigation is devoted to know the mechanical properties and modulus of elasticity of plane geopolymer concrete. The fresh and hardened properties of GPC were investigated as per **IS: 456: 2000.** So far there is no proper code provisions developed for geopolymer material the mixing. The OPC concrete testing procedure was adopted for GPC. Alkaline activator is used as geopolymer binder instead of water and fly ash and GGBS-based geopolymer concrete cured under ambient conditions. The mechanical properties and modulus of elasticity were determined for GPC20, GPC40 andGPC60. The modulus of elasticity was determined on cylinder specimens sized 150 mm diameter and 300 mm height. For each mix 3 cubes, 6 cylinders sized 150 mm diameter x 300 mm height and 3 prisms sized 100 mm x 100 mm x 500 mm were cast to determine their modulus of elasticity and their corresponding mechanical properties. The following mix proportions are adopted from the literature **(Rao GM and Rao TDG, 2016 23).**

3.1.2 PHASE-II

The phase-I investigation is aimed to study the tie-confinement effect of stress-strain behaviour of fly ash and GGBS based GPC. The experimental program consists of casting and testing of 81 prisms of size 100 × 100 × 200 mm for evaluating the stress-strain behaviour of TCGPC (3 mixes - 20, 40 and 60 MPa). In this study parameters varied are compressive strength, tie configuration (6mm and 8mm) and spacing between ties of specimens. The specimens of each mix were divided into 9 sets (each set consisting 3 specimens), each varied by confinement index: $C_i = 0.0$, $C_i = 0.051$, $C_i = 0.119$, $C_i = 0.153$, $C_i = 0.291$, $C_i = 0.354$, $C_i = 0.868$, $C_i = 0.1.029$, $C_i = 3.069$, and spacing: 25 mm, 50 mm, 75 mm and 100 mm. The specimens were cast, cured at outdoor for 28 days and tested in uniaxial compression as per IS 516: 1959.

In addition to this, 100 × 100 × 100 mm cubes were also cast and tested to obtain the compressive strength of concrete. The similar procedure was repeated for TCGPC40 with varying confinement index: C_i = 0.0, C_i = 0.031, C_i = 0.073, C_i = 0.094, C_i = 0.179, C_i = 0.218, C_i = 0.534, I C_i = 0.633, C_i = 1.889 and TCGPC60 with varying confinement index: C_i = 0.0, C_i = 0.016, C_i = 0.038, C_i = 0.049, C_i = 0.093, C_i = 0.113, C_i = 0.278, C_i = 0.330, C_i = 0.984. Based on experimental results, normalized stress-strain curves for TCGPC were developed. A common analytical stress-strain model was developed for confined GPC. By using these semi-empirical formulae, an analytical moment-curvature relationship was finally plotted.

3.1.3 PHASE-III

The phase-III investigation is designed to study the validation for the developed moment-curvature relationship on suitable experimental program. This study validated by casting and testing simply supported beams consisting of different variables. The variables were, compressive strength and percentage longitudinal steel. The test programme consisted of casting 6 rectangular RC beams of size 120x200x1800mm with an effective of span 1600 mm of three different compressive strengths (Mix A (20MPa), Mix B (40MPa) and Mix C (60MPa),) were designed to fail in flexure. In this process, mix a consisting of two beams, one under reinforced and one over reinforced beam and the similar procedure was repeated for Mix B and Mix C. In addition to this, compressive strength of each mix was determined by casting of control cube specimens along with the beams. The behaviour of these six beams was investigated under flexure. The obtained experimental results thus are compared with analytical Moment- Curvature (M-ø) relationships in the earlier study. A comparison of the moments and corresponding curvature values at ultimate and also the average and percentage mean error were reported. Based on the above detailed objectives are arrived by adopting a systematic experimental work and carried out as detailed in the subsequent chapters.

In all the phases, throughout the study the proportion of fly ash and GGBS was selected as 70:30 for TCGPC 20, 60:40 for TCGPC 40 and 50:50 for TCGPC 60 respectively.

3.2 METHODOLOGY

In order to achieve the objectives of the investigation a detailed experimental work is planned. It can be noted that mainly the work is done in three stages. In the first stage GPC was developed based on the mix design given from previous literature and the fresh, hardened properties are obtained without lateral ties and with lateral ties. In the second and third stages, the Stress-Strain curves are evaluated for unconfined and tie based geopolymer concrete and based on a single equation analytical mode was developed, the model is validated by moment-curvature relationship with flexural tests.

Chapter 4 deals with the experimental program of unconfined and tie-confined geopolymer concrete.

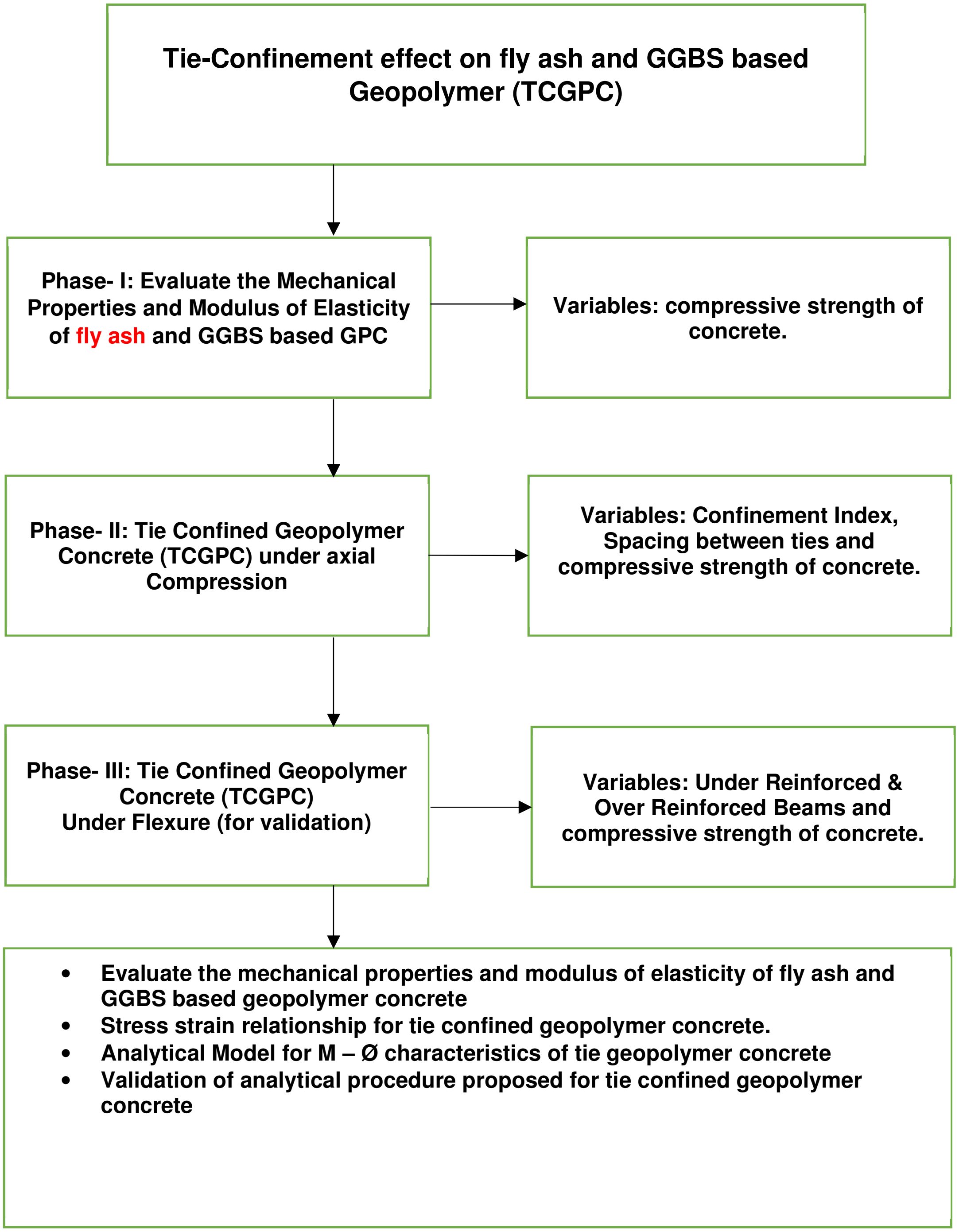

Figure 3.1: Proposed methodology

CHAPTER 4
EXPERIMENTAL INVESTIGATION ON STRESS-STRAIN BEHAVIOUR OF GEOPOLYMER CONCRETE

4.1 GENERAL

Though various authors reported that GPC has comparable mechanical properties to that of OPC concrete, not much literature is available on the modulus of elasticity of GPC under ambient curing. This study examines the performance of geopolymer concrete and aims to determine the mechanical properties and modulus of elasticity of GPC20, GPC40 and GPC60 with a combination of fly ash and GGBS as binders under ambient curing. A comprehensive assessment of their mechanical properties has been evaluated for making geopolymer concrete.

The available literature shows that the stress strain behaviour of fly ash and GGBFS-based GPC under compressive loading is similar to that of conventional concrete, and it has further been reported that the Poisson's ratio for GPC falls between 0.2 - 0.24.Various researchers proposed models for stress–strain behaviour of geopolymer concrete and concluded that the proposed GPC model has many similarities to OPC concrete and that there is an increased stiffness of GPC than that of OPC concrete. The mechanical properties and stress-strain behaviour of geopolymer concrete is presented in this present chapter.

4.2 MATERIALS

4.2.1. Binder used

Fly ash obtained from the NTPC Ramagundam Thermal Power Station, India, and GGBS obtained from Toshali Cements, Vizag, India, their chemical composition is shown in Table 4.1. Fly ash and GGBS have a relative density of 2.17 and 2.9, respectively.

Table 4.1: Mineral Composition of GGBS and fly ash

Composition	**Al_2O_3**	**CaO**	**SiO_2**	**MgO**	**SO_3**	**Fe_2O_3**	**Na_2O**	**LOI**
GGBS (%)	20.00	32.60	34.06	7.89	0.90	0.80	NIL	NIL
Fly ash (%)	26.53	4.00	60.11	1.25	0.35	4.25	0.22	0.88

4.2.2. Aggregate

River sand was used as fine aggregate (FA) and corresponds to Zone-II of IS 383:1978. Crushed rock was used as coarse aggregate (CA). The fine aggregate and coarse aggregate have specific gravities of 2.58 and 2.70 with fineness moduli of 2.70 and 6.36, respectively. Sieve analysis of aggregates is given in Table 4.2 and Table 4.3.

Table 4. 2: Sieve analysis of Coarse aggregates

Sieve analysis of Fine aggregates

IS Sieve Size	Wt. Retained (Kg)	Wt. Retained (Kg)	Cumulative % Wt. Retained	% Passing
80mm	0	0	0	100
40mm	0	0	0	100
20mm	1.52	1.52	15.2	84.8
10mm	3.33	4.85	48.5	51.5
4.75mm	5.15	10	100	0
2.36mm	0	10	100	0
1.18mm	0	10	100	0
600μ	0	10	100	0
300μ	0	10	100	0
150μ	0	10	100	0
TOTAL	10		663.7	
Fineness Modulus (FM)= 6.637				

Table 4. 3: Sieve analysis of Fine aggregates

Sieve analysis of Fine aggregates				
IS Sieve Size	Wt. Retained (Kg)	Wt. Retained (Kg)	Cumulative % Wt. Retained	% Passing
80mm	0	0	0	100
40mm	0	0	0	100
20mm	0	0	0	100
10mm	0	0	0	100
4.75mm	0.07	0.07	3.5	96.5
2.36mm	0.11	0.18	9	91
1.18mm	0.33	0.51	25.5	74.5
600μ	0.48	0.99	49.5	50.5
300μ	0.68	1.67	83.5	16.5
150μ	0.33	2	100	0
TOTAL	2		271	
Fineness Modulus (FM)= 2.71				

4.2.3. Alkaline Activator Solution

A combination of sodium silicate and sodium hydroxide in a mass ratio of 2.5 was used as an alkaline activator solution. NaOH in a pellet form and Na_2SiO_3 in a liquid form obtained from Finar Chemicals, India. The concentration of NaOH solution is 8M. The sodium silicate solution with a chemical composition of Na_2O= 8.5%, SiO_2=26.5%, H_2O=65% by mass was used. The alkaline activator solution has a Na_2O/SiO_2 (molar ratio) of 0.6. For proper mixing of the solutions, it is having been suggested to prepare the alkaline activator solution one day prior to the casting.

4.2.4. Superplasticizer (SP)

A sulphonated naphthalene-based high range water reducer, i.e.; CONPLAST SP 430, which was obtained from Fosroc Chemicals, India was used as a superplasticizer (SP) to improve the workability of the mix. The dosage of superplasticizer (SP) mentioned in Table 2 is with respect to the weight of the binder (fly ash and GGBS).

4.3 EXPERIMENTAL PROGRAM

The present chapter aims to determine the fresh and hardened properties of fly ash and GGBS-based geopolymer concrete cured under ambient conditions. The mechanical properties and modulus of elasticity were determined for GPC20, GPC40 andGPC60. The modulus of elasticity was calculated on cylindrical specimens of size 300 mm in height and 150 mm in diameter. For each mix 3 cubes of size 150 mm, 6 cylindrical specimens of size 300 mm in height and 150 mm in diameter and 3 prisms of size 500 x 100 x 100 mm were cast to determine their modulus of elasticity and their corresponding mechanical properties. The mix proportions for the GPC20, GPC40 and GPC60 are shown in Table 4.4. The following mix proportions are adopted from the literature **(Rao GM and Rao TDG, 2016).**

Table 4. 4: Quantities of Geopolymer Concrete Ingredients.

Mix	Fly ash	GGBS	Fine Agg.	Coarse Agg.	Na_2SiO_3	NaOH	SP (%)
GPC20	252	108	774	1090	141	56	3.0
GPC40	270	180	760	972	177	70	4.0
GPC60	260	260	717	915	204	81	5.0

(All the units are in kg/m^3)

4.4 PREPARATION OF THE GPC SPECIMENS

The concrete ingredients were weight batched according to the mix proportions given in Table 4.4. Initially the coarse and fine aggregates were dry mixed in a Hobart mixer for 3 minutes. Then the binder (fly ash and GGBS) was added to the aggregates and mixed for about 3 minutes, the prepared alkaline solution was added along with the superplasticizer, if any. The mixing continued for about 4 minutes until a homogeneous mixture was obtained. Before casting the specimens, the workability of the GPC in terms of slump was measured. These 3 cubes, 6 cylinders and 3 prisms were cast simultaneously. The specimens were demoulded after one day and cured under direct sunlight until the testing day (28 days). The casting and curing of the specimens are shown in Figure 4.1. The mix proportions and slump values are given in Table 4.3.

Figure 4.1: Casting and curing of the GPC specimens

4.5 TESTING OF THE GPC SPECIMENS

The young's modulus of GPC was determined from the stress-strain curve as a ratio of the stress to strain up to the elastic limit (the secant modulus). The tests were performed according to IS: 516-1959. All the prepared cylinder specimens were connected to an extensometer for recording any deformations at the corresponding loads. The tests were performed using a Tinius–Olsen testing machine with a 2000 kN capacity. The test set up is shown in Figure 4.2. The modulus of elasticity for the geopolymer cylindrical specimen was determined according to the procedure specified in ASTM standard C469-02. The following equation was used to estimate the elastic modulus of the geopolymer cylindrical specimen **(Giasuddin, 2014).**

$$E_c = 1450\,(f_c^1)^{1/2} \quad f_c^1 = \text{Peak axial stress in MPa}$$

For each mix, i.e., the GPC20, GPC40 and GPC60, three (3) cylinders were tested for the elastic modulus, then corresponding compressive, flexural strength and split tensile strength were found (IS: 516). The test setup for the splitting tensile, compressive and flexural strength are shown in Figures 4.2 to 4.5.

Figure 4.2: Test setup for Elastic Modulus

Figure 4.3: Compressive Strength of Cube

Figure 4.4: Split Tensile test

Figure 4.5: Flexural Strength

4.6 RESULTS AND DISCUSSION

1

4.6.1 Workability of GPC

The workability of the GPC for the different mixes is shown in Table 4.5.

Table 4. 5: Workability of GPC.

GPC Mix	Binder: FA: CA: Alkaline soln.	Slump (mm)
GPC20	1: 2.15: 3.05: 0.55	122
GPC40	1: 1.69: 2.16: 0.5	110
GPC60	1: 1.38: 1.76: 0.5	78

The workability of GPC mix decreases with increase in compressive strength of concrete, as seen from Table 4.5. The decrease in workability (slump) is due to presence of high amounts of GGBS content. The GGBS content for GPC20, GPC40 and GPC60 was 30%, 40% and 50% with respect to weight of binder. Therefore, it can be concluded that the increase in GGBS content negatively affects the workability, due to faster polymerization at a higher GGBS content, which results in decreased workability.

4.6.2 Mechanical properties of GPC

The compressive, flexural and split tensile strength were determined after 28 days of curing, and the results obtained are shown in Table 4.6. The values in Table 4.6 are average of the three specimens.

Table 4. 6: Mechanical Properties of GPC.

Mix	Binder Content (kg/m^3)	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)
GPC20	360	26.76	2.16	2.20
GPC40	450	43.44	3.73	4.21
GPC60	520	62.89	5.49	6.16

For the compressive strength of 20 MPa (GPC20), the fly ash and GGBS proportions were selected in a ratio of 70:30. For the GPC40 and GPC60, the fly ash: GGBS ratios are 60:40 and 50:50 respectively. As seen in Table 4.6, the increase in compressive strength is due to increase in the binder content and also due to increase in the GGBS quantity. With a higher binder content, a greater amount of alkaline solution is available for polymerization, which results in the increased strength of the concrete. With a higher GGBS content more calcium is available for polymerization, which results in the formation of additional C-A-S-H gel along with N-A-S-H gel, thereby leading to an enhancement in strength.

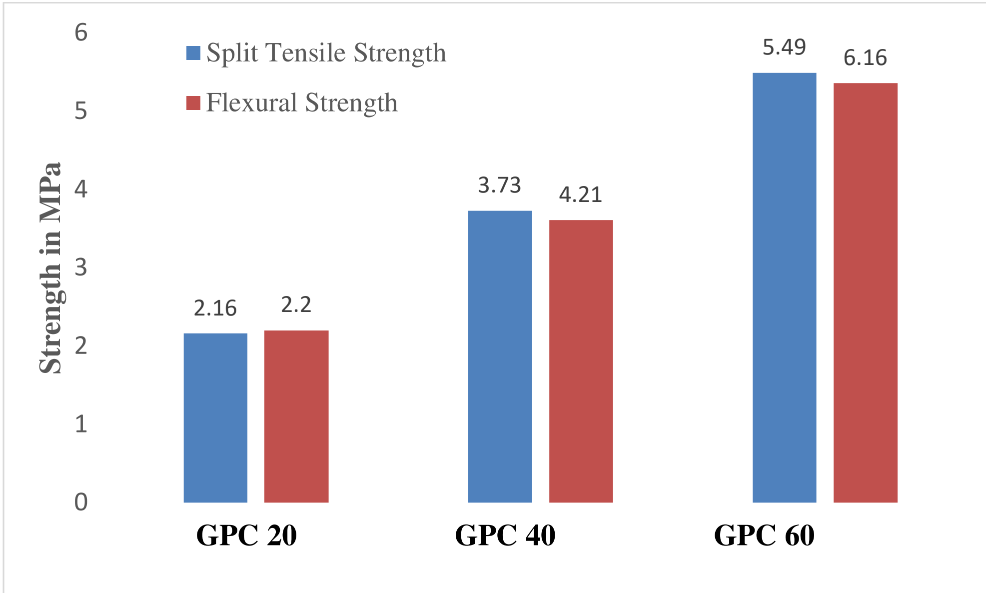

Figure 4.6: Variation of Split Tensile strength and Flexural strength

The indirect tensile strength of concrete was evaluated and the results are shown in Table 4.4 and Figure 4.6. The flexural and split tensile strengths were around 8% of their respective compressive strengths. The flexural strength of the GPC specimens was determined under two-point loading with the longitudinal axes perpendicular to the loads. The split tensile and flexural strengths of the GPC specimens cured under ambient conditions showed acceptable results of OPC concrete. The results concluded that with an increase in the slag content the split tensile and flexural strength of GPC increases. The rate of development of the tensile strength increased considerably with the inclusion of GGBS in the binder. The reaction of the slag is higher compared to that of fly ash, thereby resulting in higher strength (Puertas, 2000).

As compressive strength of concrete can be used to assess the materials ability, it can also be used to measure the flexural and split tensile strengths. Thereby increasing the compressive strength of concrete its corresponding splitting tensile and flexural strength are seen to increase in a similar manner. The results obtained indicated that the GPC mixes with GGBS and fly ash as a binder indicate good mechanical properties under ambient curing conditions without the need for heat curing as in the case of fly ash-based geopolymer concrete. Our findings are in agreement with others as well **(Siddique, 2007).**

4.6.3. Modulus of Elasticity of the GPC

The stress-strain curve of the GPC specimens tested under compression is shown in Figure 4.7, and the modulus of elasticity results along with corresponding peak stress and peak strains of GPC 20, GPC 40 and GPC 60 are shown in Table 4.5.

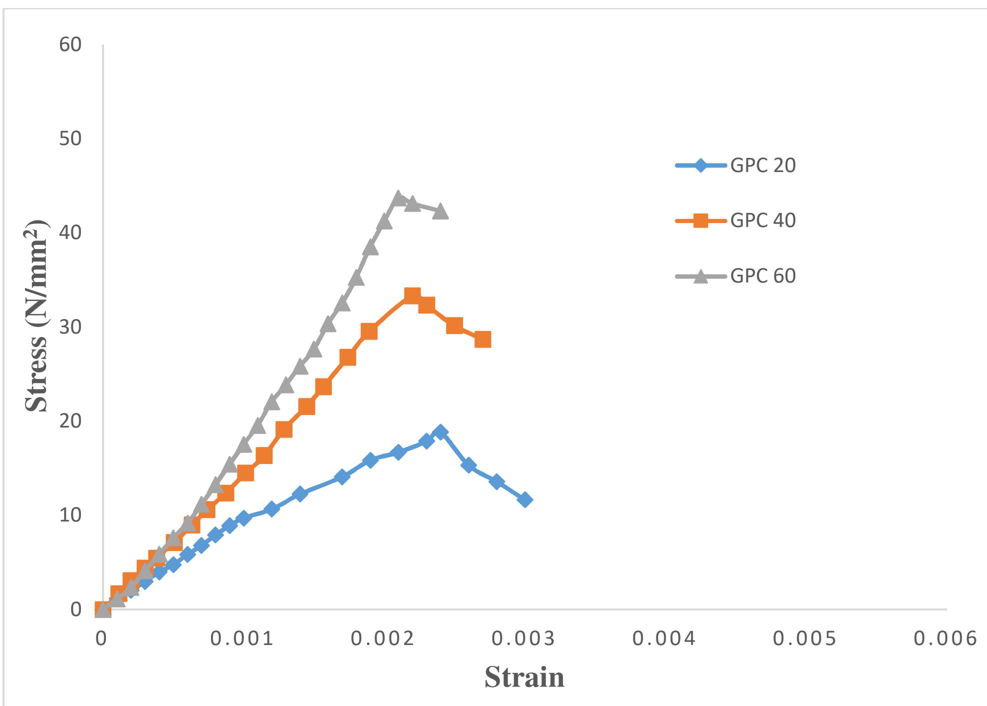

Figure 4.7: Stress-Strain Curve of the GPC

Figure 4.7, shows that the ultimate stress increased with the increase in the compressive strength of the concrete. The maximum strain is found to decrease with an increase in the compressive strength. GPC20 is more ductile than GPC40 and GPC60. A similar trend was observed in the stress-strain behaviour for the GPC40 and GPC60 up to a certain extent.

Table 4. 7: Modulus of Elasticity for the GPC mixes

Mix	Modulus of Elasticity (GPa)	Peak Stress (N/mm^2)	Strain at peak stress
GPC20	10.59	18.82	0.0024
GPC40	14.11	33.31	0.0022
GPC60	21.21	43.69	0.0021

Table 4. 8: Validation of empirical equitation

Compressive strength	Experimental values	Theoretical values	Error (%)	Avg. error (%)
GPC 20	10.59	9.83	7.10	
GPC 40	14.11	12.71	9.91	9.15
GPC 60	21.21	19.00	10.44	

The elastic modulus of the GPC is directly proportional to the compressive strength of the GPC, but the elastic modulus of GPC is comparatively less than conventional concrete for similar compressive strengths. An increase in GGBS content enhances the modulus of elasticity and compressive strength of concrete. An increase in compressive strength from 20 MPa to 40 MPa, increases the modulus of elasticity by 33%. Whereas, increase in the compressive strength from 40 MPa to 60 MPa, increases the modulus of elasticity by 50%. This might be due to an increase in the volume of the paste, which resulted in the increased homogeneity (a reduction in the voids) of the concrete by improving its compressive strength and modulus of elasticity. Higher compressive strength of GPC tends to brittle behaviour shown by decreased values of strain as seen from Table 4.7.

An equation is proposed for calculating the modulus of elasticity from the experimental results based on the compressive strength of geopolymer concrete. The proposed equation shown in Eq. 4.1 is valid for a compressive strength range of 20 MPa to 60 MPa.

$$E = [4.26C^2 - 111.74C + 10365]*10^{-3} \text{ GPa} \qquad \text{---Eqn. 4.1}$$

Where C = compressive strength of GPC

The average percentage error of the empirical equitation was incorporated in the thesis. The average percentage error is less than 10%. Hence this equitation can be used for geopolymer concrete.

4.7 CONCLUSIONS

1. An increase in the percentage of GGBS in a fly ash and GGBS based geopolymer concrete mix increases the compressive strength but decreases the workability.
2. The replacement of fly ash with GGBS is found to be a suitable alternative to avoid oven curing of geopolymer concrete members.
3. The strain at peak decreases with an increase in the compressive strength of geopolymer concrete and the post peak behavior shifts from ductile to brittle failure.
4. The modulus of elasticity increases with increase in the compressive strength of geopolymer concrete, and an equation is proposed for estimating the modulus of elasticity in terms of the compressive strength of the GPC. It is $E = [4.26C^2 - 111.74C + 10365]*10^{-3}$ GPa and a compressive strength range from 20 MPa to 60 MPa.

CHAPTER 5

Chapter 5

TIE-CONFINEMENT ASPECTS OF FLY ASH-GGBS BASED GEOPOLYMER CONCRETE SHORT COLUMNS

5.1 GENERAL:

It is observed from the literature that the deformation capacity or stiffness of GPC is quite low compared to conventional concrete. The stiffness and deformability can be improved by various methods like wrapping laminates, fibre reinforcement, confinement, etc. Of all these methods, confinement is the most effective way to enhance the ductility behaviour of concrete in the post peak region.

Stress-strain behaviour of confined concrete is very essential to obtain moment-curvature relationship to evaluate the ductility and deformability of reinforced concrete members. The parameters that affect the stress-strain behaviour of confined concrete are longitudinal reinforcement (its diameter, position), spacing of bars, active reinforcement (circular, square ties), confining reinforcement/concrete core (volumetric ratio), pseudo-active reinforcement (Ferro mesh), passive reinforcement (viz. steel, glass fibres), yield strength and diameter of confining reinforcement, strength of concrete, size and shape of tested specimen.

Studies on laminate wrapping and confined concrete evaluating the strength and deformation capacities have been receiving much attention recently. The polymer fabrics are difficult to install and are costly. A lot of research work has been reported on confined stress-strain behaviour of conventional concrete but literature on confined GPC is scantly available. It is reported that GPC exhibited almost similar structural properties to that of OPC concrete **(Albitar et al 2017).** Therefore, similar tests can be conducted on GPC to evaluate the strength and deformability characteristic similar to OPC concrete. Tests on confined concrete has proved that appropriate arrangements of transverse steel reinforcement had a significant improvement in both strength and ductility. Also, the strength improvement from confinement and descending portion slope of stress-strain curve had a significant influence on flexural tensile strength and ductility of RC members.

Presence of passive reinforcement (steel fibres) to the confined concrete has improved the stress-strain behaviour and material properties. A non-dimensional characteristic equation was developed by **Ramesh et al (2003)** to predict the behaviour of confined fibre reinforced concrete in axial compression. Addition of steel fibres (passive reinforcement) to the tie confined (active reinforcement) concrete specimens indirectly provides an additional confinement to the concrete**).** Generally high strength concrete shows brittle failure, in order to overcome this more confinement is required to achieve desired post-peak deformability in columns. Confinement of GPC has grabbed attention in recent times.

In this context most of the research work have been experimented on fly ash-based GPC with oven curing to enhance the polymerisation process. There is a need to focus on confinement aspects of geopolymer concrete to improve the structural properties. So, an attempt has been made to evaluate the stress-strain behaviour of confined GPC by varying the compressive strength of GPC, spacing of ties, diameter of tie reinforcement and a relation is proposed for tie confined GPC under axial compression.S.R Reddy developed an equation for calculating confinement index of concrete and is shown in **(S.R Reddy et al 1974**) Eqn. (5.1).

$\mathbf{C_i} = (P_b - P_{bb})(\frac{f_v}{f_c})(\sqrt{\frac{b}{s}})$ ----- Eq (5.1)

The notations used in the equation (5.1) are explained below. In this study the above equation is used for calculating confinement index.

This study intends to examine the tie effect on geopolymer concrete for GPC 20 MPa, GPC 40 MPa and GPC 60 MPa. The proportion of fly ash and GGBS was selected as 70:30 for TCGPC 20, 60:40 for TCGPC 40 and 50:50 for TCGPC 60 respectively. The structural application of confined geopolymer concrete requires stress-strain behaviour to predict the moment-curvature relationship. The present paper mainly focuses on developing a non-dimensional stress-strain curve and a semi-empirical equation for Tie-Confined geopolymer concrete (TCGPC).

	Notations		
		P_{bb}	ratio of the volume of transverse reinforcement to the volume of concrete which corresponds to a limiting pitch (=1.5b)
b, d	breadth and depth of prism		
f_y	yield stress of lateral steel	**f_v**	yield stress in lateral ties
		S	spacing between lateral ties
A_s	longitudinal steel area		
		GA	GPC mix 20MPa
f_u/f'	stress ratio		
$\varepsilon_u/\varepsilon'$	strain ratio	**GB**	GPC mix 40MPa
f'	peak stress of unconfined concrete		
f_u	peak stress of confined concrete	**GC**	GPC mix 60MPa
ε'	peak strain of unconfined concrete		
ε_u	peak strain confined concrete	**GA0**	unconfined GPC 20MPa
f_u/f'	= Tie -confined concrete strength of stress ratios	**GB0**	unconfined GPC 40MPa
		GC0	unconfined GPC 60MPa
$\varepsilon_u/\varepsilon'$			

	= Tie-confined concrete ultimate strain at ultimate stress	**6#** **8#**	lateral reinforcement diameter lateral reinforcement diameter
C_i	Confinement index = $(P_b - P_{bb})(\frac{f_v}{f_c})(\sqrt{\frac{b}{s}})$		
P_b	ratio of volume of transverse reinforcement to the volume of concrete		

5.2. EXPERIMENTAL PROGRAM

The experimental program was carried out by casting of 81 prisms of size 100x100x 200mm for evaluating the stress-strain behaviour of TCGPC (3 mixes - 20, 40 and 60MPa). In this study parameters varied are compressive strength, tie configuration (6mm & 8mm) and spacing between ties of specimens. The specimens of each mix were divided into 9 sets (each set consisting 3 specimens), each varied by confinement index: C_i = 0.0, C_i = 0.051, C_i = 0.119, C_i = 0.153, C_i = 0.291, C_i = 0.354, C_i = 0.868, C_i = 0.1.029, C_i = 3.069, and spacing: 25mm, 50mm, 75mm and 100mm. The specimens cured at outdoor for 28 days until testing. The prisms were tested under uniaxial compression as specified in IS 516: 1959.

In addition to this, 100 x 100 x 100mm cubes were also cast to determine its corresponding compressive strength of concrete. The similar procedure was repeated for TCGPC40 with varying confinement index: C_i = 0.0, C_i = 0.031, C_i = 0.073, C_i = 0.094, C_i = 0.179, C_i = 0.218, C_i = 0.534, I C_i = 0.633, C_i =1.889 and TCGPC60 with varying confinement index: C_i = 0.0, C_i =0.016, C_i = 0.038, C_i =

0.049, C_i = 0.093, C_i = 0.113, C_i = 0.278, C_i = 0.330, C_i = 0.984. The proportion details of GPC mixes were presented in Table 5.1. The following mix proportions are adopted from literature **(Rao, BV Rangan, M. Talha Junaid)**

Table 5.1: Mix Proportions of Geopolymer Concrete

Mix	Fly Ash	GGBS	Fine Agg.	Coarse Agg.	Alkaline Soln.	Na_2SiO_3	NaOH	Superplasticizer
GPC20	252	108	774	1090	198	141	56	10.8
GPC40	270	180	760	972	248	177	70	18
GPC60	260	260	717	915	286	204	81	26

All units are in kg/m^3

5.3. Materials

5.3.1 Binder used

Fly ash obtained from the NTPC Ramagundam, India and GGBS obtained from Toshali cements, Vizag, India was used in this research work and their chemical composition is shown in Table 2. Fly ash and GGBS have a specific gravity of 2.17 and 2.9 respectively.

5.3.2 Aggregate

River sand and crushed granite of 16mm nominal size were used as fine and coarse aggregates and the aggregates are conforming specifications of "**(IS 383: 1970 IS: 383 – 1970)"** Fine aggregate and coarse aggregate has a specific gravity of 2.58 and 2.7 with fineness modulus of 2.7 and 6.36 respectively.

5.3.3 Alkaline Activator Solution

The combination of sodium silicate (Na_2SiO_3) and sodium hydroxide solutions (NaOH) in the mass ratio of 2.5 is used as alkaline activator solution. NaOH in pellets form and Na_2SiO_3 in liquid form obtained from Finar chemicals, India are used. NaOH solution with a concentration of 8M is used. For proper mixing of solutions, it is suggested to prepare alkaline activator solution one day prior to the casting.

5.3.4 High range water reducing Admixture

High Range Water reducer, CONPLAST SP 430 conforming to **(ASTM 494)** obtained from Fosroc Chemicals, India was used in optimum dosages to improve the workability of mix.

5.3.5 Longitudinal steel

The Galvanised Iron wire (GI wire) is used as longitudinal reinforcement having a diameter of 4 mm and yield strength, f_v = 320 MPa was used in this experimental work. It is lower than the diameter of the lateral steel as to analyse the effect of confinement there by neglecting the longitudinal reinforcement.

5.3.6 Lateral steel (ties)

In this study lateral reinforcement used as mild steel (Fe250) and HYSD steel bars (Fe415) are conforming to IS 432 (part-1)-1982 and IS: 1786 – 2008**.** The properties of steel were shown in Table 5.2.

Table 5. 2: Properties of steel.

Steel Specification	Diameter (mm)	Yield stress (N/mm^2)	Ultimate stress (N/mm^2)	Elongation (%)
Fe250	6 mm	259	417	24.24
Fe415	8 mm	423	496	15.20

4.4 MOULDS AND EQUIPMENT

5.4.1 Cubes: Standard cube moulds of 100 × 100 × 100mm made of cast iron were used for casting and testing specimens in compression.

5.4.2 Prisms: Standard cast iron moulds of size 200 × 100 × 100mm were cast and tested under uniaxial compression to obtain stress-strain behaviour of GPC.

5.4.3 Fabrication of Specimens

Nominal diameter 4mm galvanized iron wire was used as longitudinal reinforcement and 6 mm (Fe 250) and 8 mm (Fe415) nominal diameter was used as lateral reinforcement. They were chopped to the desired length. The lateral reinforcement was made on a bar bending bench with a hand tool. The ties were tied to 4 longitudinal bars at the required pitch so that the hooks were evenly distributed at all the four corners. Different spacing used for casting were 25, 50, 75, and 100mm spacing. The details of the casted specimens were shown in Table 3 and the fabrication of specimens shown in Figure 5.1.

Figure 5. 1 Fabrication of Specimens

5.4.4 Curing:

The specimens were cured at outdoor (temperature 35±2ºC; humidity 75%) for 28 days.

5.4.5 Testing:

A compression testing machine of 3000 kN capacity was used for uniaxial compression testing of prisms as suggested by **IS: 516 (1959).** The specimens were tested longitudinally under constant rate of loading. To avoid local stress concentration, steel plates were placed on top and bottom sides of the specimen. The Data Acquisition Control (DAC) attached with two 100 mm measuring capacity Linear Variable Differential Transducers (LVDT). The schematic diagram of the test setup is shown in **Fig. 5.2 and 5.3.** The results were analysed and the stress-strain behaviour of GPC for each specimen was continued. The details of the specimens shown in Table 5.3.

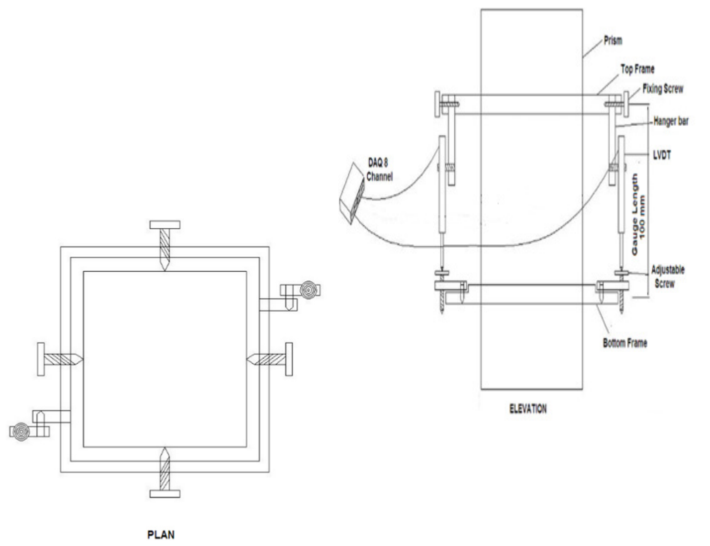

Figure 5. 2: Schematic diagram of test setup

Figure 5.3: Test set-up

Table 5.3 Details of tested specimens of different mixes.

SL No.	Designation			Lateral steel		Confinement Index		
	Mix A	Mix B	Mix C	Dia	Spacing	Mix A	Mix B	Mix C
1	GA0	GB0	GC0	-	-	0.0	0.0	0.0
2	GA6#25	GB6#25	GC6#25	6	25	1.029	0.633	0.330
3	GA6#50	GB6#50	GC6#50	6	50	0.291	0.179	0.093
4	GA6#75	GB6#75	GC6#75	6	75	0.119	0.073	0.038
5	GA6#100	GB6#100	GC6#100	6	100	0.051	0.031	0.016
6	GA8#25	GB8#25	GC8#25	8	25	3.069	1.889	0.984
7	GA8#50	GB8#50	GC8#50	8	50	0.868	0.534	0.278
8	GA8#75	GB8#75	GC8#75	8	75	0.354	0.218	0.113
9	GA8#100	GB8#100	GC8#100	8	100	0.153	0.094	0.049

Diameter of Longitudinal steel bar = 4#

4.5 RESULTS& DISCUSSIONS

5.5.1 Fresh properties and compressive strength of GPC

The workability (slump) and compressive strength of the three mixes adopted were shown in Table 5.4

Table 5.4 Slump and compressive strength results of GPC

Mix Designation	Slump (mm)	Compressive Strength at 28 days (MPa)
GA(GPC20)	122	25.88
GB(GPC40)	110	43.49
GC(GPC60)	78	60.27

Based on slump values, it can be concluded that GGBS content is indirectly proportional to workability of concrete. The increase in percentage of GGBS content in the binder has resulted in decrease workability of concrete. This may be due to faster polymerization process in GPC due to higher GGBS content.

The increase in GGBS content as a replacement of fly ash shows a gradual increase in compressive strength of GPC cured under outdoor conditions. The required target strength could be easily achieved for all mixes. This increase in strength can be attributed to the increase in calcium content available for polymerisation resulting in formation of hydrated calcium aluminosilicate gel (C-A-S-H gel) in addition to hydrated sodium aluminosilicate gel (N-A-S-H gel). Hence, it can be concluded that combination of both GGBS and fly ash as binder to produce GPC has adequate compressive strength without temperature curing.

5.5.2 Stress-Strain Behaviour of TCGPC

The response of TCGPC specimens in compression is almost similar to response of plain concrete specimen which is continuously nonlinear and the fine vertical cracks propagated along the specimens in vertical direction and these cracks are noticed about 70 to 75% of the peak load. As there is a continuous increase in load, the multiple vertical cracks were observed at low rate of loading after reaching ultimate load and further extended to the edges of specimen. In the case of TCGPC20, TCGPC40 behaviour is ductile than TCGPC60 during loading. TCGPC60 specimens showed brittle failure response and extending of cracks were observed in lesser time. Widening of cracking and decline of the load after the ultimate load (descending branch) depend upon the Tie confined index. The greater the Confinement Index, the lower is the amount of spalling of concrete and rate of decrease in load. This might be due to the development of internal crack resisting structure, dimensional firmness and integrity of the material caused by the presence of tie-confinement. However, the presence of tie-confinement might have improved the failure strain of core concrete and it leads to improvement in the ductility and compressive strength of confined GPC.

5.5.3 Effect of tie-confinement on ultimate Strength and Strain

From the stress-strain curves, the ultimate strength (f_u), strain at ultimate strength (**ε_u**) strains at 85% of ultimate on both ascending and descending region are calculated and represented in **Table 5.5 to 5.7.** From this data, the stress ratio, strain ratio, toughness and ductility factor were obtained for different confinement indices of GPC mixes A, B and C. For Mix A, for an increase in confinement index from 0 to 3.5, the ultimate stress and strain were increased by 67% and 65%. For Mix B, for an increase in confinement index from 0 to 1.89, ultimate stress and strain were increased by 84% and 75% and for Mix C, for an increase in confinement index from 0 to 0.984, the ultimate stress and strain were increased by 39% and 60%. There is a significant increase in GPC 40MPa than other mixes. The experimental stress-strain curves are shown in **Fig 5.3- 5.5.**

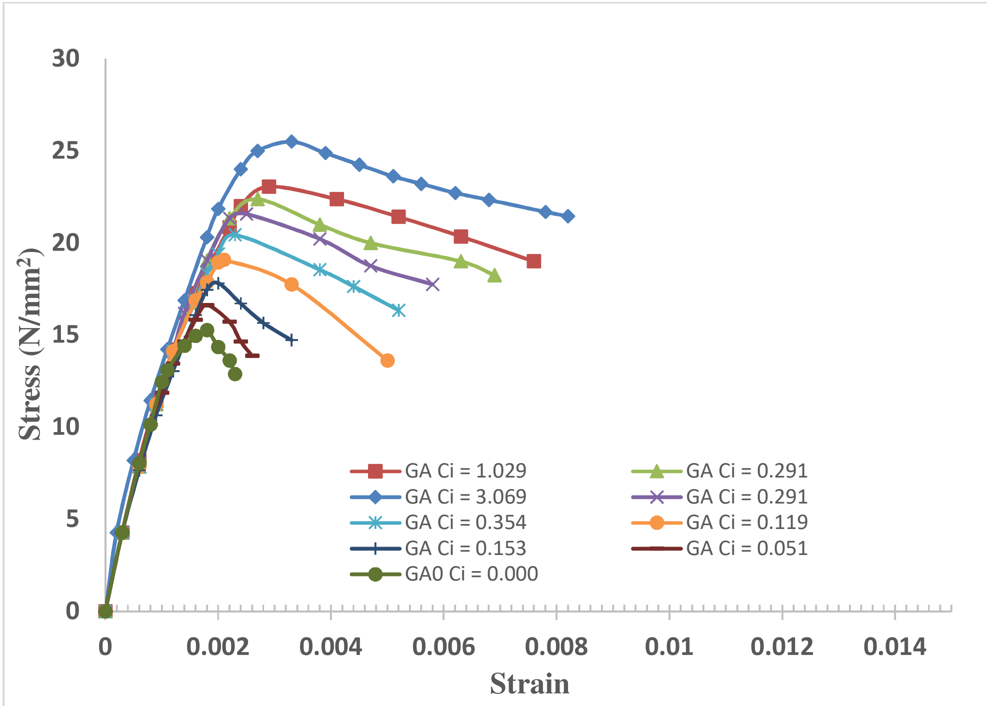

Figure 5. 3 Experimental Stress-strain for TCGPC 20 MPa with varying spacing and diameter of lateral steel

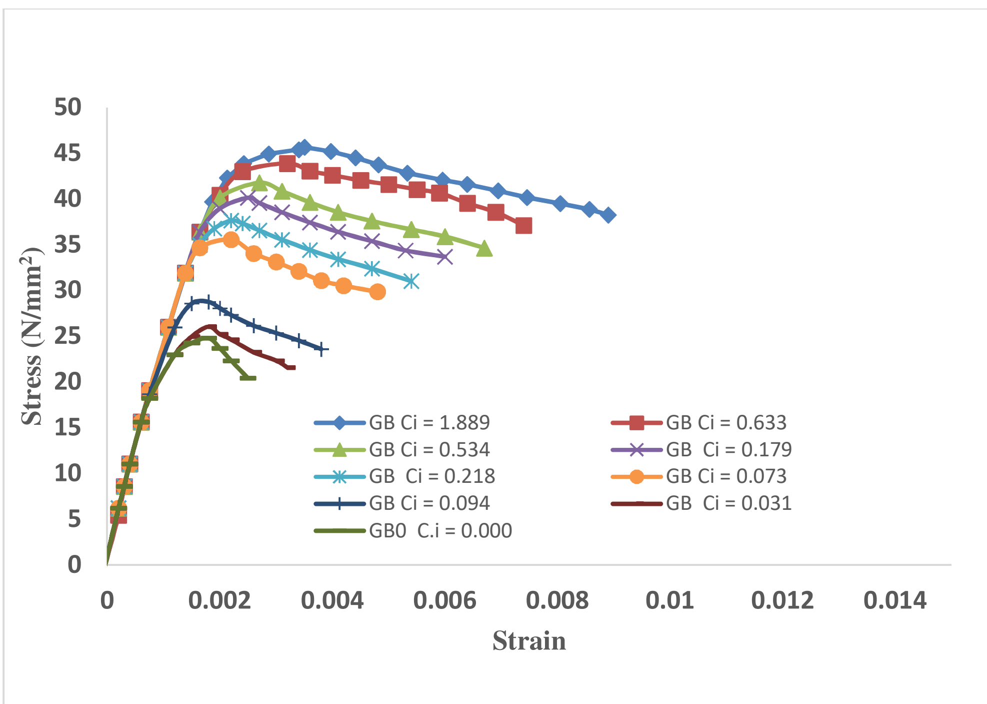

Figure 5. 4 Experimental Stress-strain for TCGPC 40 MPa with varying spacing and diameter of lateral steel

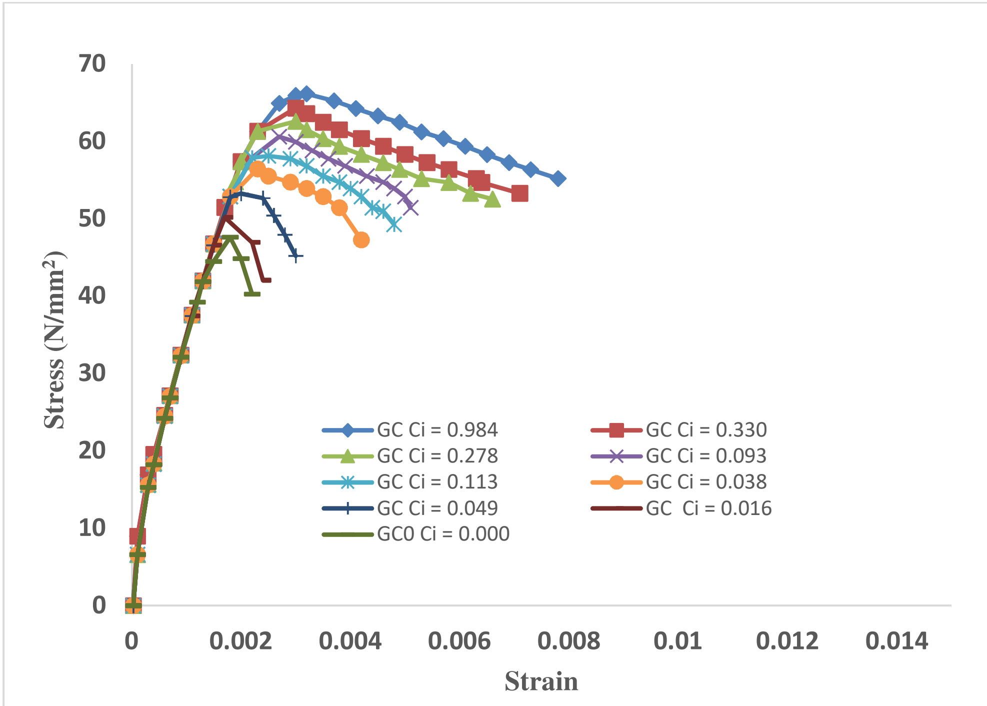

Figure 5. 5 Experimental Stress-strain for TCGPC 60 MPa with varying spacing and diameter of lateral steel

The stress-strain curves of GPC show that high confinement with low spacing contributes higher stress and higher strain in GPC20, GPC40 and GPC60 and this is due to small micro cracks are formed at peak load. The above variations can be attributed due to tie-confinement orientation in structural member. Lightly confined specimens showed less ductility in the post peak region. Multiple cracks are noticed in the post peak region. The first crack is observed at 70% of peak load for all confined and unconfined specimens and second crack was observed at 75% of peak load. The failure pattern of the specimens is shown in Figure 5.6.

Figure 5. 6 Failure pattern of specimens

Low confinement with high spacing of lateral contributes less strain that as similar to unconfined concrete. Tie-confinement with larger diameter lateral sustains higher stress and strain and this is due to high yield stress of 8mm diameter lateral steel. Concrete reinforced with high confinement shows a comparatively flat softening portion. The ultimate strain reached value 0.0035 for GPC 40MPa, about two times the ultimate strain of plain concrete. It is important to note that high confinement attributes higher strains at peak stress. It also represents that gradual incremental trend is observed and this can be due to contribution of lateral reinforcement in concrete, which is greatly enhanced the peak stress and ultimate strain with respect to spacing of ties in specimens, and it can be due to stress intervals decreased corresponding strain. Strain hardening is observed and this is due to ductile behavior of steel is taken during loading. The peak stress significantly increases in increase of diameter of lateral reinforcement. It can be concluded that increasing the confinement index leads to the increase in ductility and toughness. In the case of GPC60 maximum strain is lesser than GPC40 and this may be happened due to brittle behavior of high strength concrete. The post-test aspects of GPC specimens after failure showed either a single shear plane or a cone type failure in case of plain concrete. By contrast a large number of longitudinal cracks near the failure zone was observed for a tie confined specimen, which are parallel or near parallel to the external compressive stresses. After the initiation of first crack, ties continue to resist crack propagation and crack growth and allows concrete to sustain very high strains, of the order of four times the strains obtained in case of plain concrete. Spalling of concrete in confined GPC was much slower than compared to Unconfined GPC. It was observed that confined core Concrete is highly rigid when compared to unconfined GPC. Concrete core plays a vital role to resist the stress even after concrete fails. In this case vertical crack pattern was recorded along the specimen while loading and these cracks reaches edge of the specimen.

Longitudinal bars buckled whenever concrete reaches its strength. There is high descending portion recorded for 25mm spacing with 8mm tie reinforcement. It was observed that 25mm spacing with 8mm dia. confined specimens sustained larger strains compared to 6mm dia. confined specimens. The peak stress, peak strain, confinement indices, stress-strain ratios, ductility factor and toughness for different mixes of GPC are shown in **Table 5.5-5.7.**

Table 5. 3: Stress-Strain ratios, Confinement indices, Ductility and Toughness of Mix A (20MPa)

S. No.	Designation	Confine-ment index	Peak Stress in MPa	Peak Strain	Stress Ratio f_u/f'	Strain Ratio $\varepsilon_u/\varepsilon'$	Ascending region ε_u	Descending region $\varepsilon_{0.85u}$	Ductility Factor $\varepsilon_{0.85u}/\varepsilon_u$	Toughness
1	**GA0**	**0.000**	15.26	0.0020	1.000	1.00	0.0011	0.0022	1.93	0.0144
2	**GA6#25**	**1.029**	23.06	0.0029	1.685	1.602	0.0020	0.0070	3.52	0.0466
3	**GA6#50**	**0.291**	21.57	0.0025	1.413	1.265	0.0017	0.0051	3.04	0.0359
4	**GA6#75**	**0.119**	19.08	0.0021	1.250	1.100	0.0015	0.0043	2.88	0.0364
5	**GA6#100**	**0.051**	16.62	0.0020	1.119	1.029	0.0013	0.0026	1.98	0.0179
6	**GA8#25**	**3.069**	25.50	0.0033	1.842	1.750	0.0019	0.0086	4.39	0.092
7	**GA8#50**	**0.868**	22.38	0.0027	1.619	1.500	0.0017	0.0061	3.43	0.0414
8	**GA8#75**	**0.354**	20.44	0.0023	1.467	1.350	0.0016	0.0050	3.01	0.0222
9	**GA8#100**	**0.153**	17.82	0.0020	1.273	1.150	0.0014	0.0030	2.09	0.0144

Table 5.4: Stress-Strain ratios, confinement indices, Ductility and Toughness of Mix B (40MPa)

S. No.	Designation	Confine-ment index	Peak Stress	Peak Strain	Stress Ratio f_u/f'	Strain Ratio $\varepsilon_u/\varepsilon'$	Ascending region ε_u	Descending region $\varepsilon_{0.85u}$	Ductility Factor $\varepsilon_{0.85u}/\varepsilon_u$	Toughness
1	**GB0**	**0.000**	24.78	0.0020	1.000	1.000	0.0010	0.0024	2.464	0.022
2	**GB6#25**	**0.633**	43.88	0.0032	1.518	1.450	0.0020	0.0072	4.170	0.080
3	**GB6#50**	**0.179**	40.12	0.0025	1.315	1.157	0.0014	0.0055	3.730	0.059
4	**GB6#75**	**0.073**	35.54	0.0022	1.160	1.033	0.0013	0.0045	3.448	0.044
5	**GB6#100**	**0.031**	26.04	0.0020	1.054	1.000	0.0010	0.0031	3.100	0.026
6	**GB8#25**	**1.889**	45.64	0.0035	1.771	1.650	0.0019	0.0078	3.98	0.0491
7	**GB8#50**	**0.534**	41.76	0.0027	1.511	1.368	0.0015	0.0062	3.974	0.069
8	**GB8#75**	**0.218**	37.62	0.0022	1.339	1.250	0.0013	0.0049	3.520	0.054
9	**GB0**	**0.094**	28.74	0.0020	1.186	1.050	0.0010	0.0035	3.341	0.031

Table 5.5: Stress-Strain ratios, Confinement indices, Ductility and Toughness of Mix C (60MPa)

S. No.	Designation	Confine-ment Index	Peak Stress	Peak Strain	Stress Ratio f_u/f'	Strain ratio $\varepsilon_u/\varepsilon'$	Ascending region ε_u	Descending region $\varepsilon_{0.85u}$	Ductility Factor $\varepsilon_{0.85u}/\varepsilon_u$	Toughness
1	**GC0**	**0.000**	47.58	0.0020	1.000	1.000	0.0012	0.0022	1.75	0.0462
2	**GC6#25**	**0.330**	64.28	0.0030	1.434	1.350	0.0028	0.0063	3.39	0.1170
3	**GC6#50**	**0.093**	60.59	0.0027	1.168	1.041	0.0016	0.0050	3.00	0.0930
4	**GC6#75**	**0.038**	56.43	0.0023	1.089	1.000	0.0015	0.0041	2.64	0.0789
5	**GC6#100**	**0.017**	50.16	0.0020	1.051	1.000	0.0013	0.0023	1.78	0.0526
6	**GC8#25**	**0.984**	66.13	0.0032	1.671	1.506	0.0019	0.0073	3.81	0.1280
7	**GC8#50**	**0.278**	62.57	0.0030	1.351	1.250	0.0018	0.0062	3.37	0.1050
8	**GC8#75**	**0.113**	58.2	0.00250	1.221	1.100	0.0016	0.0047	2.93	0.0848
9	**GC8#100**	**0.049**	53.25	0.0020	1.119	1.023	0.0014	0.0029	2.10	0.0620

5.5.4 Relationship between Confinement index (C_i), stress ratio and strain ratio of all mixes

Fig 5.7-5.8 show the relationship between confinement indexes (C_i), stress ratios and strain ratios for GPC mixes A, B and C.

$$f_u/f' = -0.237x^2 + 0.9735x + 1 \text{ ------------ Eqn. (5.2)}$$

$$\varepsilon_u/\varepsilon' = -0.1505x^2 + 0.6921x + 1 \text{ ------------ Eqn. (5.3)}$$

The above equations 2 to 3 are obtained from stress ratio vs. confinement index and strain ratios vs. confinement index of Mix A, B and C respectively. The increase in confinement indices and there is gradually increased the stress and strain ratios for corresponding grades. This further lead to improvement in deformation capacity of structural members. The 75% of obtained experimental results were used for developed analytical equation and remaining 25% of experimental results were used to validating for developed analytical equation.

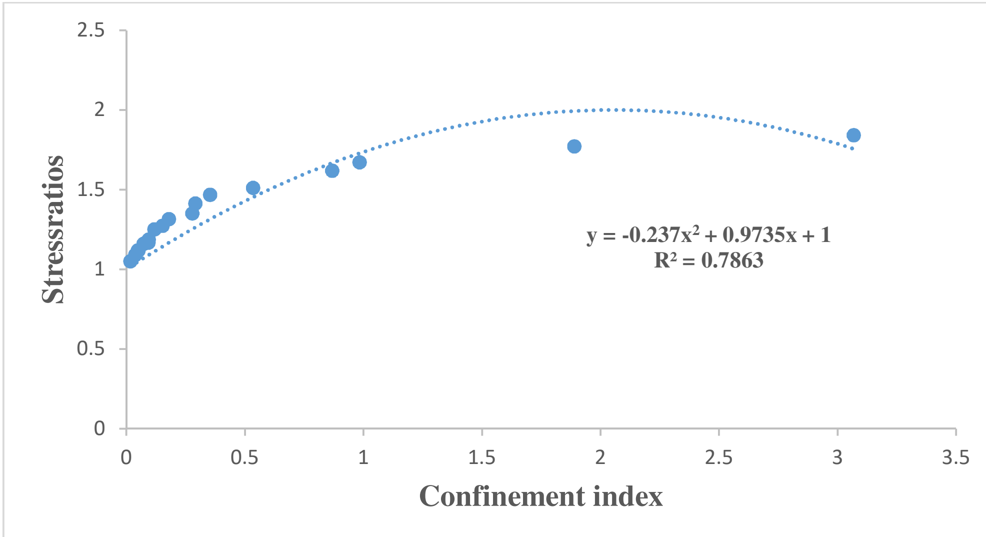

Figure 5. 7 Stress ratios (fu/f′), Strain ratios ($\varepsilon_u/\varepsilon'$) vs. Confinement indices of all Grade

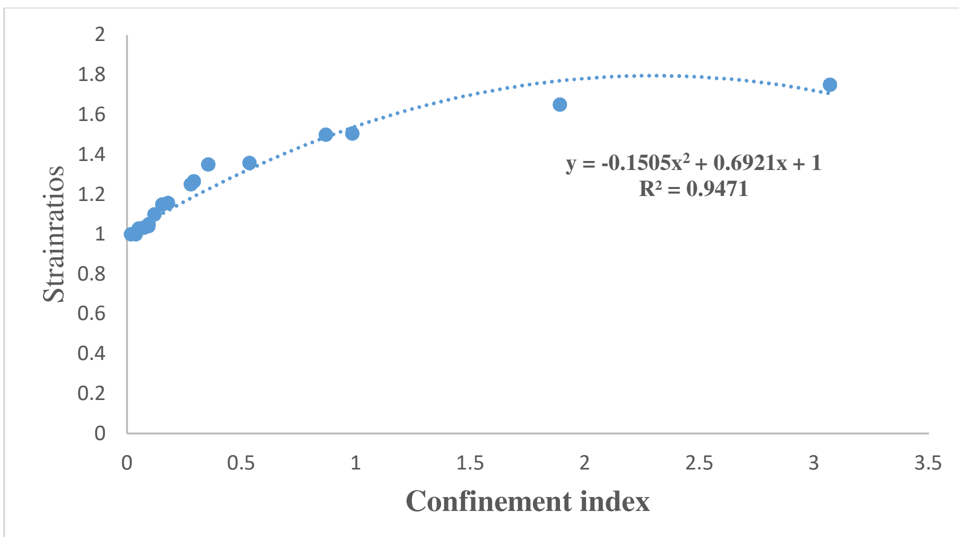

Figure 5. 8 Strain ratios ($\varepsilon_u/\varepsilon'$) vs. Confinement indices of all Grade

5.5.5. Ductility factor Vs. Confinement index

The ductility factor (DF) measures the ratio of strains at 85% of the ultimate strength in the descending and ascending portion. A plot of confinement index vs. Strain ductility depicted in **Fig. 5.9** represents the increase in strain ductility with increased confinement for low strength concrete. However, the ductility is minimum for Mix C i.e. GPC 60MPa. This is attributed due to the increase in percentage of GGBS in high strength concrete. The equation for DF is given below;

Ductility factor = $-0.4728x^2 + 1.9059x + 2.5346$ ------------------- Eqn. (5.4)

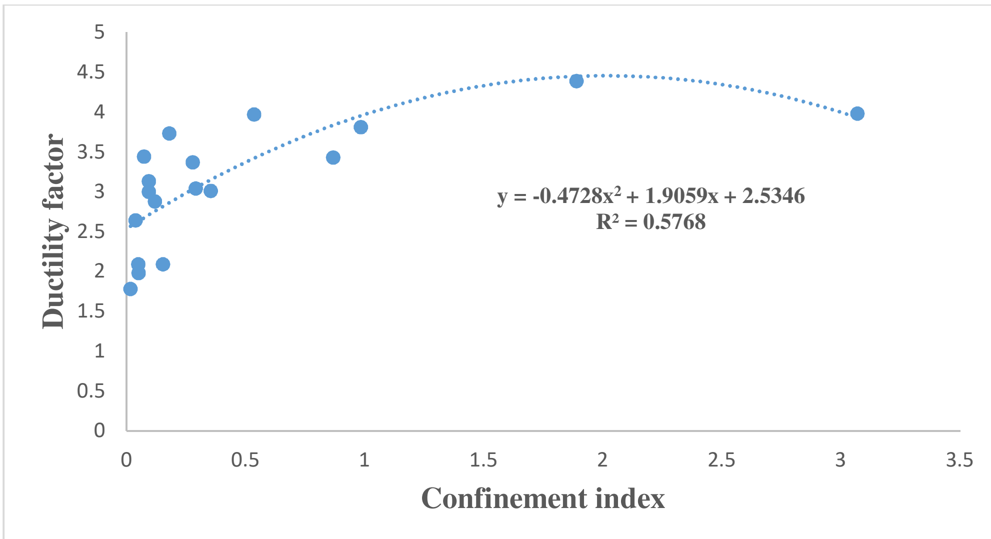

Figure 5. 9 Ductility factor vs. Confinement indices of all Grades

For **Mix A**, for an increase in confinement index from **0 to 3.5,** strain ductility increased by 134% when compared to unconfined specimens. For **Mix B**, for an increase in confinement index from **0 to 1.889,** strain ductility increased by 86% and similarly for **Mix C**, for an increase in confinement index from **0 to 0.984,** strain ductility increased by 70%. The increase in strain ductility of concrete can be attributed to confinement orientation.

5.5.6. Tie-Confinement effect on Toughness

The toughness index is calculated from the area under the stress-strain curve. It can be observed that toughness modulus of concrete is directly proportional to confinement index. Confinement of concrete with ties greatly enhanced the toughness. For **Mix A,** for an increase in confinement index from **0 to 3.5,** toughness modulus increased by **2.5** times. For Mix B, for an increase in confinement index from **0 to 1.889,** toughness modulus increased by **3 times**. Similarity trend observed for Mix C, for an increase in confinement index from **0 to 0.984**, increased toughness by **1.7** times

5.5.7. Semi Empirical Equation and Stress –Strain curve for TCGPC

An observation of the stress-strain curves for TCGPC presents that a similar response is observed for all the confined specimens. The similarity in the responses indicates that there is a unique form of the stress-strain response when both the axes are expressed in a non-dimensional form. The unique form is calculated by dividing the stress at any level by the ultimate stress, and also by dividing strain at any stress level by the strain at ultimate stress and plot the stress ratio vs. strain ratio graph represented. This indicate same behaviour stress-strain curve and confinement is neglected.

The proposed stress-strain model by Sargin's **(Y.F. Wuet al)** for confined ordinary concrete is extended to GPC. The single proposed equation is;

$$\frac{f}{fc} = \frac{A\left(\frac{\epsilon}{\epsilon_c}\right) + (D-1)\left(\frac{\epsilon}{\epsilon_c}\right)^2}{1 + (A-2)\left(\frac{\epsilon}{\epsilon_c}\right) + D\left(\frac{\epsilon}{\epsilon_c}\right)^2} \qquad \text{------ Eqn (5.5)}$$

Where, $\boldsymbol{\varepsilon_u/\varepsilon'}$ = ratio of confined concrete peak strain to unconfined concrete peak strain, f_u/f' = ratio of confined concrete peak stress to unconfined concrete peak stress and

A, D are constants to control the ascending and descending region of stress-strain curves respectively.

Equation (5.5) is fit for the non dimensionalised characteristic stress-strain curve for CGPC in axial compression. To represent the non-dimensional stress-strain of

TCGPC, the stress ratio and strain ratio are considered as independent and dependent variables instead of stress and strain as developed by Sargin. The following boundary conditions are used for ascending and descending region.

i. At $\left(\frac{\epsilon}{\epsilon_u}\right)$ =1.0, $(\frac{f}{fu})$ =1.0

ii. At $\left(\frac{\epsilon}{\epsilon_u}\right)$ = 1.0, $\frac{d\left(\frac{f}{fu}\right)}{d(\frac{\epsilon}{\epsilon_u})}$ = 0.0

Additional boundary limits of stress-strain curve for ascending and descending region is

iii. At $\left(\frac{\epsilon}{\epsilon_u}\right)$ = 0.6, $(\frac{f}{fu})$ = 0.85

iv. At $\left(\frac{\epsilon}{\epsilon_u}\right)$ = 1.8, $(\frac{f}{fu})$ = 0.85

The condition (iii) and (iv) are obtained from the experimental data. The semi empirical values, minimum stress ratios, average stress ratios, maximum stress ratios and characteristic values are plotted in the **Fig.5.10** the stress-strain response can be represented by a general form, which also represents the curve of proposed equation satisfies all experimental values. Hence the stress-strain equation for TCGPC of strength 20 to 60 MPa can be proposed as:

$$f = \frac{A(\epsilon)+(D-1)(\epsilon)^2}{1+(A-2)(\epsilon)+D(\epsilon)^2} \quad \text{--------- Eqn (5.6)}$$

A = $A_1\left(\frac{\epsilon}{\epsilon_u}\right)$, B = $B_1(D-1)(\frac{\epsilon}{\epsilon_u})^2$, C= $C_1(A-2)\left(\frac{\epsilon}{\epsilon_u}\right)$, D = $D_1(\frac{\epsilon}{\epsilon_u})^2$

The below constants for Ascending and Descending portion were obtained from the satisfying the boundary conditions.

A_1 = 2.11, B_1 = 0.11, C_1 = 1.13, D_1 = 0.13 (for Ascending and Descending portion)

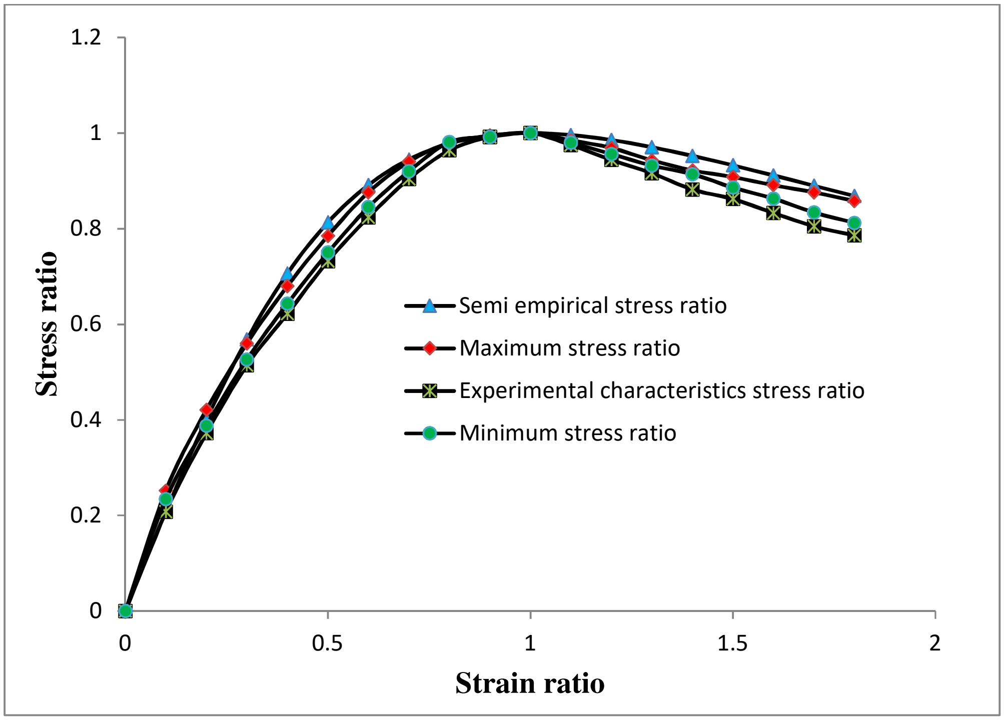

Figure 5.10 Characteristic stress ratios vs. strain ratio

Therefore, the theoretical stress-strain equation for ascending and descending branch is $\frac{f}{fc} = \frac{(2.11)\left(\frac{\epsilon}{\epsilon_u}\right)+(0.11)\left(\frac{\epsilon}{\epsilon_u}\right)^2}{1+(1.13)\left(\frac{\epsilon}{\epsilon_u}\right)+(0.13)\left(\frac{\epsilon}{\epsilon_u}\right)^2}$ ------- Eqn (5.7)

4.6 CONCLUSIONS

From the Experimental study the following conclusions are obtained:

- The confinement of geopolymer concrete increased the post peak response of GPC specimens, in terms of ductility.
- Tie confined GPC specimens, exhibited better peak stress, ductility ratio and modulus of toughness compared to unconfined GPC specimens
- Confinement in geopolymer concrete greatly enhanced the strain at peak stress and strain at 85% of the ultimate strength in descending region.

- The ultimate strength of confined GPC can be related to the compressive strength of un-confined GPC and confinement index as $f_u = f'(-0.237x^2 + 0.9735x + 1)$
- The strain at peak stress of confined GPC can be related to the strain at peak stress of un-confined GPC and confinement index as

  $\boldsymbol{\varepsilon}_u = \boldsymbol{\varepsilon}'(-0.1505x^2 + 0.6921x + 1)$
- The strain ductility of confined GPC can be related to the un-confined GPC and confinement index as ductility factor = $-0.4728x^2 + 1.9059x + 2.5346$
- The obtained experimental results were compared with the proposed semi empirical formulae. A non-dimensionalised stress-strain equation developed in this experimental investigation can be used to predict stress-strain behaviour of TCGPC.
- The predicted model is proposed for tie-confined GPC specimens by comparing Sargin's existing model and it shows appropriateness. The theoretical stress-strain equation for TCGPC is

  $$\frac{f}{fc} = \frac{(2.11)\left(\frac{\epsilon}{\epsilon_u}\right)+(0.11)(\frac{\epsilon}{\epsilon_u})^2}{1+(1.13)\left(\frac{\epsilon}{\epsilon_u}\right)+(0.13)(\frac{\epsilon}{\epsilon_u})^2}$$
- The mean percentage error of stress, and strain ratios between experimental and analytical results is 12% and 5% respectively. It shows the good agreement between experimental and analytical results.
- The mean percentage error of ductility factor between experimental and analytical results is 13%.
- The current investigation is proved that GPC is an alternative and sustainable material to Ordinary Portland cement concrete. Geopolymer technology can be a possible solution for adopting it, in construction industry.

CHAPTER 6

CHAPTER 6
THE PREDICTION OF MOMENT-CURVATURE RELATIONSHIP OF FLY ASH and GGBS BASED GEOPOLYMER CONCRETE

6.1 GENERAL

Strength and deformation are interrelated and need to be considered simultaneously in the design of reinforced concrete beams. Thus, the prediction of the safe and economic conditions of geopolymer reinforced concrete is needed to evaluate the conditions of ultimate moments and its corresponding curvatures under particular constrains.

There is only a limited literature available about the fly ash and GGBS based flexural response of geopolymer concrete to predict the moment curvature relationship. This study emerges to focus on structural performance of reinforced GPC to predict the moment-curvature relationship of different mixes. Experimental results validated with analytical data is investigated. In this study, M-Ø relationship of reinforced GPC of three mixes, Mix A, Mix B and Mix C is determined.

It is observed from the literature that the deformation capacity or stiffness of geopolymer concrete is quite low compared to conventional concrete. The available literature reports that GPC exhibited almost similar structural properties to that of OPC concrete **[W.M. Hassan et al]**. Therefore, similar tests were conducted on GPC to evaluate the strength and deformability characteristic similar to OPC concrete. The parameters affecting the stress-strain behaviour of confined concrete are longitudinal reinforcement (its diameter, position and amount), spacing of bars, active reinforcement (ties), diameter and yield strength of confining reinforcement, strength of concrete, confining reinforcement/concrete core (volumetric ratio), size and shape of tested specimen.

However, the flexural strength will vary depending on the size specimen due to size effect. Hence, there is need to focus on confinement aspects of fly ash and GGBS based geopolymer concrete beams. Moreover, the prediction of the moment curvature response is most fundamental requirement to assess the ductility behaviour of structural concrete.

6.2. Experimental program

The test programme consisted of casting 6 rectangular RC beams of size 120x200x1800mm with an effective of span 1600 mm of three different compressive strengths GPC20, GPC40 and GPC60 were designed to fail in flexure. In this, GPC20 consisting of two beams, one under reinforced and one over reinforced beam and the similar procedure was repeated for GPC40 and GPC60. The reinforcement details of the all beams are shown in **Table 6.1.** In addition to this, compressive strength of each mix was determined by casting of control cube specimens along with the beams. The following mix proportions adopted from literature **(Rao GM et al. 2016)** were shown in **Table 6.2**.

Table 6.1: Reinforcement details of tested beams

Beam Designation	Top bars	Bottom bars	Required steel (mm2)	Provided steel (mm2)	8 mm stirrups spacing
GPC 20 UR	2-8 mm	3-10 mm	371	226	120 mm
GPC 20 OR	2-8 mm	2-16mm & 2-10mm		557	90 mm
GPC 40 UR	2-8 mm	4-12 mm	742	452	80 mm
GPC 40 OR	2-8 mm	3-20 mm		942	60 mm
GPC 60 UR	2-8 mm	3-16 mm	1040	600	70 mm
GPC 60 OR	2-8 mm	4-20 mm		1144	50 mm

Table 6.2: Mix proportions of Geopolymer Concrete

Mix	Fly ash	GGBS	Fine Agg.	Coarse Agg.	Alkaline Soln	Na_2SiO_3	NaOH	SP (%)
GPC20	252	108	774	1090.8	198	141.42	56.57	3
GPC40	270	180	760	972	248	177.15	70.85	4
GPC60	260	260	717.6	915.2	286	204.28	81.72	5

All units are in kg/m^3

6.3 Materials:

6.3.1 Binder

Fly ash obtained from the NTPC Ramagundam, India and GGBS obtained from Toshali cements, Vizag, India is used in this research work and their chemical composition is shown in **Table 6.3.** Fly ash and GGBS has a specific gravity of 2.17 and 2.9 respectively.

Table 6. 3. Chemical composition of Fly ash & GGBS.

Composition	SiO_2	Al_2O_3	Fe_2O_3	SO_3	CaO	MgO	Na_2O	LOI
Fly ash	60.11	26.53	4.25	0.35	4.00	1.25	0.22	0.88
GGBS	34.06	20	0.8	0.9	32.6	7.89	NIL	NIL

6.3.2 Aggregate

River sand is used as fine aggregate (FA) and corresponds to Zone-2 of IS 383:1978. Crushed rock is used as coarse aggregate (CA). Fine aggregate and coarse aggregate have a specific gravity of 2.58 and 2.7 with fineness modulus of 2.7 and 6.36 respectively. The size distribution of the aggregates is given in previous chapter 4.

6.3.3 Alkaline Activator Solution

A combination of sodium silicate and sodium hydroxide in the mass ratio of 2.5 is used as alkaline activator solution. NaOH in pellets form and Na_2SiO_3 in liquid form obtained from Finar chemicals, India. NaOH solution with a concentration of 8M is used. For proper mixing of solutions, it is suggested to prepare alkaline activator solution one day prior to the casting.

6.3.4 Super Plasticizer

High Range Water reducer, CONPLAST SP 430 obtained from Fosroc Chemicals, India is used as super plasticizer to improve the workability of mix.

6.3.5 Curing and Testing

The casted specimens were kept under ambient temperature (Room temperature) for 28 days and these were tested under servo controlled dynamic testing machine with a capacity of 1000 kN of two-point bending.

6.4 Results &Discussions

6.4.1 Semi Empirical Equation and Stress –Strain curve for TCGPC

An observation of the stress-strain curves for TCGPC presents that the response is similar for all confined specimens. The similarity leads to the conclusion that there is a unique form of the stress-strain response, if expressed in non- dimensional form, along the both axes. The unique form is obtained dividing the stress at any level by the stress and strain at any stress level by the strain at ultimate stress and plot the stress ratio vs. strain ratio graph represented. This indicate same behaviour stress-strain curve and confinement is neglected.

The stress-strain model proposed by Sargin for confined ordinary concrete is extended to GPC. The single proposed equation is

$$\frac{f}{f_c} = \frac{A(\frac{\varepsilon}{\varepsilon_u}) + (D-1)(\frac{\varepsilon}{\varepsilon_u})^2}{1 + (A-2)(\frac{\varepsilon}{\varepsilon_u}) + D(\frac{\varepsilon}{\varepsilon_u})^2} \quad \text{------ Eqn. (6.1)}$$

Where, f_u/f' = ratio of confined concrete peak stress to unconfined concrete peak stress and $\boldsymbol{\varepsilon_u/\varepsilon'}$ = ratio of confined concrete peak strain to unconfined concrete peak strain

A, D are constants to control the ascending and descending region of stress-strain curves respectively.

Equation (5) is fit for the non dimensionalised characteristic stress-strain curve for CGPC in axial compression. To represent the non-dimensional stress-strain of TCGPC, the stress ratio and strain ratio are considered as independent and dependent variables instead of stress and strain as developed by Sargin. The following boundary conditions are used for ascending and descending region.

v. At $(\frac{\varepsilon}{\varepsilon_u})$ 1.0, $(\frac{f}{f_u})$ =1.0

vi. At $(\frac{\varepsilon}{\varepsilon_u})$ = 1.0, $\frac{d(\frac{f}{f_u})}{d(\frac{\varepsilon}{\varepsilon_u})}$ = 0.0

Additional boundary limits for ascending and descending region of stress-strain curve is

vii. At $(\frac{\varepsilon}{\varepsilon_u})$ = 0.6, $(\frac{f}{f_u})$ = 0.85

viii. At $(\frac{\varepsilon}{\varepsilon_u})$ = 1.8, $(\frac{f}{f_u})$ = 0.88

The condition (iii) and (iv) are obtained from the experimental data. The stress-strain response can be represented by a general form, which consider as also represents the curve of proposed equation satisfies all experimental values. Hence the stress-strain equation for TCGPC of strength 20 to 60 MPa can be proposed as:

$$f = \frac{A(\varepsilon)+(D-1)(\varepsilon)^2}{1+(A-2)(\varepsilon)+D(\varepsilon)^2} \quad \text{--------- Eqn. (2)}$$

Where, *f* is the stress at any level and ε is the strain at any level. To express in non-dimensional stress-strain curves the following form is proposed.

A = $A_1(\frac{\varepsilon}{\varepsilon_u})$ B = $B_1(D-1)(\frac{\varepsilon}{\varepsilon_u})^2$, C= $C_1(A-2)$, $(\frac{\varepsilon}{\varepsilon_u})$ D = $D_1(\frac{\varepsilon}{\varepsilon_u})^2$

The below constants for Ascending and Descending portion were obtained from the satisfying the boundary conditions.

$A_1 = 2.11$, $B_1 = 0.11$, $C_1 = 1.13$, $D_1 = 0.13$ (for Ascending and Descending portion)

Therefore, the theoretical stress-strain equation for ascending and descending branch is

$$\frac{f}{f_c} = \frac{(2.11)(\frac{\varepsilon}{\varepsilon_u}) + (0.11)(\frac{\varepsilon}{\varepsilon_u})^2}{1 + (1.13)(\frac{\varepsilon}{\varepsilon_u}) + (0.13)(\frac{\varepsilon}{\varepsilon_u})^2} \quad \text{------- Eqn. (3)}$$

6.4.2 Procedure for obtaining analytical moment curvature relationship

Based on the analytical model explained, for the behaviour of TCGPC in compression, it is now developed to predict the analytical M-Ø behaviour of TCGPC under ambient curing condition. In order to obtaining the moment-curvature for concrete sections confined with ties, the same assumptions of conventional concrete were followed for geopolymer concrete. In addition to the above, the necessary and sufficient conditions including the equilibrium of forces, strain relations and compatibility of strains have to be satisfied **Figure 6.1.** The proposed analytical model was developed using MATLAB coding based on following assumptions.

a) The extreme fibre concrete compressive strain (ε_c) was assumed to be in the range of 0.0001 to the failure strain (i.e.0.1).

(b) The neutral axis depth, nd was assumed initially as 0.1 times the effective depth (i.e. 0.1d).

(c) For this value of neutral axis depth, the compressive force in the concrete, is arrived at from the respective stress-strain model developed by the present authors.

(d) Using the assumption of strain compatibility, the stress in tension and compression will be calculated.

(e) In the case of beams confinement index is to be calculated on the assumption that concrete in the compression zone only is confined.

(f) The tensile strength of concrete is neglected.

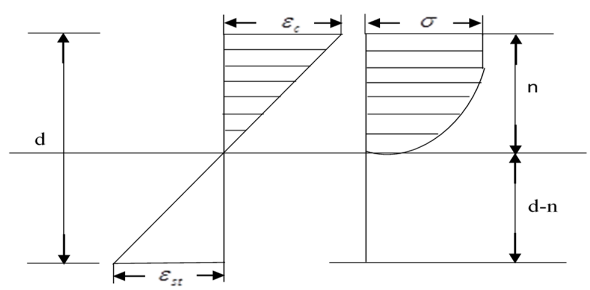

Figure 6.1: Stress-Strain distribution of a member in flexure

The following steps have been considered for calculating the moment-curvature of geopolymer concrete.

Step1: Assume ε_c = strain in compression (extreme fibre)

Step 2: The stress diagram was divided into number of strips to obtain the total compressive stress, which is calculated by summation of stresses from each strip.

Step 3: Compressive stress $f = f_c \times \dfrac{A(\frac{\varepsilon}{\varepsilon_c}) + (D-1)(\frac{\varepsilon}{\varepsilon_c})^2}{1 + (A-2)(\frac{\varepsilon}{\varepsilon_c}) + D(\frac{\varepsilon}{\varepsilon_c})^2}$

Step 4: Compression force, compression moment is calculated.

Step 5: Sum of all compression moments from each strip gives the total moment in compression (M_c).

Step 6: By using similar triangle, ε_{st} was calculated

$\varepsilon_{st} = \dfrac{d-n}{n}\varepsilon_c$

Step 7: Determining the stress in steel is depending on the strain in mild steel

$f_s = f_y$ for $\varepsilon_{st} > \dfrac{f_y}{2\times10^5} > \dfrac{f_y}{E}$

$f_s = \varepsilon_{st} \times 2\times10^5$ for $\varepsilon_{st} <= \dfrac{f_y}{2\times10^5} > \dfrac{f_y}{E}$

Step 8: calculation of force in steel $P_s = f_s \times A_{st}$

Step 9: Moment in steel $M_t = P_s \times (d-n)$

Step 10: Total moment M_{Total} = compression moment (M_c) + Tension moment (M_t)

Curvature (Ø) = $\dfrac{\varepsilon_{cc}}{n}$ where, ε_{cc} = maximum strain in concrete at failure.

Step 11: Check for neutral axis for condition TC – TT = 0. For an error of 1%.

Step 12: Plot M vs. Ø

6.4.3: Experimental moment curvature relationship:

The present experimental programme was carried out to study the flexural behaviour of reinforced geopolymer concrete beams cured under ambient temperature condition. The varied parameters are compressive strength of concrete, percentage of longitudinal reinforcement and spacing between stirrups. The servo controlled dynamic testing machine with a capacity of 1000 kN at a rate of loading 1 mm/min was used for testing beams. This is according to ASTM C 469 (ASTM, 2002). The curvatures in the central zone of the beam were measured by using curvature meters. Two digital dial gauges were attached between two successive rectangular frames, these dial gauges are 0.001 mm least count and 25 mm travel. As part of setup dial gauges were provided, one at the top and another one at the bottom of the rectangular frame. In addition to this, four rectangular frames were used to fix the three curvature meters. From this, average readings of curvature were considered obtained from the strains at the top and bottom of the frame. The deflections were measured under the two load points, and the point's midway between the midpoint and the supports by using with a help of dial gauges. These dial gauges are 0.01 mm least count and 50 mm travel. The schematic view of the test set-up is shown in **Figure 6.2.**

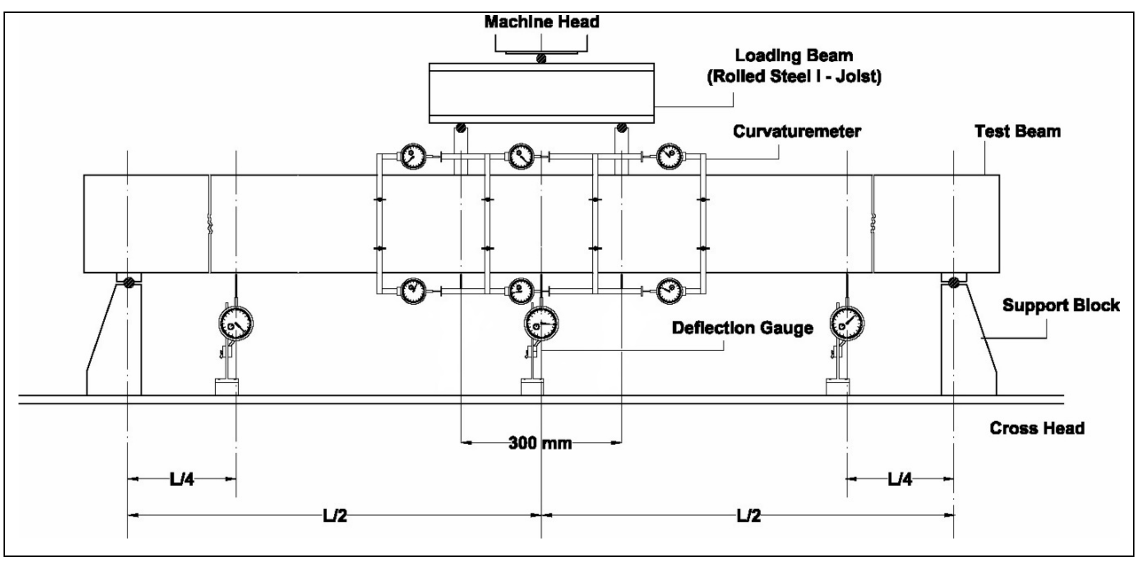

Figure 6.2: Schematic diagram for developing moment curvature under flexure

6.4.4 Comparison between analytical and experimental behaviour of the beams

The predicted moment-curvature relation obtained using developed empirical equation (Venu et al. 2017) and it was compared with the experimental M-Ø results. From the **Figure 6.3-6.5** represents that graphical comparison of the M-Ø relationship of the three mixes. Based on numerical comparison, two important points were taken – which are named,

(a) the ultimate moment and corresponding curvature (M_u and $Ø_u$);

(b) % of increment of ultimate moment and curvature when compare to unconfined ultimate moment and curvature.

The obtained experimental strain in concrete (ε_c) and strain in steel (ε_s) were taken for comparison of their corresponding M-Ø values at the above-mentioned points. **Table 6.4 and 6.5** shows that M–Ø values of corresponding under-reinforced (UR) and over-reinforced (OR) GPC beams. From these, it can be seen that the predicted analytical M–Ø curves are much near to the experimental M–Ø curves. There is an effect of compressive strength is also evident that there is increase in strength and there is an increase in ultimate moment but there is a decrease in curvature of the beams. Hence, it can be observed that, increase in percentage of reinforcement of beams obviously there as an increase in resistance offered by the beam while undergoing bending.

It is also represented that experimental and analytical moments, corresponding curvatures. The analytical and experimental results are obtained; thus, this can be used for the numerical comparison. From these tables, it is observed that the ratio of analytical to experimental were determined at all significant points. Similarly, for the average of both analytical to experimental ratio and prediction of mean error was calculated for comparison. The above results also concluded that a comparison between moment and corresponding curvature at significant points for the predicted model. The mean and average error in the prediction was found that there was no significant differ. This indicates that accuracy of the model in predicting the M–Ø values of both experimental and analytical results.

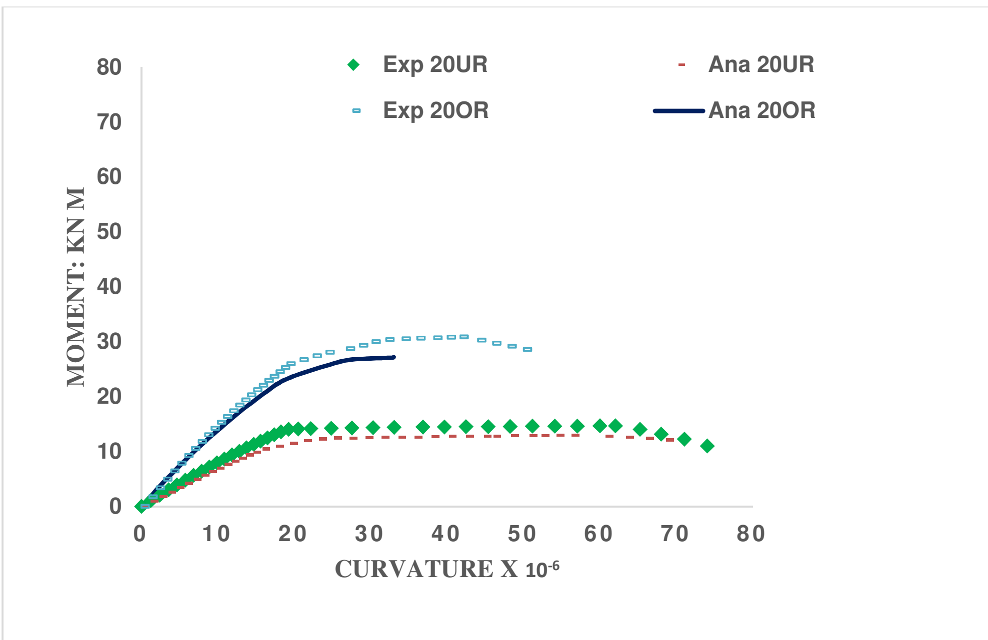

Figure 6. 3: Experimental and Analytical M-Φ of GPC 20 UR&OR

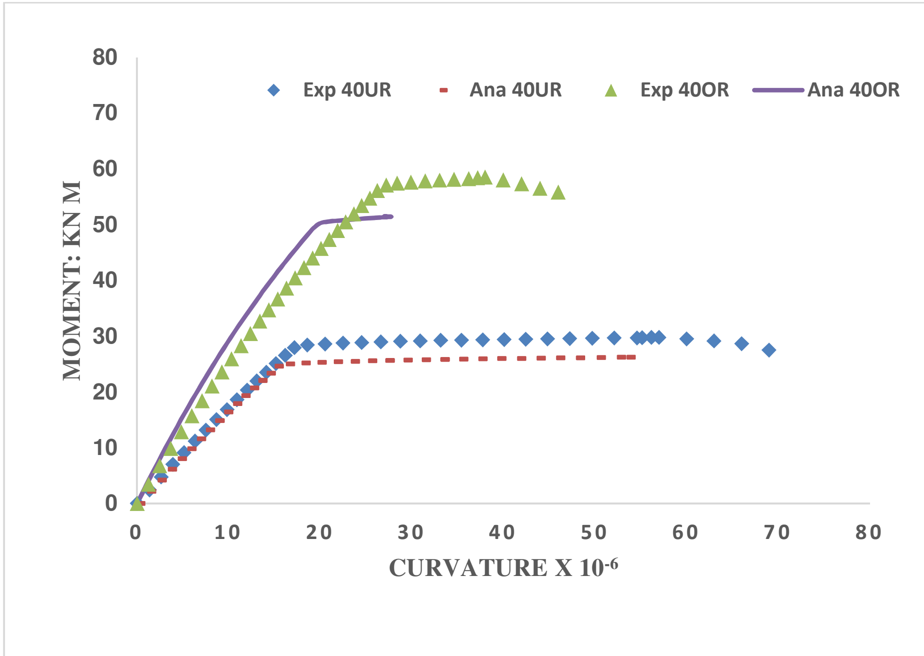

Figure 6.4: Experimental and Analytical M-Φ of GPC 40 UR&OR

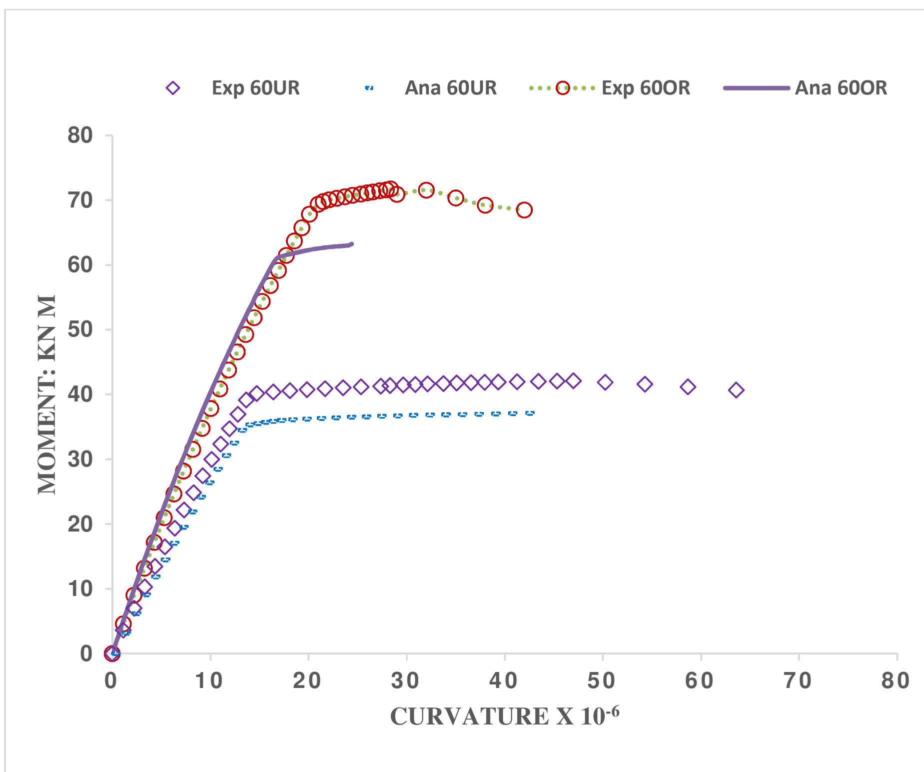

Figure 6.5: Experimental and Analytical M-Φ of GPC 60 UR&OR

Figure 6.6: Crack pattern of GPC failed specimens

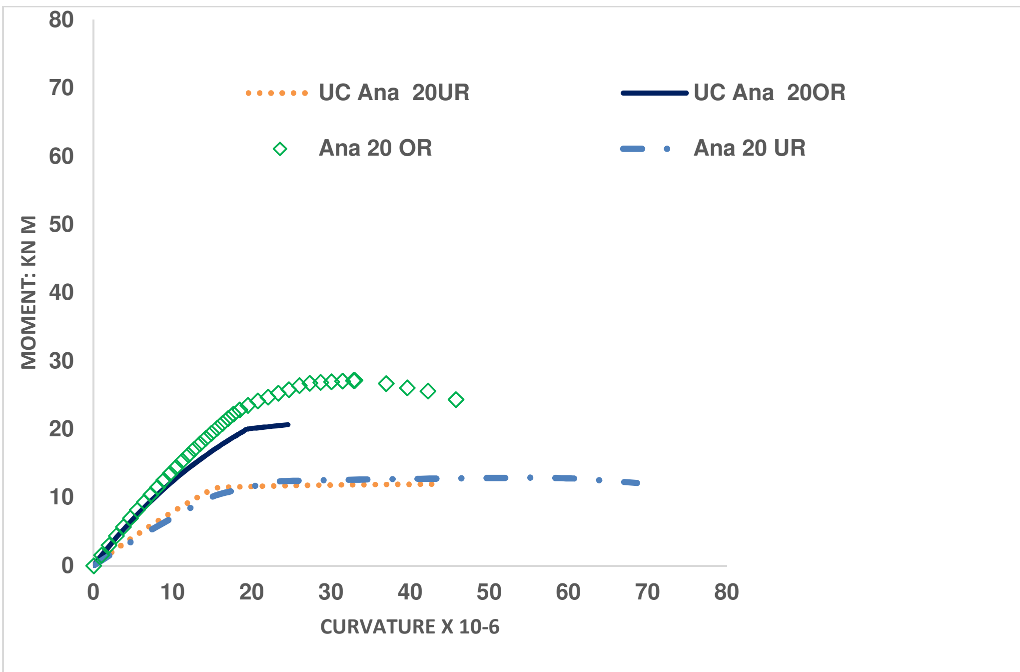

Figure 6. 7: Analytical unconfined and confined values of simply supported ambient-cured GPC beams of 20UR&OR

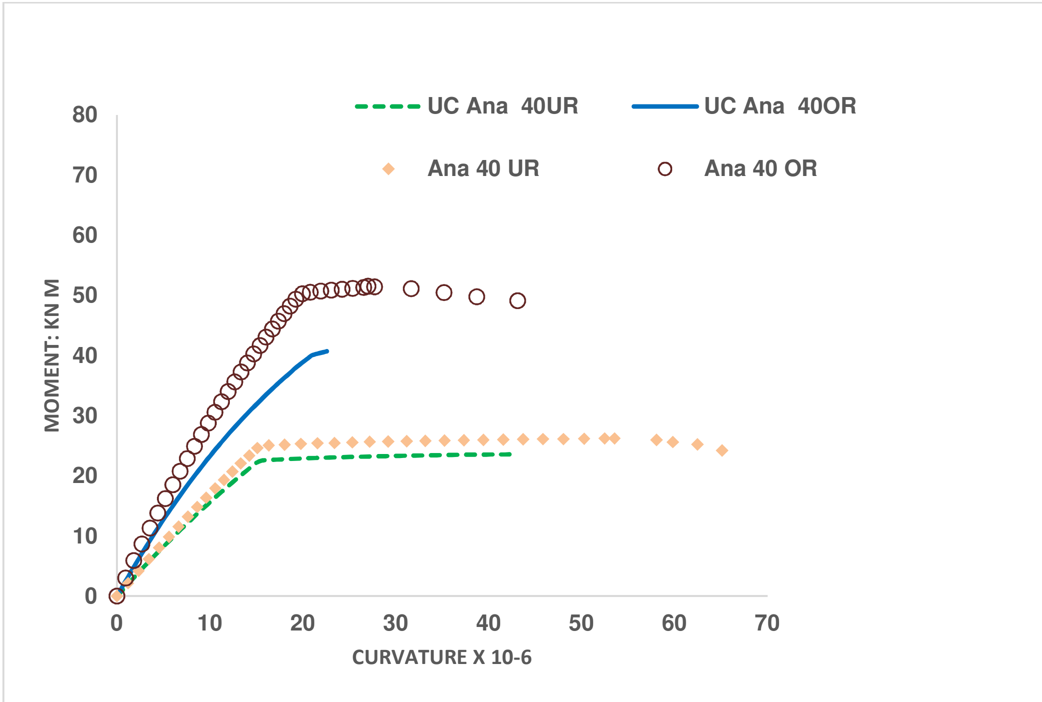

Figure 6. 8: Analytical unconfined and confined values of simply supported ambient-cured GPC beams of 40UR&OR

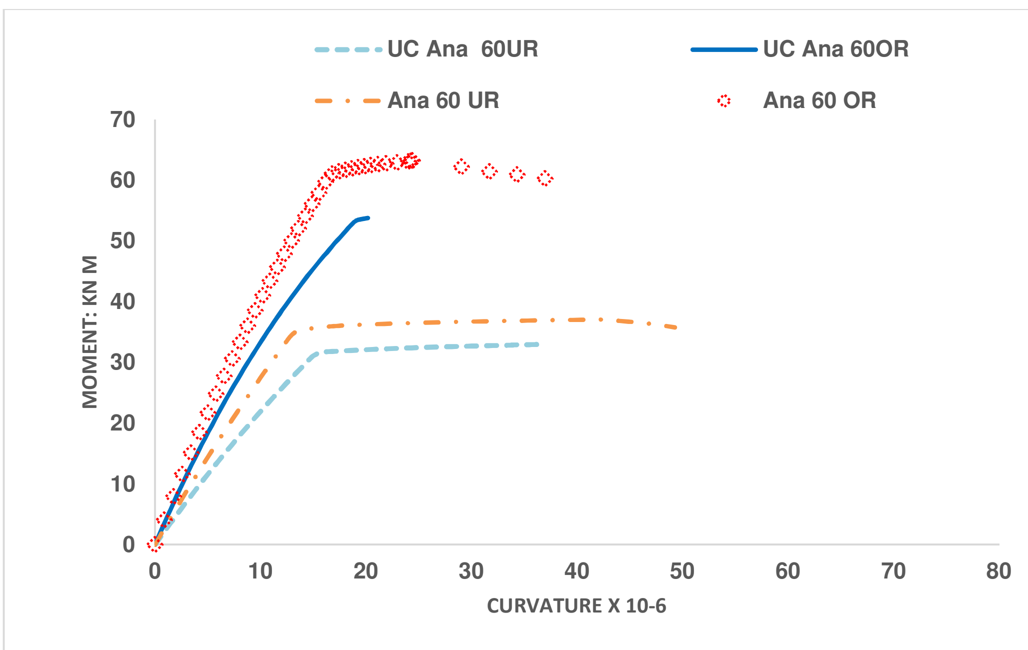

Figure 6.9: Analytical unconfined and confined values of simply supported ambient-cured GPC beams of 60UR&OR

Table 6.4: Experimental and analytical values of moment and curvature at ultimate of simply supported ambient-cured GPC beams

Ultimate values								
Experimental values					Analytical values			
Beam Designation	M (kN-m)	Ø x10^{-6}	ε_c x 10^{-6}	ε_s x 10^{-6}	M (kN m)	Ø x10^{-6}	$\frac{M_{ana}}{M_{\exp}}$	$\frac{\phi_{ana}}{\phi_{\exp}}$
GPC 20 UR	14.67	62.00	2967.00	5483.00	12.91	56.29	0.88	0.90
GPC 20 OR	30.87	41.69	3885.00	1382.00	27.17	33.00	0.88	0.79
GPC 40 UR	29.82	57.00	3947.00	7216.00	26.24	53.54	0.87	0.93
GPC 40 OR	58.50	38.00	5082.00	2162.00	51.54	27.00	0.87	0.71
GPC 60 UR	42.12	47.00	4226.00	6052.00	37.07	42.19	0.88	0.89
GPC 60 OR	70.87	29.00	5257.00	1692.00	63.25	24.39	0.89	0.84
Average							0.87	0.84
Standard deviation							0.007	0.074
%Mean error							12.78	14.85

Table 6.5: Analytical unconfined and confined values of simply supported ambient-cured GPC beams

Beam Designation	Confinement index	UC Ana M (kN m)	UC Ana Ø x10^{-6}	Ana M (kN m)	Ana Ø x10^{-6}	% of increase in moment (unconfined to confined)	% of increase in curvature (unconfined to co confined)
GPC 20 UR	0.017	11.94	44.06	12.91	56.29	8.00	28.00
GPC 20 OR	0.300	20.65	24.56	27.17	33.00	31.00	35.00
GPC 40 UR	0.124	23.57	42.24	26.24	53.54	11.00	27.00
GPC 40 OR	0.370	40.72	22.59	51.54	27.00	26.00	20.00
GPC 60 UR	0.230	33.05	38.12	37.07	42.19	12.00	11.00
GPC 60 OR	0.380	53.78	20.18	63.25	24.39	17.00	21.00

UC = Unconfined   Ana = Analytical

6.5 Discussion

The experimental strains in steel& concrete were also calculated at the ultimate moment. In general, for under-reinforced GPC strain in steel is the governing criteria, and similarly for over-reinforced section concrete strain is the governing criteria. A comparison was made between the predicted model analytical M–Ø and experimental M–Ø results. Furthermore, to prove the analytical results, the analytical/experimental ratio were calculated for the developed model with respect to the M_u and corresponding $Ø_u$.

Figure 6.10: Crack pattern of GPC 20 MPa

Figure 6.11: Crack pattern of GPC 40 MPa

Figure 6.12: Crack pattern of GPC 60 MPa

From the Figure 6.10 to 6.12 it is observed that the crack pattern and failure observed for GPC beams are found to be failed initially by yielding steel in tension zone along with the crushing of concrete in the compression zone. It could be observed that typical crack pattern of GPC beams during loading. The First crack prorogation is observed at 35% of ultimate load for all GPC beams and second crack propagation was observed at 50% of ultimate load. It is behaving similar to conventional concrete. As there is a continuous increase in load, the several vertical cracks were observed in flexure zone and these were extended to the edges of the beam.

6.5.1 Ultimate Moment (Mu) and corresponding Curvature (Øu):

The results presented in **Table 6.4** indicates that the ultimate moment and corresponding curvature were compared for the developed analytical model. The peak moment average mean error was predicted by the developed analytical model is also shown. It can be observed that there is an increase in curvature increased from GPC20 to GPC40 MPa, but there is a decrease in curvature from GPC40 to GPC60 MPa. This can be due to brittle behaviour of high strength concrete during loading. In the case of ultimate moment, there is significant increase in GPC40 to GPC60 MPa. There is a good correlation in both the analytical and experimental values, and in the case of ratios of moment and curvature were near to 1, it means that accurate in prediction.

From the Table 4, it can be observed that there is a mean percentage error of 12% and 14% in between experimental and analytical ultimate moment-curvature values. Hence, there is a good agreement between analytical and experimental results. From the Tables 6.5 represents that a comparison between confined and unconfined analytical results results.

6.5.2 Comparison between analytical confined and unconfined M-Ø

From the moment-curvature curves, the ultimate moment (M_u), curvature at ultimate moment ($Ø_u$) were significantly increased.

From the **Figure 6.7 to 6.9**, represents that comparison between analytical and experimental results obtained for confined and unconfined. However, presence of confinement improves moment carrying capacity of beams. It can be seen that ultimate moment and corresponding curvature of concrete is directly proportional to confinement index. In this study, a comparison between ultimate moment and curvatures of unconfined beams (GPC20 UR&OR, GPC40 UR&OR and GPC60 UR&OR) was made. In the case of GPC20 UR, for an increase in confinement index from 0 to 0.18, ultimate moment (M_u) and corresponding curvature (Ø) increased by 8% and 28% respectively. Similarly, for GPC20 OR, for an increase in confinement index from 0 to 0.3, (M_u, Ø) increased by 31% and 35% respectively. For GPC 40UR, for an increase in confinement index from 0 to 0.13, (M_u, Ø) increased by 11% and 27% respectively. Similarly, for GPC40 OR, for an increase in confinement index from 0 to 0.37, (M_u, Ø) increased by 26% and 20% respectively. For GPC 60UR, for an increase in confinement index from 0 to 0.23, (M_u, Ø) increased by 12% and 11% respectively. Similarly, for GPC60 OR, for an increase in confinement index from 0 to 0.38, ultimate moment and corresponding curvature increased by 17% and 21% respectively.

6.6 Conclusions

From the present study the following conclusions were drawn.

1. An analytical M–Ø for GPC beams cured under ambient temperature is developed by using the general stress-strain curve and which was proposed in the earlier chapter.
2. The GPC were found to be good as structural members and could be considered as competent material for replacement of OPC concrete even in reinforced members.
3. It was concluded that the analytical and experimental values of TCGPC beams compared well and appropriate model have been proposed to predict the M–Ø of GPC beams.
4. The increase in ultimate moment carrying capacity with an increase in strength of concrete is noticed. However, this decreased the ductility.
5. However, the predicted analytical value is slightly lower than that of the obtained experimental values. Hence it could be concluded that, the M-Ø relationship of the geopolymer concrete beam at ambient temperature is found to be satisfactory and it could be predicted well by adopting strain compatibility criteria.
6. From the results, it can be observed that there is a mean percentage error of 12% and 14% in between experimental and analytical ultimate moment-curvature values. Hence, there is a good agreement between analytical and experimental results.
7. In the case of GPC20 UR, for an increase in confinement index from 0 to 0.18, ultimate moment (M_u) and corresponding curvature (Ø) increased by 8% and 28% respectively. Similarly, for GPC20 OR, for an increase in confinement index from 0 to 0.3, (M_u, Ø) increased by 31% and 35% respectively.

8. For GPC 40UR, for an increase in confinement index from 0 to 0.13, (M_u, Ø) increased by 11% and 27% respectively. Similarly, for GPC40 OR, for an increase in confinement index from 0 to 0.37, (M_u, Ø) increased by 26% and 20% respectively.
9. For GPC 60UR, for an increase in confinement index from 0 to 0.23, (M_u, Ø) increased by 12% and 11% respectively. Similarly, for GPC60 OR, for an increase in confinement index from 0 to 0.38, ultimate moment and corresponding curvature increased by 17% and 21% respectively.

CHAPTER 7

CHAPTER 7
CONCLUSIONS AND SCOPE FOR FURTHER STUDY

7.1 CONCLUSIONS

Based onthree phases of the experimental and analytical investigation the following conclusions have been obtained:

7.1.1 PHASE-I

- An increase in the percentage of GGBS in binder increases the compressive strength but decreases the workability of the mix.
- The strain at peak decreases with an increase in the compressive strength of geopolymer concrete and the post peak behavior shifts from ductile to brittle failure.
- The modulus of elasticity increases with increase in the compressive strength of geopolymer concrete, and an equation is proposed for estimating the modulus of elasticity in terms of the compressive strength of the GPC. It is $E = [4.26C^2 - 111.74C + 10365]*10^{-3}$ GPa and a compressive strength range from 20 MPa to 60 MPa.

7.1.2 PHASE-II

- The confinement of geopolymer concrete increased the post peak response of GPC specimens, in terms of ductility.
- Tie confined GPC specimens, exhibited better peak stress, ductility ratio and modulus of toughness compared to unconfined GPC specimens.
- Confinement in geopolymer concrete greatly enhanced the strain at peak stress and strain at 85% of the ultimate strength in descending region.

- The ultimate strength of confined GPC can be related to the compressive strength of un-confined GPC and confinement index as $f_u = f' (-0.237x^2 + 0.9735x + 1)$
- The strain at peak stress of confined GPC can be related to the strain at peak stress of un-confined GPC and confinement index as
  $\boldsymbol{\varepsilon_u} = \boldsymbol{\varepsilon'} (-0.1505x^2 + 0.6921x + 1)$
- The strain ductility of confined GPC can be related to the un-confined GPC and confinement index as ductility factor = $-0.4728x^2 + 1.9059x + 2.5346$
- The obtained experimental results were compared with the proposed semi empirical formulae. A non-dimensionalised stress-strain equation developed in this experimental investigation can be used to predict stress-strain behaviour of TCGPC.
- The predicted model is proposed for tie-confined GPC specimens by comparing Sargin's existing model and it shows appropriateness. The theoretical stress-strain equation for TCGPC is

$$\frac{f}{fc} = \frac{(2.11)\left(\frac{\epsilon}{\epsilon_u}\right) + (0.11)\left(\frac{\epsilon}{\epsilon_u}\right)^2}{1 + (1.13)\left(\frac{\epsilon}{\epsilon_u}\right) + (0.13)\left(\frac{\epsilon}{\epsilon_u}\right)^2}$$

- The mean percentage error of stress, and strain ratios between experimental and analytical results is 12% and 5% respectively. It shows the good agreement between experimental and analytical results.
- The mean percentage error of ductility factor between experimental and analytical results is 13%.
- The current investigation is proved that GPC is an alternative and sustainable material to Ordinary Portland cement concrete. Geopolymer technology can be a possible solution for adopting it, in construction industry.

7.1.3 PHASE-III

- An analytical M–Ø for GPC beams cured under ambient temperature is developed by using the general stress-strain curve and which was proposed by the authors in line with Sargin's model for tie-confined geopolymer concrete.
- The GPC were found to be good as structural members and could be considered as competent material for replacement of OPC concrete.
- It was concluded that the analytical and experimental values of TCGPC beams compared well and appropriate model have been proposed to predict the M–Ø of GPC beams.
- The significant increase in ultimate moment carrying capacity with an increase in strength of concrete but less increase in curvature of GPC40 MPa to GPC60 MPa.
- However, the predicted analytical value is only slightly lower than that of the obtained experimental values. Hence it could be concluded that, the M-Ø relationship of the geopolymer concrete beam at ambient temperature is found to be satisfactory and it could be predicted well by adopting strain compatibility criteria.

1.2 SPECIFIC CONTRIBUTION OF THE RESEARCH

A study on the concept of developing GPC using combination of fly ash and GGBS from industrial waste products. Further, "Studies on Behaviour of Tie-confined fly ash &GGBS based geopolymer concrete Under Axial Compression" (TCGPC) was established. A systematic analytical procedure for developing the moment – curvature relationship for TCGPC has been proposed. The developed model validated by conducting studies on simply supported reinforced concrete beams. This behaviour will be helpful for design practices.

1.3 SCOPE FOR FURTHER WORK

Further study may be attempted in the following focuses:

1. Behaviour of Reinforced GPC beams provided with Tie & Fibre Confinement subjected to different loading dynamic and repeated loading.
2. Effect of Tie &Fibre Confinement studies subjected to uniaxial and biaxial bending of reinforced GPC columns.
3. Shear and Torsion behaviour of Fibre and Tie confined GPC using Recycled Aggregate.

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Appendix:

1. Confinement index
2. Alkaline solution preparation
3. Analytical M - Ø procedure

1. Calculation of confinement index:

Ci = $(P_b - P_{bb})(\frac{f_y}{f_c})\sqrt{(\frac{b}{s})}$ ----- Eq. (1.1)

Where,

P_b **=** $\frac{\pi(d^2)a}{a^2 s}$ **=** ratio of volume of transverse reinforcement to the volume of concrete

P_{bb} = $\frac{\pi(d^2)a}{1.5a^2 b}$ ratio of the volume of transverse reinforcement to the volume of concrete which corresponds to a limiting pitch (=1.5b) yield stress in lateral ties

S = spacing between lateral ties = 25, 50, 75 and 100mm.

b and d = breadth and depth of prism = 100mm and 200mm

f_y= yield stress in lateral ties = 525

f_c = compressive strength of concrete

2. Alkaline solution preparation

The sodium hydroxide (NaOH) solution was prepared by dissolving the sodium hydroxide pellets in distilled water. The mass of NaOH solids in a solution varied depending on the concentration of the solution expressed in terms of molarity (M). In this project the solution used is of 8 molarity. Sodium hydroxide pellets and sodium silicate solution is shown in Fig. Molar concentration or molarities is most commonly in units of moles of solute per litre of solution. For use in broader applications, it is defined as amount of solute per unit volume of solution.

3. **Procedure for obtaining analytical moment curvature relationship**

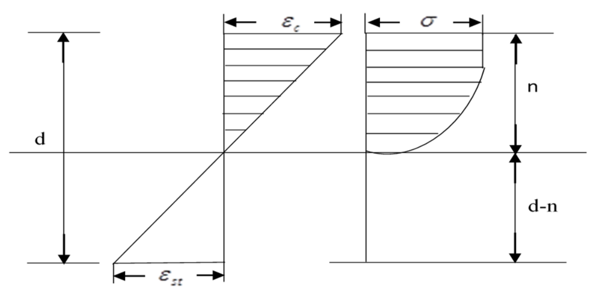

Figure: Stress-Strain distribution of a member in flexure

The following steps have been considered for calculating the moment-curvature of geopolymer concrete.

Step1: Assume ε_c = strain in compression (extreme fibre)

Step 2: The stress diagram was divided into number of strips to obtain the total compressive stress, which is calculated by summation of stresses from each strip.

Step 3: Compressive stress $f = f_c \times \dfrac{A(\frac{\varepsilon}{\varepsilon_c}) + (D-1)(\frac{\varepsilon}{\varepsilon_c})^2}{1 + (A-2)(\frac{\varepsilon}{\varepsilon_c}) + D(\frac{\varepsilon}{\varepsilon_c})^2}$

Step 4: Compression force, compression moment is calculated.

Step 5: Sum of all compression moments from each strip gives the total moment in compression (M_c).

Step 6: By using similar triangle, ε_{st} was calculated

$$\varepsilon_{st} = \frac{d-n}{n}\varepsilon_c$$

Step 7: Determining the stress in steel is depending on the strain in mild steel

$f_s = f_y$ for $\varepsilon_{st} > \frac{f_y}{2\times10^5} > \frac{f_y}{E}$

$f_s = \varepsilon_{st} \times 2\times10^5$ for $\varepsilon_{st} <= \frac{f_y}{2\times10^5} > \frac{f_y}{E}$

Step 8: calculation of force in steel $P_s = f_s \times A_{st}$

Step 9: Moment in steel $M_t = P_s \times (d-n)$

Step 10: Total moment M_{Total} = compression moment (M_c) + Tension moment (M_t)

Curvature (Ø) = $\frac{\varepsilon_{cc}}{n}$ where, ε_{cc} = maximum strain in concrete at failure.

Step 11: Check for neutral axis for condition TC – TT = 0. For an error of 1%.

Step 12: Plot M vs. Ø.

Journals:

- Venu, M., and Gunneswara Rao, T.D., **"Tie-confinement aspects of fly ash-GGBS based geopolymer concrete short columns",** Construction and Building Materials (ELSEVIER Publication), Vol. 151, pp. 28-35, October 2017.
- Venu, M., and Gunneswara Rao, T.D., **"A Study on Stress-Strain behaviour of fly ash-GGBS based Geopolymer concrete",** Slovak journal of civil Engineering (DE GRUYTER publication), Vol. 26(2), pp. 9-13, 2018, DOI: 10.2478/sjce-2018-0008.
- Venu, M., and Gunneswara Rao, T.D., "**The prediction of Moment-Curvature relationship of Tie-Confined fly ash-GGBS based geopolymer concrete",** Engineering structures, (under review).

Conference:

- Venu, M., and Gunneswara Rao, T.D., "**An Experimental Investigation on Stress-Strain behaviour of fly ash-GGBS based Geopolymer concrete",** International Conference on Trends and Recent Advances in Civil Engineering was held at AMITY university Noida in 2016.