ASSESSMNET OF PUNCHING SHEAR OF FLAT SLABS USING GROUND SLAG

Journal:	*ACI Structural and Materials Journals*
Manuscript ID	M-2017-232.R2
Journal Name:	ACI Structural Journal
Date Submitted by the Author:	02-Aug-2017
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Keywords:	Concrete, punching shear, Flat Slab, GGBFS, , Codes

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ABSTRACT

Supplementary Cementitious Material (SCM) in concrete is widely used in concrete including Ground Granulated Blast Furnace Slag (GGBF) to offset the environmental impact of cement manufacturing. However the structural behavior of such cements blended with GGBF and used in concrete, require further research. Flat slab is widely constructed in modern buildings to achieve maximum space utilization. The design of flat slab system for punching shear in various Codes is based on empirical and simplified equations, as the actual behavior of punching shear is still not well understood. In this research four flat slabs were tested such that one flat slab was cast from normal concrete with no BBGF and the remaining 3 slabs were cast with 30%, 40% and 50% replacement of cement by GGBFS. Experimental punching shear results were compared with the nominal punching shear capacities proposed by BS 8110, BS EN1992-1-1/ EC2 and ACI 318.

Keywords: *Concrete, flat slab, punching shear, GGBS, Codes*

INTRODUCTION

Extensive emissions of CO_2, are one of the major causes of Global Warming (GW) and Climate Change (CC). Cement manufacturing processes generate large amounts of CO_2. The world cement production has reached at the level of 4.3 billion tons per annum, during 2014 and consequently an equal amount of CO_2 is also generated. The world cement industry is presently responsible for about 8% of the total CO_2, production [1]. Research is underway to explore Supplementary Cementitious Material (*SCM*), such as Fly Ash, Silica Fumes, Rice

Husk Ash, Ground Granulated Blast furnace Slag (GGBF), Fibers and natural pozzolans, to reduce the consumption of cement in concrete. Zi Qiao jin *et al* [2] , Wang and Tian Yao Yan [3] have shown the partial replacement of cement by SCM has reduced the cement consumption to some extent, yet there are some inherent problems associated with their uses. The researchers have, however developed new techniques to overcome such shortcomings in the use of SCM.

Ground Granulated Blast Furnace Slag (GGBS) has been used as partial replacement to cement in many researches and in various forms, to develop high strength and High Performance Concrete (HPC). Alkali Silicate Activated Slag (ASAS), cements at higher temperatures were also used [4-8]. The concepts of sustainable concrete, green buildings and green material are more frequently appearing in the research literature. The US Green Building Council (USGBC), Leadership in Energy and Environmental Design (LEEDS), Building Research Establishment's Environmental Assessment Methods (BREEAM), Green Star, German Green Building Council (DGNB), MINERGIE Building Standards, High Quality Environment (HQE), EU Green Building Programme and Comprehensive Assessment System for Built Environment Efficiency (CASBEE), are some of the major assessment systems and related organization, promoting sustainable use of building material around the world [9]. In Flat slab systems, the slabs are placed directly over the columns to increase the height and space of the floor and reduce the cost of concrete [10]. But the area of the slab around the column is often subjected to highly complex stresses, which allow little redistribution of stresses. This results in decrease of the load carrying capacity of the slab and the punching shear failure can be often abrupt and sudden giving very little warning, particularly in case of high strength concrete. The design of flat slabs is often governed by the punching shear [11]. This brittle failure of flat slabs is avoided by employing various techniques such as, increasing the area of the column capital at the contact point, strengthening of flexural reinforcement or providing shear reinforcement [12]. In practice, the design for punching is based on empirical equation adopted by various Building Codes. The variety of design equations and types of shear reinforcement used in flat slabs further increases the uncertainty about the behavior of punching shear [13]. The thickness of flat slab is governed by the serviceability conditions and ultimate limit state [14]. With the increase in the compressive strength of concrete, incorporating blended cement using Fly Ash, Silica Fume, Slags, and the resultant high strength concrete is expected to be more brittle and hence the punching shear failure for flat slabs can be more sudden and dangerous. Investigation of punching shear of concrete produced with blended cement is considered an important area of research [15]. The strength of concrete and punching shear resistance of RC flats slabs cast with blended cements can be increased with the use various admixtures. The chemical and physical composition of such admixtures, their dosage, age and mix design of concrete can have varying effects on the properties of RC, both in fresh and hardened forms [16-18]. Hanai and Holanda [19], reported that the punching behavior of flat slabs and beams made from Steel Fiber Reinforced Concrete (SFRC) is analogous. The use of GGBS in structural concrete has been used by many researchers. Tan [20], reported no detrimental effects on the strength of concrete, with of 50% replacement of cement by GGBS. The heat of hydration of cement blended with GGBS is normally lower than ordinary cement, and as a result, GGBS has been recommended for use in repairs of cracks in slabs and beams [21]. The high concentrations of GGBS in concrete have retardation effect on the strength of concrete and an optimum level of GGBS is always identified before partial replacement of cement by GGBS [22]. The research on punching shear of High Performance Concrete (HPC) slabs has revealed that due to brittle failure of High Strength Concrete, as well as the sudden failure of the punching shear, the exiting provisions of the Codes are less conservative for HSC slabs [23]. Very little research work is available on analysis of punching shear of RC slabs blended with GGBS. The punching shear of RC flat slab is determined with the help of empirical equations proposed by various Codes as discussed below:

Punching shear capacity according to BS EN 1992-1: 2004. Eurocode 2(EC2) [24]

According to BS EN 1992-1 (EC2), the following three checks are done for assessing punching shear resistance.

i. At the column head or the perimeter of the loaded area the maximum shear stress should not be exceeded. $V_{ED} \leq V_{Rd\,max}$

ii. Punching shear reinforcement is not necessary if $V_{ED} \leq VRd,c$

In case, V_{Ed} exceeds the value $V_{Rd,c}$ for the control section considered, punching shear reinforcement should be provided. Punching shear capacity of a flat slab without shear reinforcement at the basic control perimeter is given by the expression below in EC2.

$$V_{Rdc} = C_{Rdc} k (100 \rho l f_{ck})^{1/3} ud / 1000 \quad (1)$$

Where recommended value of C_{Rdc} is 0.18 and k is given as:

$$k = 1 + (200/d)^{0.5} \leq 2 \quad (2)$$

d in mm (shape factor), u is the first perimeter of punching shear at a distance of "2d" from the face of the column.

$\rho l = (\rho l_y . \rho l_z)^{0.5}$ For equal steel in both direction, this should be the same as ρst = 0.82%).

ρl_y and ρl_z relate to the bonded tension reinforcement in each direction. These should be calculated as a mean value, if the steel is not uniformly provided over a slab width of *"3d"* from each face of the column plus the column dimension (b), i.e. *(b + 6d)* for a square column.

$$V_{Ed} = \beta V_{Ed} / u_i d \quad (3)$$

"u_i" is the length of control perimeter considered.

"V_{Ed}" is the applied shear force

The value of maximum shear resistance $V_{Rd,max}$ is calculated by following equation:

$$V_{Rd,max}\ 0.2(1 - f_{ck}/250)\ f_{ck} \quad (4)$$

Punching Shear Capacity according to BS8110 [25]

The ultimate punching shear capacity of slab without shear reinforcement and removing partial safety factor $\gamma = 1.25$, is given in the equation below:

$$V_{cu} = 0.27(100\rho_{st} f_{cu})0.33(400/d)0.25(u_d/1000) \quad (5)$$

Where $(400/d) \geq 1$ (shape factor), $u = 4 \times 3d + u_o$

In the calculation of punching shear capacity of slabs, the limit of 40N/mm^2 for f_{cu} is ignored

***Punching Shear Capacity according to ACI-318*-2014** [26]

According to ACI 318, the ultimate shear strength of slabs without pre stress is given by the following equation. $V_{uo} = V_n\, ud$ (6)

Where, u is the length of the critical perimeter taken at a distance of $d/2$ from the face of the loaded area,. d is the effective depth in mm, V_n is the nominal punching shear strength in MPa and shall be the smallest of following values;

$$V_n = \phi(1 + 2/\beta_c)\sqrt{f_c}/6 \quad or \quad V_n = \phi(\alpha_s u + 2)/12 \quad (7)$$

$$V_n = \varphi\ (1+2/\beta_c)\ \sqrt{f_c}/6 \quad (8)$$

or $V_n = \phi(\alpha_s d/u + 2)\sqrt{f_c}/12$ (9)

$$V_n = \varphi\ \sqrt{f_c}/3 \quad (10)$$

φ is the partial safety or capacity reduction factor and its value is *0.75* but is ignored for the calculation of Punching shear resistance in this exercise. Where α_s, is 40 for interior column, 30 for edge and 20 for corner column. β_c is the ratio of longest column dimension to the shorter column and should be equal to or greater than 2. f_c' is the concrete cylinder crushing strength at 28 days.

All the three Codes have used different parameters and partial safety factors for the calculation of punching shear resistance, which affects the final results. The partial safety factors of 1.5, 1/1.25 and 0.75 are used by BS-EN 1992-1-1/EC2, BS8110 and ACI318, respectively for the calculation of punching shear strength, which shows the variation about the Code recommendations as well.

Model Code MC2010: [27]

The provision of Model Code MC2010 for punching shear are based on the Critical Shear Crack Theory (CSCT), which has four levels of designs of which Levels I to III are intended for design and Level IV for assessment. Level III is recommended for slabs with irregular geometry. For level II, the slab rotation is calculated as:

$$\psi = 1.5\frac{r_s f_{yd}}{dE_s}(\frac{m_{Ed}}{m_{Rd}})^{1.5} \tag{11}$$

- Where r_s denotes the position where the radial bending moment is zero with respect to the column axis,
- m_{Ed} is the average bending moment per unit width in the support strip, which is assumed to be of width $1.5rs$ where $rs = 0.22L$,
- and m_{Rd} is the design average flexural strength per unit width of the support strip. For concentrically loaded inner columns, $mEd = V_d/8$ for Level II.

The punching resistance is calculated as $VRd = VRd,c + VRd,s$ where VRd,c is given as:

$$V_{Rd,c} = k_\psi \frac{\sqrt{f_{ck}}}{\gamma_c} u d_v \tag{12}$$

in which f_{ck} is in MPa (1MPa=145 psi) and dv is the shear resisting effective depth which is taken as d at u in The parameter k_ψ depends on the rotations of the slab around the support region and is calculated as:

$$k_\psi = \frac{1}{1.5 + 0.9 k_{dg} \psi d} \leq 0.6$$

$$k_{dg} = \frac{32}{16 + d_g} \geq 0.75 \quad (12)$$

Where d_g is the maximum aggregates sizes

The shear resistance provided by transverse reinforcement is calculated as:

$$V_{Rds} = \Sigma_{d_v} A_{sw} k_e \sigma_{sw} \quad (13)$$

$$\sigma_{sw} = \frac{E_s \psi}{6}(1 + \frac{f_b}{\gamma_c f_{ywd}} \frac{d}{d_b}) \leq f_{ywd} \quad (14)$$

On the basis of analytical comparison of the punching shear failure data of earlier researchers, Soares and Vullum [28], has reported that BS 8110 and EC-02, based on empirical design methods seem better suited for normal design, whereas MC2010 is useful for assessment purpose mainly.

In this research, four full scale flat slabs, one cast from control mix with no fly ash and three specimen of flat slab cast from concrete with 10%, 20% and 30% replacement of cement by fly ash were tested. The result of punching shear capacity was compared with the values determined by equations proposed by EC2, BS8110 and ACI-318.

RESEARCH SIGNIFICANCE

The punching shear is still considered a complex phenomenon, by most of the Codes. With the increase in compressive strength of concrete due to use SCM, the punching shear failure is more brittle and behaves differently than the normal concrete without SCM [29]

In this research GGBS, has been used as partial replacement of cement and the punching shear capacity of RC flat slabs produced with such blended cements, is determined in the laboratory. The observed values of punching shear are compared with the provisions of the various Codes. The results of the research will improve understanding of punching shear of flat slabs and enrich the research database of the area.

EXPERIMENTAL INVESTIGATION

Slab Specimen:

Four reinforced concrete slab specimens were tested for punching shear strength. Dimensions were the same for all slab specimens i.e. *1150 mm X 1150 mm (29in X 29in)* in plan and depth of *120 mm (4.8 in).* The specimens had a square central stub column, *200 mm X 200 mm (8in X 8in)*. Each slab specimen had holes drilled for rods and the rods were connected on to the steel sections placed over the slab to hold it down. This was meant to offer reactions on the sides of a square *990 mm X 990* mm *(39.5in x 39.5 in),* corresponding to the nominal lines of contra flexure at *495 mm (19.8 in)* from the center of the column (0.2 L of the span) as shown in Figure 1. The dimensions of slabs and its depth may vary in actual practice than adopted in research. The thickness of slab and reinforcement ratio can affect the crack pattern and punching shear strength of the flat slab. In the flat slab tests reported by Chana and Desai [30], slab specimen for punching shear strength were simply supported at the nominal line of contra flexure, which is assumed to be at a distance of *0.2 L* from the center of the column (L=Span of the slab). The same concept has been used for the flat slab tests reported in the present work and the specimens are meant to represent a flat slab continuous over columns at *2.5 m (8.2 ft)* centers.

Figure 1: Schematic diagram of testing arrangements of flat slabs

Steel reinforcement:

Grade 500 steel reinforcement was used with a characteristic tensile steel of 500 MPa (72.50Ksi). Individual tests of the steel bars were however not conducted and the manufacturer provided data was mainly used for calculation. The individual yield stress of steel bars may change the calculations. The steel used in all the slabs specimen were selected from a single supply and procured in one lot. In all four slab specimens, twelve *10 mm (#3)* ribbed bars were used as tension reinforcement in both directions at *100 mm (4in)* centers, which gave the reinforcement ratio ρ_{st} as *0.82%.* With *15 mm (0.60in)* as the clear cover, the mean effective depth *d* for the two-way reinforcement is given as *95 mm (3.8in)*. Equal steel amount has been used in both directions due to symmetry of the slab and column (being square), as uniform punching shear can be anticipated for such sections. This can be resisted by equal amount of steel in both directions in the flat slab. Seven *6 mm(#2))* bars were provided in each direction at *180 mm (7.2in)* centers, as nominal reinforcement near the other face of the slab. The stub column was provided with four 12 mm (1/2 in), high yield bars and three 8 mm (#3), links at equal centers. The reinforcement details are given in Fig.2.

Fig 2 Reinforcement details of flat slabs

Mix proportioning of concrete

Concrete was designed for 28 days compressive strength of 30 MPa (4350psi) with a margin of 5 MPa (725 psi), for all slab specimens, except the trial specimen, which were designed for 40 MPa (5800psi), with a margin of 5 MPa(725psi). The design compressive strength for all the slab specimens was kept the same to check the effect of partial replacement of cement with GGBS in concrete on punching shear strength performed after 28 days. The mix proportions of the slab mixes are given in Table 1. The concrete mixes used for different

RCC slab specimens are summarized below.

100PC- Trial: represents the 100% PC concrete trial mix.

100PC-Control: represents the 100% PC concrete control mix.

70PC/30GGBS: represents the concrete mix with 70% PC & 30% GGBS by weight.

60PC/40GGBS: represents the concrete mix with 60% PC & 40% GGBS by weight.

50PC/50GGBS: represents the concrete mix with 50% PC & 50% GGBFS by weight

Testing procedure:

Test arrangement is shown in Figure 1. The load was applied upwards by means of a hydraulic jack, in equal increments of *10 kN (1450psi)*. The reaction was offered by the steel box spandrels sections placed over the rubber pads to transmit uniform load to the column at the punching area of the slab. The location of these reaction beams is shown in the Fig 3.

At each load level, deflection and the cracking pattern was recorded. Four Linear Variable Differential Transducers (LVDTs) were used to determine deflections near the column and the two supports in one direction for the calculation of average mid-span deflection. The maximum size of aggregate used in slabs was *14mm (5/8in)*.

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Table 1 Concrete Mix proportions

Figure 3 Location of the reaction beams over the slab

EXPERIMENTAL RESULTS AND DISCUSSION

Failure loads and estimates of punching shear capacity

Punching shear strength tests was carried out after twenty eight days of casting, for all the slab specimens. Table 2 shows the experimental results of the punching shear failure loads and the nominal punching shear capacities calculated according to BSEN1992-1-1/EC2, BS 8100 and ACI 318. The values given in the Table 2, shows nominal punching shear or characteristic strengths ignoring the capacity reduction or safety factors. All the slab specimens failed in the range between 245 kN (55.08Kips) and 255 kN (50.58Kips). The difference between the punching shear resistances of slabs is about 7 %, which is negligible and it can be observed, that that the punching shear failure load for the 100PC-Control concrete mix is higher than the punching shear failure load of other slab specimens. The punching shear failure load of 60PC/40GGBFS concrete mix is similar to the 100PC, control concrete mix, while reduction of 2 % and 4 % were observed for 70PC/30GGBFS and 50PC/50GGBFS concrete mixes respectively. It can be concluded from these results that partial replacement of PC by GGBS up to 50 % has negligible effect on the punching shear strength. This is unlike the behavior of steel fibers used in the slabs. The comparison of observed values with the Code values, shows that when these values are multiplied by the safety factors (capacity reduction factors), these are further reduced, whereas the actual punching shear capacity of the slabs is observed on higher sides, hence the Code give relatively safe values i.e. on relatively low side than actual. The results have further supported the previous researches, as the punching shear strength of the reinforced concrete slab is independent of the Cementitious material used in the concrete and depends on the concrete compressive strength, reinforcement ratio and the shape factor as described by Park *et al* [31]. The punching shear failure of concrete elements without shear reinforcement is directly related to the tensile strength of concrete, which is often defined as function of compressive strength of concrete by Building Codes. The use of GGBS in concrete as a partial replacement of PC saves embodied CO_2 emissions and the embodied energy of concrete, thereby making it relatively green material than conventional PC. It can be seen in Table 2 that the ratios (V_F/V) between the experimental punching shear failure load (V_F) and the failure load estimated according to BS 8110 (V) are between 1.08 and 1.20 with Coefficient of Variation (CoV) as 4.8%, which is the ratio between the mean value of observations divided by the standard deviation. A lower value represents less variation in the test data. The ratios (V_F/V_{Rdc}) between the experimental failure loads and the failure loads estimates (V_{Rdc}) of EC2 (BS EN 1992-1, are between 1.11 and 1.23 with coefficient of variation (CoV) as 4.8%. The ratio indicates that the EuroCode 2, estimates are lower than the actual experimental results and hence the equations are on safer side.

The ratios V_F/V_{uo} between the experimental failure loads and the failure loads calculated according to ACI 318 are between 1.17 and 1.26 with CoV as 3.5% . From these observations it can be concluded that the estimates of the BS 8110, EuroCode 2, and ACI318 for punching shear strength are also safer for RC with partial replacement of cement by GGBS.

Crack Pattern:

Almost similar pattern of cracking was observed in all specimens of flat slabs. Initially radial cracks originate in the middle of the slab, which gradually extended to the edges. Some circumferential cracks also developed before punching shear failure. The same cracking pattern was also observed by Chana and Desai in their work [32]. The average crack width at the point of failure was nearly similar for all slab specimens and was in the range of 0.25 mm *(0.01in)* to 0.35 mm *(0.014in),* which is similar to the maximum crack width of 0.31 mm *(0.0124in)* as recorded in earlier research [33], in his research on punching shear resistance of RCC flat slabs.

Table 2 Experimental & Code predictions of punching shear strength of flat slabs

The final patterns of the cracks after failure for different slab specimens are shown in Figure 4. The circumferential cracks observed on the tension face of the slab were at a distance of *25 mm (1in)* from the center of the loaded column, which was measured once the crack around the column initiated. These cracks do not indicate the exact location of crack leading to punching failure, as the distance can vary with the depth of slab. The punching shear capacity was noted at the maximum load carrying capacity of the section, when no further load was taken by the section, as shown in Fig 5. Since the slab was not completely cut to observe the crack geometry, hence the exact location of the crack cannot be measured. The circumferential cracks on tension face of the slab can be expected to move diagonally at the complete shear failure. It can be seen from the Fig 4, that these cracks were at a distance of *250 mm (10in)* from the center of loaded column or *150 mm (6in)* from the face of the column and it was in the similar range for all test specimen. Hence it can be deduced that the actual failure zone falls within the first critical parameter at a distance of 2d (190mm or 7.6in), from the face of the column, as defined in the EC2.

Mid span deflection:

In testing arrangements, the flats slab was simply supported at four sides. This was ensured through fixing a spreader beam on top of each support for uniform distribution of loads. However when the loads were applied, supports also moved slightly showing deflections at the supports as well. The average mid span deflection was thus adjusted by subtracting the supports deflections from the mid span deflection. Data collected from the data logger for LVDT's was analyzed to calculate the average mid-span deflection and is presented in Table 3. The average mid-span deflection for all the slab specimens was between 4 mm and 4.4 mm. The deflections observed fall in the range earlier reposted by Channa and Desai [32], and KV Papanikolaou *et al* [33]. The comparison of mid span deflections of the four specimen of flat slabs tested are given in Fig. 6

The average mid- span deflection of the GGBFS blended concrete slab specimen is about 0.4 mm (0.16in) higher than the 100PC-Control slab specimen but is not considered significant with regards to design requirements. The mid span deflections at various load levels and cracks are also given in Fig 7 for the entire four specimens. The development of respective cracks is also indicated by different colored letters at various load levels on the slabs as well as the representative load defection curves. The load displacement curves for all the slab specimens have nearly the same pattern. The first crack appeared in the load range of 80kN to 90 kN (17.984 Kips to 20.232Kips) for all slab specimen.

Figure 4 Failure mode and crack patterns of flats slabs

The typical punching of column in flat slab is shown in Fig. 5

Fig 5 Punching of column in the flat slab after failure.

Fig 6: Mid span Deflection curves of flat slab for various mixes of concrete

Fig 7 Mid span deflections at various cracks levels.

Strain in steel reinforcement:

For determining the strains in the main reinforcement bars, micro measurements strain gauges (CEA series linear steel strain gauges) were used. These strain gauges were installed on the two tension bars, two in each direction for measuring the strains in these. The location of the strain gauges on the steel bars was chosen in the maximum moment area which is around the perimeter of the column area as shown in Fig 8. The strain is steel bars for various slabs is shown in Fig.9

Fig 8 Location of strain gauges at tension bars near the face of column region

Data obtained from the data logger attached to the strain gauges was analyzed to get the values of strain at different levels of load applied on the slab. A relationship between the applied load and the strain in reinforcement bar at each load level is presented in Figure 7. At the initial load stages, the strain in the reinforcement bar increased with the increase of applied load. As the load approached the punching shear capacity there were irregularities in the strain distribution due to cracking.

For steel used in the experiment the yield strain is equal to yield stress/ modulus of elasticity i.e. 500/200000=2500 µmm/mm. The modulus elasticity of steel is taken as 200000 MPa ($29x10^6$ psi) and the yield stress for grade 500 steel is 500 MPa (72.5 Ksi). From the strain results of steel in the slab specimens it can be seen that the strain in the steel was in the range of 2500 to 3500 µmm/mm at the point of failure, based on the specified yield strength of steel bars. It means that the reinforcement in the slab has exceeded its yield strength, and has yielded in the punching shear test. This is in accordance with the earlier research of Regan [34]. At the time of failure, severe cracking and deterioration in the compression block concrete appears to have caused excessive strains in the tension reinforcement and corresponds to the excess of its yield strength. The strain value of reinforcement confirms the quality of the reinforcement bars in accordance with the characteristic strain at maximum force for class A reinforcement bars (ε_{uk} %) ≥ 2.5 given by BS-EN1992-1-1(2004).

Fig 9: Strain in steel bars at different levels of applied load (μmm/mm)

Strain in Concrete:

Strains on the compression face of the slab specimens were recorded by using the electric concrete strain gauges. Strain values were recorded at the point of maximum moment just near the central stub column where the load was applied. The strain gauges were fixed at the point of maximum moment on the compression face of the column, just near the column as shown in Figure 10. It was discussed by Kotsovos and Kotsovos [35], that loss of bond between longitudinal reinforcement and the surrounding concrete may lead to transverse tensile stresses within the compressive zone, in the region where the maximum bending moment combines with shear force.

Figure 10 Concrete strain gauges on compression face of slab

According to Kupfer's [36], test results, the compressive strength under bi-axial compression is not greater than 15% of the uniaxial compression test. Also the concrete tensile strength under bi-axial compression-tension is not significantly different than the uni-axial compression-tension [36]. The measurement was mainly used for comparative analysis of the strain in GGBS concrete and ordinary concrete. Hence uniaxial gauges were equally suitable for the measurement.

Strains on the concrete surface of different slab specimens at different levels of applied load are presented in Figure 11. As for the strains in the main tension reinforcement, strain on the compression face of concrete slab increased with the increase in load applied and as this reached the punching shear failure load; there were irregularities in the strain values of concrete. The strains on the compression face of the slab specimens almost all had same pattern.

Fig. 11: Strain of concrete in the punching region on compression face for various slabs

It can be seen that the strain on the compression face of concrete increased with GGBS level at a given applied load. Overall there is a negligible difference in the strain values of concrete for all slab specimens at the failure load and suggest no specific consideration for their use in structural applications. The ultimate yield strain of normal weight concrete falls within 3500 µmm/mm, which are complying BS-EN 1992-1, given values. It can be seen from the strain results that the compression block of concrete for the slab specimens has not reached its crushing point at failure load and confirms the failure mechanism as punching shear failure, rather than compression failure of concrete.

CONCLUSIONS

This research aims at understanding the effects of using GGBS as partial replacement of cement on the punching shear capacity of the RC flat slabs, as limited work is available in this context. Square slab *1150mmx1150mm* having thickness of *120mm* was checked for various mixes of cement concrete blended with GGBS. The load carrying capacity of the flat slab, cracking pattern, mid span deflection, strain in concrete and steel were observed. The thickness of slab and reinforcement ratio can affect the crack pattern and punching shear strength of the flat slab. In this research the particular sizes of flat slab and reinforcement ratio has been selected to compare the behavior of RC flat slabs made with GGBS as partial replacement of cement and the flat slab cast from control mix, having no GGBS. For the tested specimen of flat slabs and mix proportion, partial replacement of PC by GGBS up to 50% by weight has no major change in the punching strength and deflection of slabs.

Based on the tests carried out and the materials used, concrete containing GGBS can be used in flat slab structures without any special requirements for design and the design methods and equation recommended by various Codes, for RC concrete can be used without any modification. The provisions of EC2, BS8110 and ACI-318 for design of punching shear of flat slab have been observed as safe for the slabs tested.

The relationship between average mid-span deflections at different levels of load applied has a similar pattern for GGBS and PC concrete mixes. The average mid span deflection at the failure load for the different slab specimens was in the range of 4 mm (0.16in) for 100PC-Control specimen and 4.4 mm (0.173in), for 50PC/50GGBS concrete slab specimens. The average mid span deflection for the slab specimen containing GGBBS is slightly more than the 100PC-Control slab specimen but is negligible to be considered for design considerations and also confirms the failure of the slab specimens as punching shear.

The pattern of cracking on all specimens was similar. Radial cracks formed in the middle of the slab, extending gradually to the edges. Some circumferential cracks developed before punching shear failure. The average crack width at the point of failure was almost similar for all slab specimens and was in the range of 0.25 mm (0.009in) to 0.35 mm (0.014in). The first crack appeared in the load range of 80 kN (17.984 Kips) to 90 kN (20.23Kips) for all slab specimens. In all the slab specimens the cracks falls within 2d parameter given by EC2. There is no significant difference in the concrete strain on the compression face of the slab specimen and steel strain in the main reinforcement for different RCC slab specimens containing GGBBS, which is important for their use in structural applications. No major change in the compressive strength, punching shear, cracking pattern, mid span deflection and strain in steel bars as well as concrete has been observed in the RC flat slabs having 50% replacement of cement by GGBS, which justifies its suitability in structural concrete and complex structures like flat slabs. The authors have recommended the use of RC with 50%

replacement of cement by GGBS, for use in structural concrete and flat slabs. However more such tests are required to improve the body of knowledge on the topic.

Authors' Biographies:

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Acknowledgement: The experimental work was carried out at Civil/Structural Engineering Labs, Kingston University UK. The authors are grateful for the support of management and staff of the University and labs

Conversion Factors:

1mm= 0.039in

1mm^2 = 0.00152in^2

1kN = 0.2248 kips

1 MPa = 145 psi

List of symbols Used

d — *effective depth of slab mm (Overall depth "h" minus the diameter of bar)*

A_{st} — *Area of tension steel bar (mm^2) ;*

HPC: — *High Performance Concrete*

ρ_{st} — *Ratio of tensile reinforcement = A_s/bd*

s — *Spacing of bars in tension steel layer*

f_{cu} — *Characteristic Compressive Cube Strength*

f_{ck} — *Characteristic Compressive Cylinder Strength*

u_o — *Shear perimeter at the face of column (4b for a square column size "b")*

u — *First critical shear perimeter*

Vcu — *Ultimate punching shear capacity without shear reinforcement*

V_{Rdc} — *Ultimate Punching shear capacity without shear reinforcement*

$V_{Rd,max}$ *is the design value of the maximum punching shear resistance along the control section considered.*

V_F — *Experimental Punching Shear failure load.*

Vuo *Ultimate punching shear strength*

CoV: *Coefficient of Variation= Mean/standard deviation*

$V_{ED:}$ *is the maximum punching shear stress at the column perimeter or the perimeter of the loaded area.*

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TABLES AND FIGURES

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Table 3 Concrete Mix proportions

Mix	Constituent Materials kg/m^3					W/C ratio
	Free Water (ml/ft^3)	Cement (Kg/lbs)	GGBFS (Kg/lbs)	Aggregate (Kg/lbs)		
				Coarse	Fine	
100PC-Trial	195	375	-	1220	575	0.52
100PC-Control	195	325	-	1245	600	0.6
70PC/30GGBFS	195	227.5	97.5	1245	600	0.6
60PC/40GGBFS	195	195	130	1245	600	0.6
50PC/50GGBFS	195	162	162	1245	600	0.6

Mix	Constituent Materials (lbs)					W/C ratio
	Free Water (ft^3)	Cement (lbs)	GGBFS (lbs)	Aggregate (bs)		
				Coarse	Fine	
100PC-Trial	0.0088	826	-	2690	1268	0.52
100PC-Control	0.0088	716	-	2745	1223	0.6
70PC/30GGBFS	0.0088	502	215	2745	1223	0.6
60PC/40GGBFS	0.0088	430	287	2745	600	0.6
50PC/50GGBFS	0.0088	357	357	2745	600	0.6

Table 4 Experimental & Code predictions of punching shear strength of flat slabs

MIX	Compressive Strength	Punching shear strength (Kg/lbs)				ACI	EC2	BS
		Experimental V_n	BSEN1992-1/ (EC2) V_{Rdc}	BS8110 V	ACI318 V_{uo}	V_F/V_{uo}	V_F/V_{Rdc}	V_F/V
	MPa/Ksi	kN	kN	kN	kN			
100PC-Control	40 /5.8	255/562	203/448	229/505	212/467	~~1.26~~	~~1.11~~	~~1.20~~
70PC/30GGBFS	40/5.8	250/551	203/448	229/505	212/467	1.18	1.23	1.09
60PC/40GGBFS	42/6.1	255/562	207/456	233/514	217/456	1.18	1.23	1.09
50PC/50GGBFS	39/5.61	245/540	202/445	227/500	209/461	1.17	1.21	1.08
Mean	40.25/5.84	251/553	204/450	230/507	213/470	1.20	1.20	1.12
CoV (%)	3.1%	1.9%	1.1 %	1.1%	1.5%	3.50%	4.8%	4.8%

MIX	Compressive Strength	Punching shear strength (lbs)				ACI	EC2	BS
		Experimental V_n	BSEN1992-1/ (EC2) V_{Rdc}	BS8110 V	ACI318 V_{uo}	V_F/V_{uo}	V_F/V_{Rdc}	V_F/V
	Ksi	lbs.	lbs	lbs	lbs			
100PC-Control	5.8	562	448	505	467	1.26	1.11	1.20
70PC/30GGBFS	5.8	551	448	505	467	1.18	1.23	1.09
60PC/40GGBFS	6.1	562	456	514	456	1.18	1.23	1.09
50PC/50GGBFS	5.61	540	445	500	461	1.17	1.21	1.08
Mean	5.84	553	450	230/507	470	1.20	1.20	1.12
CoV (%)	3.1%	1.9%	1.1 %	1.1%	1.5%	3.50%	4.8%	4.8%

Table3 . Average mid span deflections for various specimens of slabs.

Mixes	Average mid span deflection (mm)
100PC-Control	4.0
70PC/30GGBFS	4.2
60PC/40GGBFS	4.4
50PC/50GGBFS	4.3

Mixes	Average mid span deflection (in)
100PC-Control	0.160
70PC/30GGBFS	0.165
60PC/40GGBFS	0.173
50PC/50GGBFS	0.169

Figure 1: Schematic diagram of testing arrangements of flat slabs

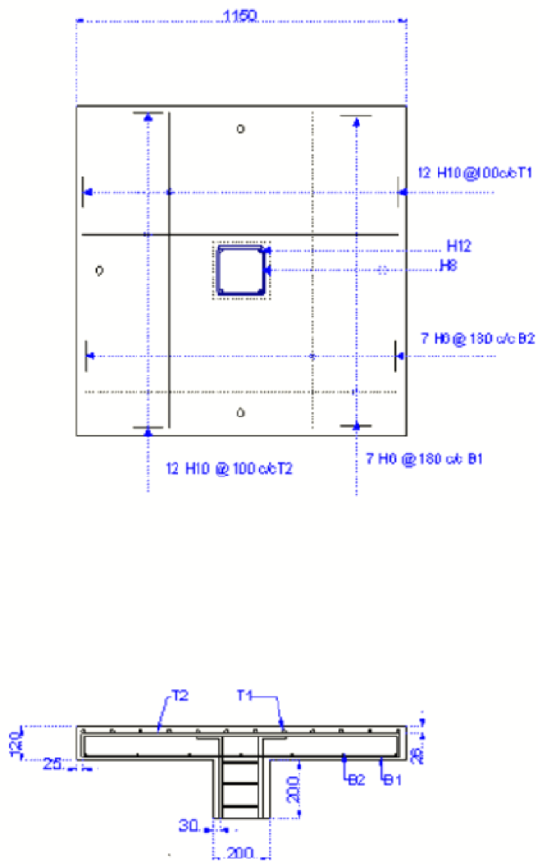


Fig 2 Reinforcement details of flat slabs

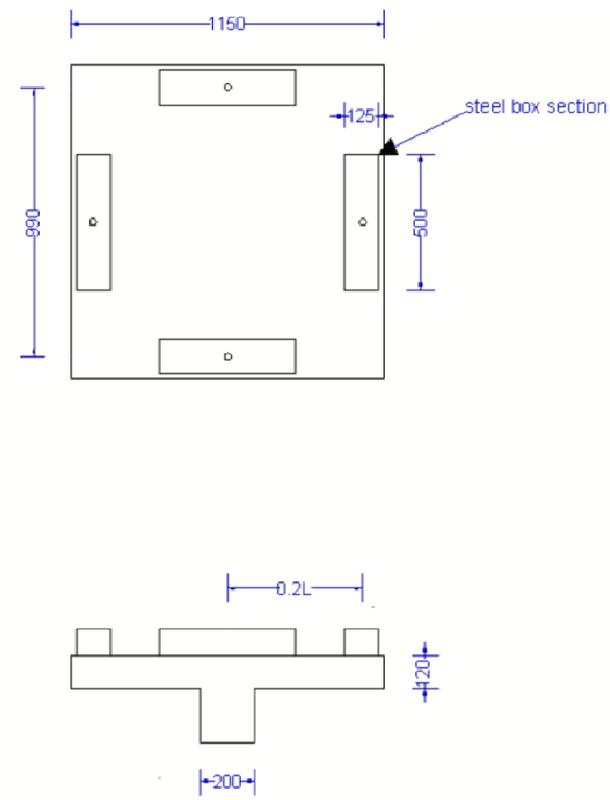
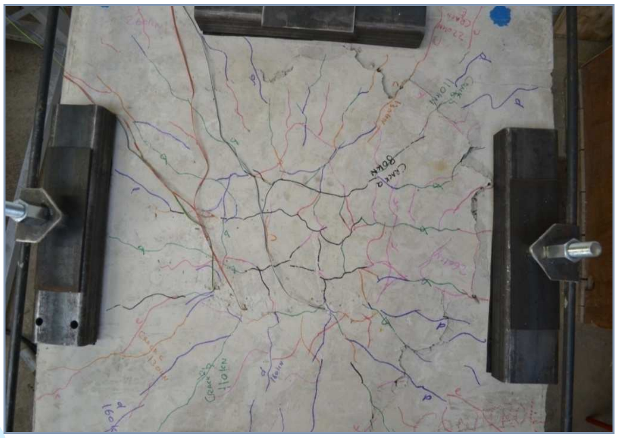
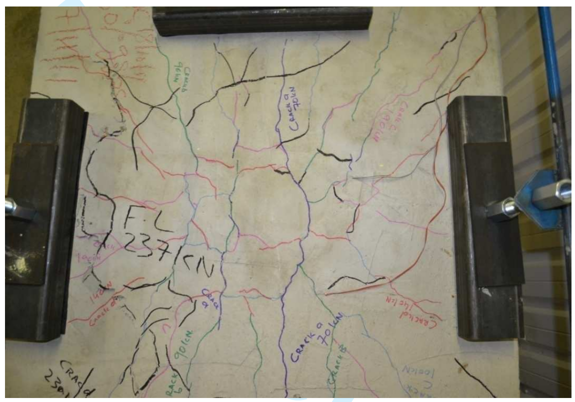


Figure 3 Location of the reaction beams over the slab (dimension in mm)
1mm=0.039in

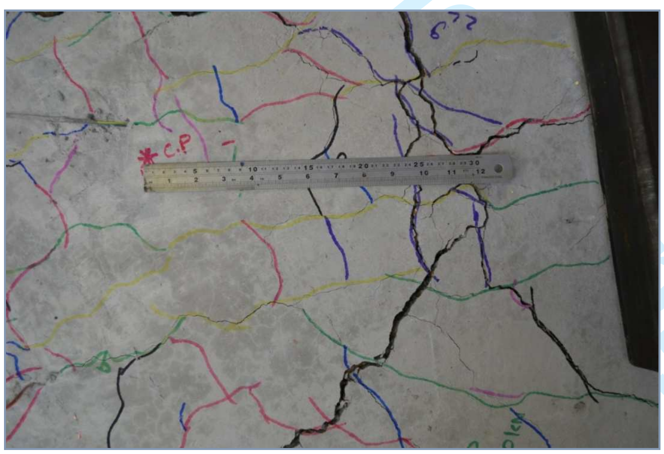
a. 100 PC- Control slab



b. 60 PC/40 GGBFS



c. 50PC/50GGBFS



d. Critical perimeter of punching shear

Figure 4 Failure mode and crack patterns of flats slabs

Fig 5 Punching of column in the flat slab after failure.

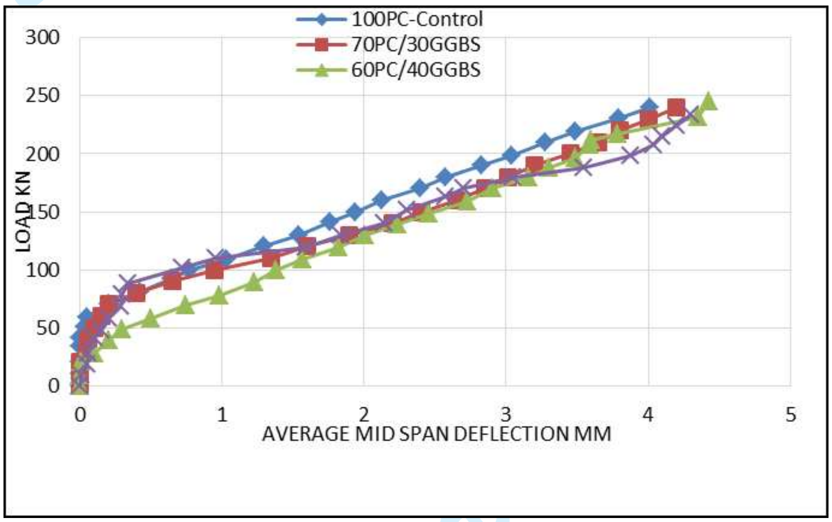
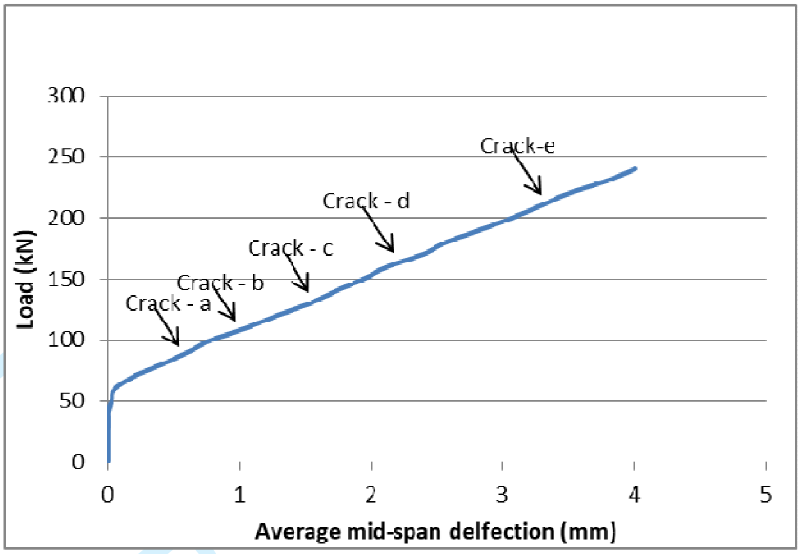
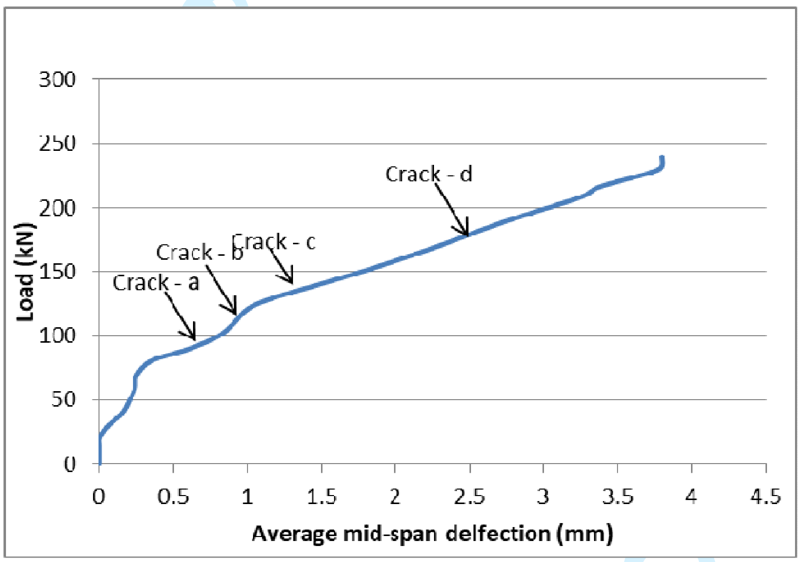


Fig 6: Mid span Deflection curves of flat slab for various mixes of concrete

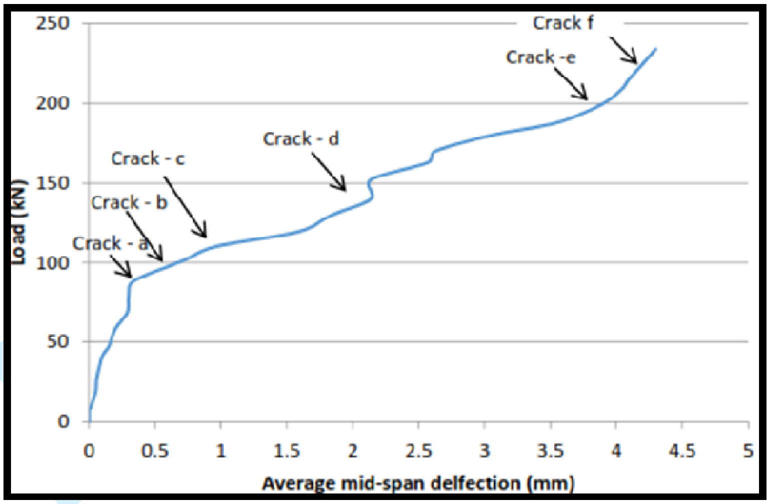
(1mm=0.039in)



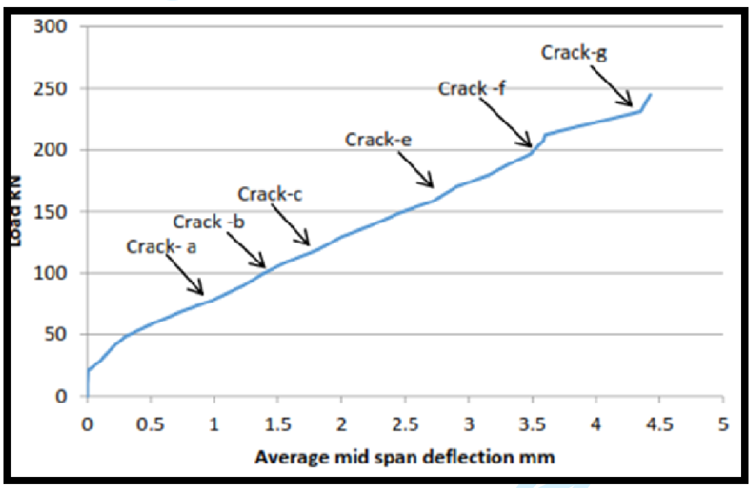
a. 100PC



b. 70PC/30GGBFS



c.60PC/40GBBS



c. 50PC/50GBBS

Fig 7 Mid span deflections at various cracks levels.

Fig 8 Location of strain gauges at tension bars near the face of column region

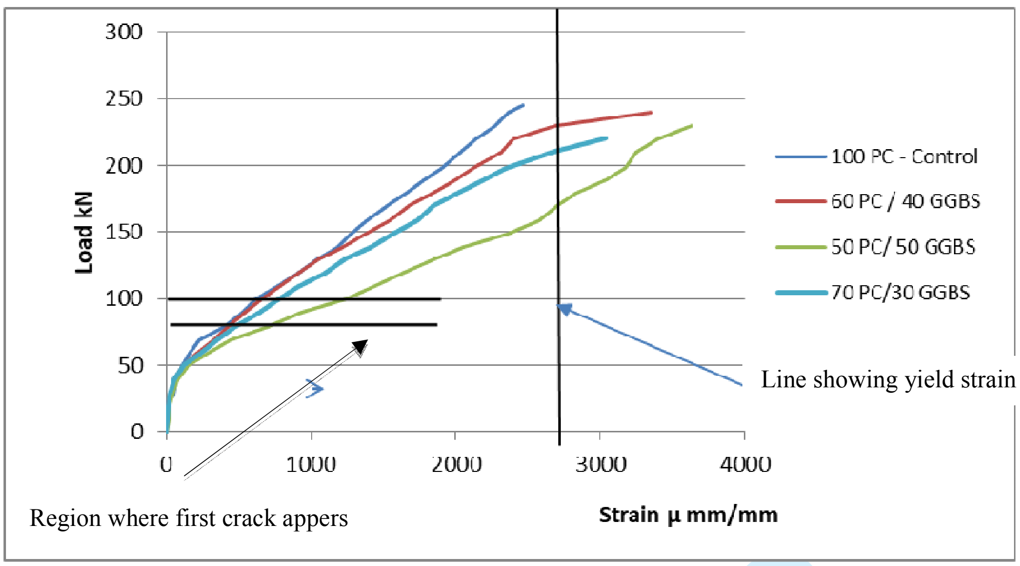


Fig 9: Strain in steel bars at different levels of applied load (µmm/mm)

Figure 20 Concrete strain gauges on compression face of slab

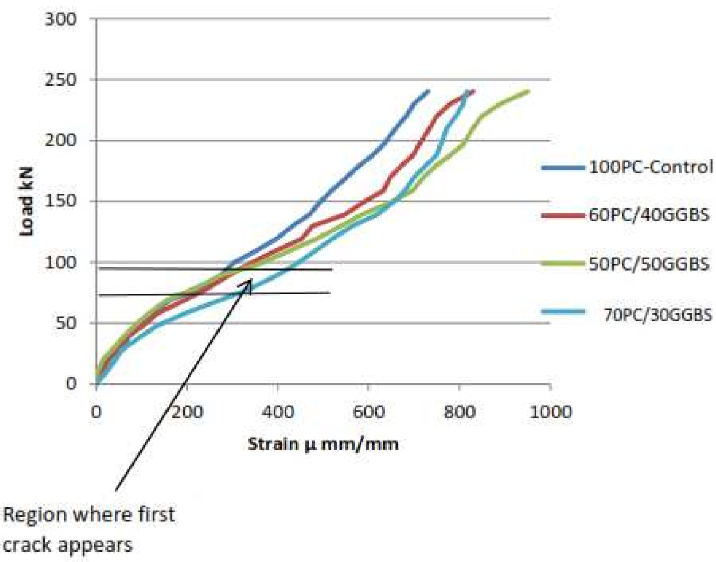


Fig. 11: Strain of concrete in the punching region on compression face for various slabs