Proc. 1st International Conference on Structural Engineering Research (iCSER 2017)
20-22 Nov 2017, Sydney, Australia
ISBN: 978-0-6480147-6-8

Experimental Study on the Behaviour of Headed Stud Shear Connectors for Composite Steel-Concrete Beams Incorporating Geopolymer Concrete

Youtam Mamo[1], Ee Loon Tan[2], Zhu Pan[3], Olivia Mirza[2] and Balbir Singh[4]

[1]Undergraduate Student, Western Sydney University
[2]Lecturer, Western Sydney University
[3]Post Doctorate Researcher, Western Sydney University
[4]PHD Student, Western Sydney University
Corresponding author's E-mail: balbir.singh@westernsydney.edu.au

Abstract
Recent academic research has focused on the need to develop an environmentally sustainable substitute for conventional Ordinary Portland Cement (OPC) based concrete. The need to develop such substitute stems from the global effort to reduce the consumption of natural resources and minimize carbon dioxide emissions. In this regard, the utilisation of Fly Ash (FA) based Geopolymer Concrete (GPC) within global construction applications can significantly reduce pollution and landfill issues associated with cement production and FA burial, respectively. However, essential additives such as Granulated Blast Furnace Slag (GBFS) and Superplasticizers (SPs) are required to achieve effective ambient temperature curing. Without effective curing within ambient temperature conditions, GPC behaves poorly with respect to important factors such as, strength development and workability Bakharev (2005). Consequently, this paper presents and discusses the methodology and results for both the fabrication and testing stages of eight push test specimens which incorporate GPC. A total of four specimens consist of standard Solid Slab (SS1, SS2, SS3, SS4) push tests and the remaining four specimens (B1, B2, B3, B4) consist of identical Solid Slab specimen dimensions with the additional implementation of Bondek (Profiled-Steel-Sheeting). Specimen SS1 outperformed all other Solid Slab (SS2, SS3) specimens which incorporated GPC in terms of maximum shear resistance capacity (MSRC) by achieving a value of 927kN, additionally, Bondek specimen B2 achieved a MSRC of 393.04kN, thus proving that outdoor temperature curing is superior than indoor temperature curing conditions and that the implementation of up to 30% recycled coarse aggregate (RCA) does not negatively impact the performance or durability of concrete with respect to 100% Natural Coarse Aggregate (NCA), respectively. Furthermore, the comparison of specimens SS1 and B2 to the control OPC based specimens, SS4 and B4 proves that GPC is capable of effectively replicating characteristics such as strength and durability of conventional OPC based concrete.

***Keywords**:* Headed stud shear connector, Geopolymer, Fly ash, Slag, Alkaline solution, Push test.

1. INTRODUCTION

The demand for concrete within the construction industry is expected to have a 200% increase by the year 2050. Currently, 1 ton of OPC requires the consumption of 2.5 tons worth of raw materials and produces one ton worth of carbon dioxide emissions Xie & Ozbakkaloglu (2015). Due to the unsustainability of cement production, academic attention aims to substitute OPC based concrete with FA based GPC. Fly Ash is an increasingly abundant by-product produced when coal is burned within power pants. According to Hardjito and Wallah et al. (2004) the annual global production of fly ash exceeds 390 million tons, however less than 15% is utilised. Research conducted by Albitar and Visintin et al. (2015) affirms the benefits of FA based GPC, as the authors observed strong binding properties and high compressive strength in addition to minimal dry shrinkage, low creep and good resistance to sulphate attack. Hence, due to the abundance and 'cement-like' characteristics of GPC, research has intensified with the aim of finding an appropriate GPC mix design suitable for worldwide construction applications.

Thus, the aim of this experimental research is to effectively investigate the behaviour of headed stud shear connectors incorporating Geopolymer Concrete (GPC) within standard size composite steel-concrete push test specimens, as recommended by Eurocode 2005. The push test specimens within this experimental research represent beams with a degree of full shear connection. Ultimately, this paper will provide a comparison between the performance of GPC and OPC based concrete, whilst also comparing shear strength and shear stud behaviour within both Bondek and conventional Solid Slab specimens. Additional research objectives include the investigation of the superior curing condition i.e. indoor versus outdoor temperature curing and the influence of RCA on concrete compressive strength and durability within GPC in comparison to NCA.

2. EXPERIMENTAL PROGRAM

2.1. Materials

The type of FA used within this experimental research consists of low calcium Class-F FA. Since, an objective of this research is to develop a GPC mix design which possesses appropriate workability and strength development when cured at ambient temperature, the implementation of Grounded Blasted Furnace Slag (GBFS) was utilised as an additive for fly ash based GPC. GBFS is attributed with the ability to cure GPC within ambient temperature conditions. The GBFS used within this experimental research consists of 20kg paper packages produced by the Australian Builders company. The chemical compositions of FA, GBFS and Cement are presented in Table 1, where it can be observed that FA and GBFS complement each other to effectively replicate the composition of cement.

Table 1. Chemical composition of dry components.

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO	K_2O	SO_3	LOI
Fly Ash	52.2	24.0	13.7	3.18	0.65	1.32	0.78	0.18	1.08
Slag	32.6	13.4	0.35	43.0	0.20	5.5	0.25	3.41	0.14
Cement	18.2	4.9	2.6	60.7	0.2	1.0	0.4	2.2	3.0

The alkaline activator solution (AAS) used to activate the binder content within the GPC mix designs is a combination of Sodium Hydroxide (NaOH) and Sodium Silicate solution (Na_2SiO_3). The pellets consist of 99% purity and have a specific gravity of 2.13, and are white in appearance. A D-Grade Sodium Silicate solution was used which consisted of a Silicon Dioxide ($SiO_{2)}$ to Sodium Oxide (Na_2O) ratio of 2.0. The solution was comprised of 55.9% of water and 44.1% of Sodium Silicate, whereby the latter component consisted of 14.7% of Na_2O and 29.4% of SiO_2. Overall, the ratio of Sodium Hydroxide solution to Sodium Silicate solution by mass is 2.5 and the concentration/molarity (M) of the Sodium Hydroxide used to prepare the GPC was 10M.

The fine aggregate used is Nepean River Sand whereas the natural coarse aggregate consisted of 20mm Basalt rock known as Blue Metal. The binder to fine aggregate ratio within the GPC mix designs was 2:1. The type of Superplasticiser brand utilised was SIKA Visco-Crete PC-HRF-2 Superplasticiser which is commercially available and designed for OPC based concrete applications. However, this experimental research utilised this brand of SP to improve the workability of GPC.

2.2. Mixture Proportions

A 90:10 (FA:GBFS) binder ratio was utilised for all the GPC mix designs. The total aggregate content consisted of 77% of the total volume of concrete, whereby the coarse aggregate was 63% and fine aggregate was 37%, however, within concrete mix design GPC2, 30% of the NCA was substituted for RCA. The amount of liquid in the form of components such as AAS, SPs and extra water was kept constant for all three mix designs. The OPC based concrete mix design was obtained from British Standards. Therefore, the recommended water to cement ratio was adopted as 0.55 and the total aggregate content was 76% of total volume of the concrete. The mixture proportions for both the GPC and OPC based concrete mix designs are provided in Table 2.

Table 2. Mixture proportion.

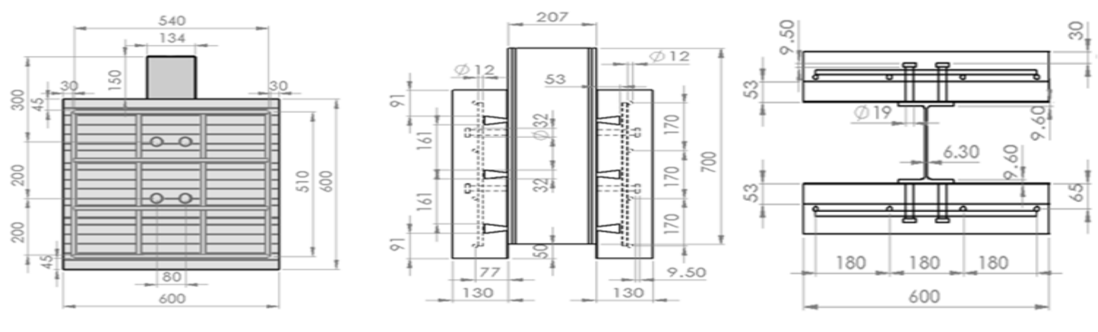
Mix (No.)	Mix Proportion (kg)									Push Test Specimen Type		Curing Conditions
	Cement	Fly Ash	Slag	Sand	NCA	RCA	Alkaline Solution (10M)	Extra Water	SP	Solid Slab	Bondek	
GPC1	-				312	-				SS1	B1	Outdoor Temperature Curing
GPC2	-	92	10	184	218	94	45.91	3	2	SS2	B2	30% RCA
GPC3	-				312	-				SS3	B3	Indoor Temperature Curing
OPC	85	-	-	188	248	-	-	47	-	SS4	B4	Control Mix

2.3. Mixing

The preparation of the GPC involved the mixing of all dry components together prior to the addition of any liquids. Therefore, dry materials were pre-mixed for approximately 2 minutes to ensure a uniform distribution of particles within the finished concrete. The liquid components are then added into the concrete mixer using a 50:50 method. This method was adopted to further ensure that all dry and liquid components are thoroughly mixed together. Hence, 50% of the AAS was added to the concrete mixer and allowed to mix for 2 minutes, followed by 50% of SP for an additional 2 minutes. Afterwards, the remaining 50% of the AAS and SP was poured into the mixer and mixed for 2 minutes. Extra water was added at last and was mixed for approximately 5 additional minutes. The completion of the mixing procedure allows for the finished concrete to be poured within the push test specimen formwork and various other sample testing moulds (i.e. compressive strength cylinders etc.).

2.4. Test Specimen

A total of 8 composite push test specimens were fabricated within this experimental study. The dimensions of the slab component for each push test specimen consist of 600x600x130mm. The steel beam component consists of a 700mm long 200UB29.8 section fabricated by stitch welding the flanges of two symmetrical T-sections together. Figures 1 illustrates the detailed dimensions of the Bondek push test specimens. The dimensions for the Solid Slab specimens are identical to those shown in Figure 1, withholding the presence of Bondek sheeting. These dimensions are slightly modified versions of the standard push test specimen dimensions outlined in Eurocode 2005.



(a) Front View (b) Side View (c) Top View

Figure 1. Detailed specimen dimensions.

2.5. Curing Conditions

Two pairs of push test specimens were cured within two different curing conditions to determine the effect of ambient temperature fluctuation. This was achieved by curing one pair of push test specimens (SS1 and B1) within an open environment and curing specimens SS3 and B3 within a closed environment. Specimens corresponding to design mix GPC2 (SS2 and B2) were also kept within the open environment curing condition, along with specimens SS4 and B4 which correspond to the control OPC design mix. The curing conditions used to cure each push test specimens and their corresponding concrete cylinder samples were designed to replicate both closed and open air room conditions found when typical OPC based concrete is cured within on-site building application. Hence, no water- bath curing was implemented within this study due to the unwanted chemical reaction which would occur in regards to specimen's incorporating GPC.

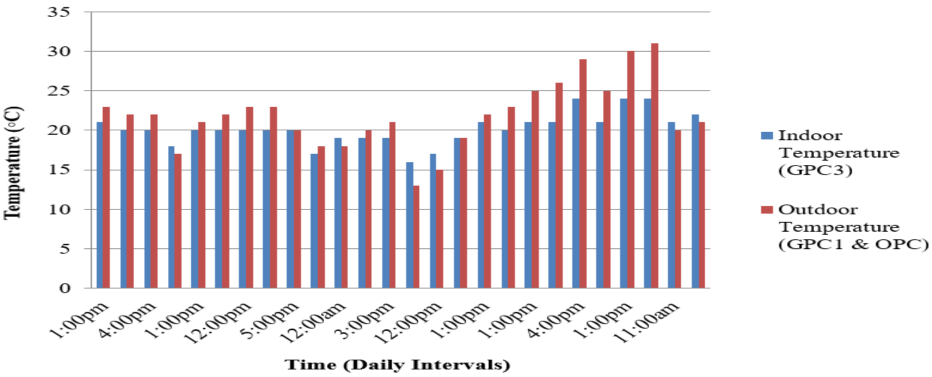


Figure 2. Temperature fluctuation graph.

2.6. Testing of Specimens

2.6.1. Overview of Test Procedure

The push test specimen design and arrangement utilised within this experimental study represents the behaviour caused by direct shear loading within full scale beam applications. The support condition consists of a fixed-roller support for the north and south slab, respectively. The specimens are placed onto a rigid steel plate which is supported by laboratory grade hard-floor concrete. Direct shear loading is then applied onto the steel section component of the specimen using an Instron Hydraulic Oscillator (IHO). The IHO has a maximum capacity of 1000kN.

2.6.2. Test Samples

The values for both the Compressive Strength and Young's Modulus of Elasticity of each concrete mix design were obtained by pouring small samples from each concrete mix into cylindrical moulds. These moulds are of 100 x200mm in dimension. The internal surface area of each mould is lubricated with engine oil prior to pouring of concrete to ensure swift demoulding at various stages within the curing period (i.e. 7, 14, 21 days etc.). An IHO was used to determine the compressive strength of the concrete cylinders, whereby each cylinder would be subjected to shear load at a constant rate of 20 MPa/min. The compressive strength test was performed in accordance with Australian Standard 1012.8.1:2014. Additional beam moulds of 100mm width and 400mm length were also poured to determine the concrete's Modulus of Rupture (Tensile Strength) values for each concrete mix design.

3. RESULT AND DISCUSSION

3.1. Compressive Strength

The compressive strength values for each concrete mix design were obtained by testing three individual samples at each curing stage as shown in Figure 3. The values achieved by the three GPC mix designs show slight variation in both the initial and final compressive strength recordings, however, samples attributed to GPC3 are slightly lower than GPC1 and GPC2. This can be attributed to the lack in strength development caused by indoor temperature curing which involves a lower maximum temperature value than outdoor curing.

The OPC based concrete mix possesses a significantly greater early strength development characteristic in comparison to all other GPC mix designs. However, the difference between the OPC based mix and most superior GPC mix at the final 28-Day strength curing stage is approximately 6MPa. This shows that the strength development rate for GPC is significantly more constant than conventional OPC based concrete and that the long term compressive strength values are similar.

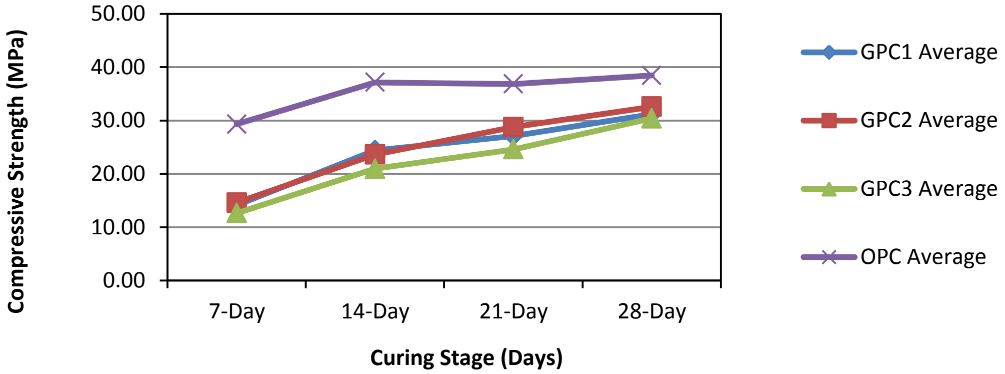


Figure 3. Average compressive strength values.

3.2. Young's Modulus of Elasticity

The Young's Modulus of Elasticity (***E***) values obtained during this experimental research reveal that GPC is less stiff and therefore more flexible than the conventional OPC based concrete mix design. A difference of approximately 15GPa exists between the OPC mix and the remaining three GPC mix designs, as shown in Figure 4. Based on this, the push test specimens utilising the GPC mix designs are expected to fail in a manner whereby signs of failure such as cracking and deformation appear gradually on the specimens. Whereas, the specimens utilising the OPC based concrete mix are expected to fail in a more sudden manner, whereby large cracks and brittle concrete failure occurs at a late stage within the push test loading procedure.

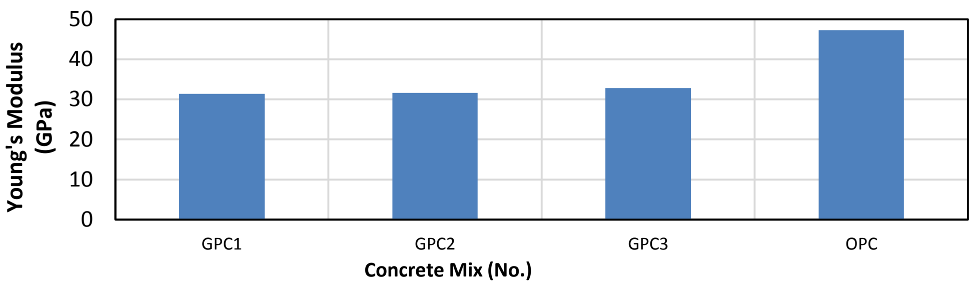


Figure 4. Young's modulus of elasticity.

3.3. Concrete Tensile Strength

The strong binding characteristic of GPC is validated based on the results obtained within this experimental research, as shown in Figure 5. All three GPC mix designs achieved greater tensile strength in comparison to the OPC based mix, however design mix GPC1 outperformed all other GPC mix designs. This can be attributed but not limited to the materials used and the curing conditions of GPC1 in respect to GPC2 and GPC3 respectively.

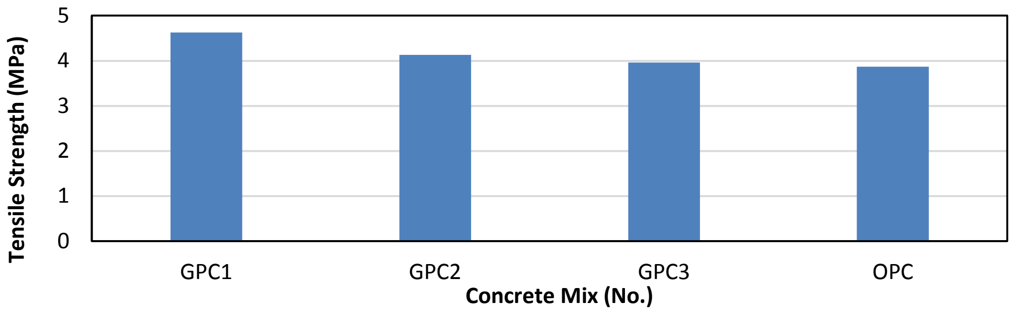


Figure 5. Concrete tensile strength.

Since GPC1 was subjected to outdoor temperature curing, the greater maximum temperature value of $31°C$ in comparison to $24°C$ allows for an improved geopolymerisation reaction to occur within GPC1 than GPC3 which causes greater binding between concrete particles. Furthermore, since GPC2 incorporated the use of 30% RCA, a lower concrete tensile strength can be attributed to the already depleted mineral structure and composition of particles within the RCA in comparison the mineral rich and uniform structure of particles within the NCA used within GPC1.

3.3.1. Push Test Results and Discussion

The overall MSRC achieved by each push test specimen represents the respective tensile, compressive and stiffness values obtained by each concrete mix type. Additionally, the dominant failure mode for both Solid Slab and Bondek type specimens is constant amongst all three GPC mix designs. Hence, Table 3 shows that the Solid Slab specimens all failed from concrete splitting type failure and the Bondek specimens failed from conical type failure, irrespective of the different concrete mix designs. However, the varying concrete mix designs effectively influenced the magnitude of shear loading required to cause specimen failure. Therefore, the durability and superior strength development of GPC1 is reflected by the MSRC achieved by specimen SS1 in comparison to specimen SS4, which possessed significantly greater compressive strength and stiffness values.

A comparison of the Bondek specimens shows that specimen B3 achieved the lowest MSRC of 329.84kN amongst all three Bondek specimens. Therefore, it can be deduced that specimen B1 outperformed specimen B3 in the same manner that specimen SS1 outperformed specimen SS3, which is based on the influences of outdoor and indoor temperature curing conditions. Consequently, specimen B2 has also outperformed specimen B3 based on the varying temperature conditions during curing. Furthermore, the superior performance of specimen B2 can be attributed to the fact that specimen B1 was subjected to an expected 40% failure load of 256kN. This may have caused the specimen to experience significant over-fatigue during cyclic loading, thus causing premature failure to weaken the specimen before the load-to-failure phase of testing commenced.

Therefore, the comparison of the MSRC values obtained by specimen B2, the optimum GPC specimen which implemented Bondek sheeting, and specimen B4, the control OPC based specimen, reveals that GPC can match the performance of conventional OPC based concrete withstanding the reduction in durability caused by the implementation of both 30% recycled aggregate and Bondek sheeting.

A performance pattern can be easily distinguished in regards to the significantly reduced MSRC of Bondek specimens in regards to Solid Slab specimens. This can be attributed to the presence of embossments, which ultimately reduce the amount of local concrete surrounding the shear connectors. Thus, causing the Bondek specimens to become increasingly prone to conical type concrete failure. Consequently, conical type concrete failure results in the significant separation of the concrete component from the steel section component which then reduces the amount of interaction between the concrete and steel components within the composite member and causes ineffectiveness in regards to shear load resistance.

Table 3. Push test results summary.

Specimen (*No.*)	Maximum Shear Resistance (*kN*)	Governing Failure Mode
SS1	927.56	Concrete Splitting Failure
B1	355.75	Conical Type Failure
SS2	705.44	Combination of Splitting and Cracking Failure
B2	393.04	Conical Type Failure
SS3	730.42	Concrete Splitting Failure
B3	329.84	Combination of Conical and Splitting Failure
SS4	947.46	Concrete Splitting Failure
B4	458.32	Conical Type Failure

Figure 6 (a) depicts an example of concrete splitting failure caused by significant outward and downward movement of the South (Roller-Support) slab. Whereas, Figure 6 (b) depicts an example of conical failure caused by the prevention of effective interaction between the local concrete surrounding the headed stud shear connectors and remaining volume of concrete. This reduction in effective interaction is attributed to the presence of embossments within the profiled steel sheeting (Bondek) which reduce the amount of concrete surrounding the shank of the headed stud shear connectors.

(a) Specimen SS3 (b) Specimen B2

Figure 6. Governing failure mode examples.

The Headed Stud Shear Connectors (HSSCs) within all the tested push test specimens within this experimental research experienced slight bending deformation. Additionally, none of the concrete compressive strengths within this experimental research was high enough to cause shear stud failure. Therefore, the results obtained for all the push test specimens within this research can be deemed favourable since early failure signs such as concrete cracking occurred for all specimens, rather than sudden failure without warning.

4. CONCLUSION

- Solid Slab push test specimens significantly outperform specimens incorporating Bondek sheeting due to the reduction in the amount of concrete surrounding each pair of shear studs caused by the presence of Bondek flanges. The Solid Slab specimens all failed due to concrete splitting type failure and Bondek specimens all failed from conical type separation of the local concrete surrounding each pair of shear studs.

- In regards to the implementation of up to 30% of Recycled Aggregate, a significant reduction in concrete durability occurs. Thus explain the lower MSRC achieved by specimen SS2 in comparison to specimen SS1. Therefore, GPC1 can be classified as the optimum GPC mix design.

- The expected calculations in regards to the shear resistance capacity of HSSCs installed within Solid Slab specimens in accordance with Eurocode 2005 are too conservative. Since the average shear resistance capacity of all three Solid Slab specimens equates to 98.5kN per stud in comparison to the calculated value of 74.4kN.

- The expected calculations in regards to the shear resistance capacity of HSSCs installed within Bondek specimens in accordance with Eurocode 2005 are extremely accurate. Since the average shear resistance capacity of all three Bondek specimens equates to 44.94kN per stud in comparison to the calculated value of 52.08kN.

- The high-performance expectation brought about by the results obtained by specimen SS1 (115kN per stud) resulted in overloading to cause premature failure in regards to specimen B1. Therefore, the accuracy of expected results calculated using Eurocode 2004 is again reinforced and the inaccuracy of expected calculations using AS2327.1 in regards to Bondek specimens is again reinforced.

5. REFERENCE

Albitar, M, Visintin, P, Mohamed Ali, M & Drechsler, M (2015). Assessing behaviour of fresh and hardened geopolymer concrete mixed with class-F fly as', KSCE Journal of Civil Engineering, vol. 19, no. 5, pp. 1445-55.

Bakharev, T (2005). Geopolymeric materials prepared using Class F fly ash and elevated temperature curing, Cement and Concrete Research, vol. 35, no. 6, p. 1224.

Hardjito, D, Wallah, SE, Sumajouw, DM & Rangan, BV (2004). On the development of fly ash-based geopolymer concrete, ACI Materials Journal-American Concrete Institute, vol. 101, no. 6, pp. 467-72.

Xie, T and Ozbakkaloglu, T (2015). Behavior of low-calcium fly and bottom ash-based geopolymer concrete cured at ambient temperature, Ceramics International, vol. 41, no. 4, pp. 5945-58.