# Does High-volume Fly Ash or GGBFS Replacement Make Concrete More Susceptible to Cracking?

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**Abstract**: The impact of cement replacement with supplementary cementitious materials (SCMs) on early age concrete cracking due to restrained shrinkage was investigated. A total number of eight mixes in two strength grades (32 MPa and 40 MPa) were considered. The crack resistance performance of concrete mixes with 30% fly ash replacement and 40% and 60% ground granulated blast furnace slag (GGBFS) replacement was assessed and compared to the performance of control mixes (with no SCMs). Cracking induced by restrained shrinkage was investigated using the restrained shrinkage ring test. Free shrinkage of unrestrained rings was monitored as well. The results showed that cracking was accelerated for GGBFS blended concrete but delayed for fly ash blended concrete for both strength grades.

**Keywords**: Ring test, Restrained shrinkage, Fly ash, Slag, Cracking

## 1. Introduction

Concrete technology is introducing new possibilities every day with high-performance concrete, self-consolidating concrete, fibre reinforced concrete, polymer concrete, low carbon concrete along with others [1-5]. From these new opportunities, new challenges of assessing the performance of new concrete technology in every aspect emerge. Among others, cracking due to restrained shrinkage at an early age is a critical parameter dictating the overall durability performance of concrete [6]. The cracking behaviour of concrete is time dependant and results from a combined effect of various factors such as shrinkage, creep, elasticity modulus, degree of restraint, and tensile strength of concrete [7-9].

Replacing cement content with supplementary cementitious materials (SCMs) leads to a reduction in carbon emission [10]. It is of utmost necessity to achieve a lower carbon footprint in producing concrete. Concrete mixes with SCMs replacing cement perform differently in terms of mechanical and durability parameters. Several studies explored the effect of SCMs inclusion on concrete cracking properties and overall performance [9, 11-13]. Fly ash blended concretes were reported to have improved crack resistance [9, 13, 14]. However, some studies found a weaker response of fly ash against cracking [15]. Slag replacement in producing concrete showed inconsistent crack resisting performances in literature [9, 11, 15]. Slag replacement mitigated [9], accelerated [15] and had no effect in case of low replacement level [11] on the cracking behaviour. Therefore, the effect of SCMs on early-age cracking needs further investigation to identify the critical factors that affect concrete cracking.

In this study, a grade-based approach was followed to observe the changes in cracking behaviour of GGBFS and fly ash blended concrete with respect to the control (no SCMs) mixes. This grade-based approach highlighted the fact that the cracking of concrete can be different depending on their constituents within a similar compressive strength range. It also provided a guideline for material selection under different performance requirements. Two different strength grades and two different SCMs were selected for the current investigation. High replacement ratios of 30% fly ash and 60% GGBFS were included in the mix design. For a total of eight mixes, restrained shrinkage induced cracking by doing the ring test and other mechanical properties were monitored up to cracking.

## 2. Materials and experimental setups

### *2.1 Raw materials and mix design*

General purpose (GP) cement, ground granulated blast furnace slag (GGBFS) and fly ash were used as raw materials for concrete. The oxide compositions of raw materials are summarized in Table 1.

**Table 1. Oxide compositions (%) of raw materials**

| Oxide | Cement | GGBFS | Fly ash |
|---|---|---|---|
| $SiO_2$ | 18.96 | 36.27 | 64.01 |
| $Al_2O_3$ | 4.81 | 10.11 | 24.75 |
| $Fe_2O_3$ | 3.14 | 0.36 | 2.87 |
| CaO | 63.76 | 42.18 | 1.63 |
| MgO | 1.20 | 6.52 | 0.57 |
| $SO_3$ | 2.37 | 1.24 | 0.10 |
| $Na_2O$ | 0.21 | 0.22 | 0.75 |
| $P_2O_5$ | 0.08 | 0.01 | 0.11 |
| $K_2O$ | 0.46 | 0.34 | 2.24 |
| L.O.I. | 3.96 | 1.03 | 1.03 |

Note: (i) L.0.I.= loss on ignition at 1,050 °C.

Two grades i.e., 32 MPa and 40 MPa were considered for concrete mixes. Again, for each grade, there were four categories: control with no SCMs, 40% replacement of cement by GGBFS, 60% replacement of cement by GGBFS and 30% replacement of cement by fly ash. 10 mm basalt and Sydney sand were used as coarse and fine aggregates respectively. The details of the mix designs are shown in Table 2.

**Table 2. Mix proportions of concrete mixes**

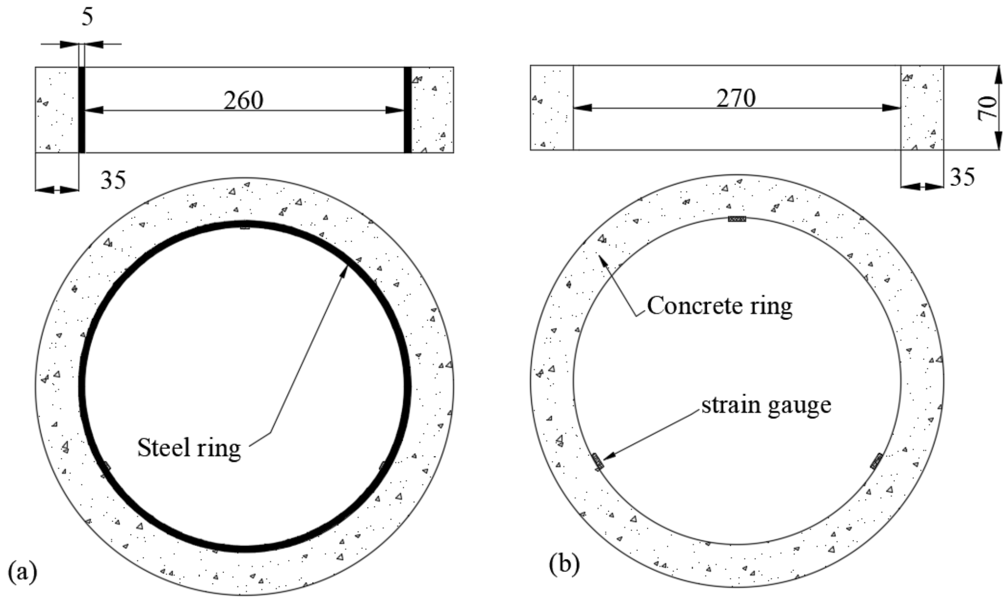
| Mix | Grade | Mix proportions by weight (kg/m$^3$) | | | | | | water to binder ratio |
|---|---|---|---|---|---|---|---|---|
| | | Cement | Slag | Fly ash | Total binder | Coarse Aggregate | Fine Aggregate | |
| N32-0 | 32 | 360 | 0 | 0 | 360 | 1025 | 839 | 0.49 |
| N32-FA30 | 32 | 250 | 0 | 110 | 360 | 1043 | 853 | 0.4 |
| N32-G40 | 32 | 215 | 145 | 0 | 360 | 1033 | 845 | 0.45 |
| N32-G60 | 32 | 145 | 215 | 0 | 360 | 1037 | 848 | 0.43 |
| N40-0 | 40 | 450 | 0 | 0 | 450 | 966 | 790 | 0.43 |
| N40-FA30 | 40 | 315 | 0 | 135 | 450 | 983 | 804 | 0.34 |
| N40-G40 | 40 | 270 | 180 | 0 | 450 | 974 | 797 | 0.41 |
| N40-G60 | 40 | 180 | 270 | 0 | 450 | 981 | 803 | 0.37 |

## *2.2 Ring test*

The restrained ring test was performed to assess the potential of cracking of concrete. The ring consisted of an outer concrete ring and an inner steel ring providing the restraint (see Figure 1). The outer surface of steel was oiled before casting concrete [16]. Three strain gauges were attached on the inner steel surface at the mid-height at equal distances and were connected to a data logger system. This strain was reported as steel strain. This strain is imposed on the concrete under the assumption that the steel and the concrete experienced equal and opposing compressive forces at the interface due to the restraint [16]. Restrained strain or shrinkage of the concrete was monitored over time starting from day 1 after casting and up to crack formation. A sudden drop in steel strain indicated the cracking of the concrete ring [17]. The exact time of cracking was assessed thanks to the continuous recording of the steel strain using an automatic data logger system. The top, bottom and outer face of the restrained rings were free to dry.

Companion unrestrained rings were used for monitoring the free shrinkage of the ring with identical dimensions and exposure conditions to the corresponding restrained rings. The inner surface of the unrestrained ring was covered with adhesive aluminium foil to maintain the same drying condition as for the restrained shrinkage ring.

For both restrained and unrestrained rings, three strain gages were used to collect deformation data of each ring and two replicates were considered for each condition. The rings were stored at 50±3% relative humidity and 23±2ºC temperature maintained throughout the process from casting to end of the test. The details and dimensions of the rings are illustrated in Figure 1.




Note: dimensions are in mm

**Figure 1. Geometry of (a) restrained and (b) unrestrained rings**

### *2.3 Mechanical properties test*

Tensile strength and modulus of elasticity were determined according to AS1012.10 [18] and AS1012.17 [19] respectively. After demolding the cylindrical specimens were cured at 50±3 % relative humidity and 23±2 ºC temperature in air ensuring identical exposure conditions with the rings.

## 3. Results and discussion

### *3.1 Correlation between time to crack and shrinkages*

The free shrinkage of concrete and the steel strain at the time of cracking were compared as illustrated in Figure 2. Figure 2 also shows the time to cracking for all concrete, plotted as a bar chart. The circular points in Figure 2 presents the free shrinkage of all mixes at the time of cracking. The free shrinkage values at time to cracking, appeared in a random manner. No correlation could be drawn between the time to cracking and free shrinkage at that time. It could be expected that an increasing free shrinkage would lead to a reduction in time to cracking but experimental results are not showing this trend.

The values of the steel strain for different mixes in their respective grades showed similar values at the time of cracking except N40-FA30 (see the diamond points shown in Figure 2). Grade 32 and 40 mixes showed an average steel strain of 82 x$10^6$ μm/m and 69.5 x$10^6$ μm/m respectively before cracking. Therefore, with the increase in strength grade, the steel strain decreased.

The formation of the first crack was considered as the time to cracking. Concrete mixes of grade 40 cracked earlier than grade 32 in agreement with the observation made about steel strain above. Therefore, the risk of cracking is higher for concrete with higher strength.

Slag blended concrete mixes i.e., N32-G40, N32-G60, N40-G40, N40-G60 cracked earlier than corresponding control mixes in each grade. With high GGBFS replacement (60% replacement), the cracking was accelerated by 31% and 36% with respect to the control mix for 32 and 40 grades, respectively. The fly ash blended mixes i.e., N32-FA30 and N40-FA30 showed delayed cracking. In the case of N32-FA30, the cracking was delayed by 35% compared to N32-0. The time to cracking approximately doubled in the case of N40-FA30 compared to N40-0. This study shows a general trend that GGBFS reduces the time to cracking but fly ash delays the cracking time.

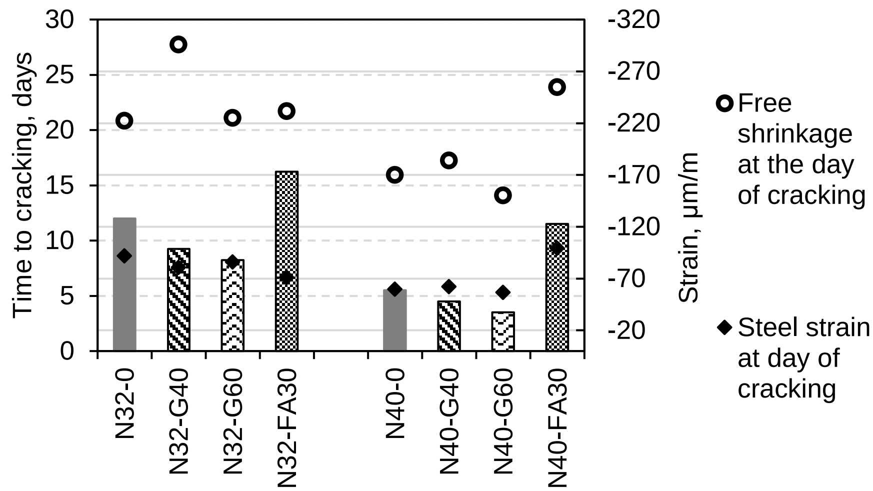



**Figure 2. Weak correlation among time to cracking, steel strain at day of cracking and free shrinkage at the day of cracking**

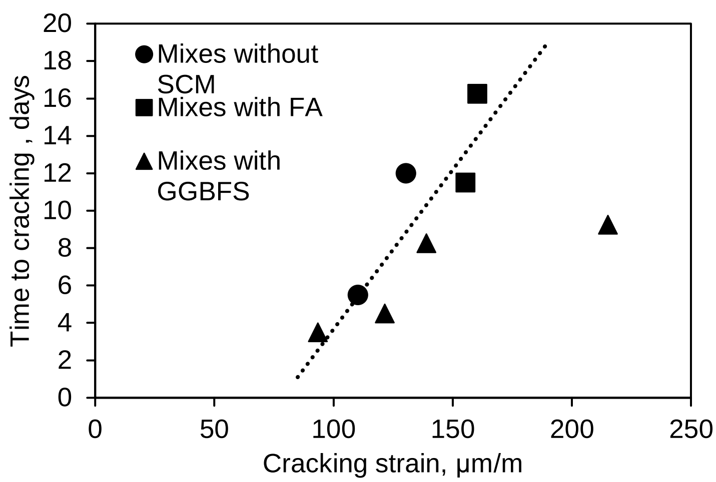



**Figure 3. Time to cracking as a function of cracking strain (defined as the differene between the free shrinkage and steel strain)**

In this studny, the restrained shrinkage was calculated from the difference between the free shrinkage and steel strain. This restrained shrinkage includes the effects of tensile creep that causes stress relaxation in concrete under restraint. The restrained shrinkage at the time of cracking is the cracking strain [20]. When the restraint induced tensile strain in concrete exceeds the tensile strain capacity of concrete, concrete cracks. The tensile strain capacity of concrete can be determined by modulus of rupture test or direct tension test [21] which is out of scope of this current study. However, the value of cracking strain is somewhat proportional to the time to cracking as showed in Figure 3 except for N32-G40.

## *3.2 Mechanical properties*

### *3.2.1 Tensile strength*

Mechanical properties of different mixes were considered and compared at 7 days to reflect the early age cracking behaviour. The overall trend from Figure 4 shows that tensile strength at 7 days decreased with the increasing replacement ratio of SCMs. It exhibited the following trend in general: control (0% replacement) > 30% of fly ash and 40% of slag replacements > 60% of slag replacement. Reduced tensile strength by increasing the replacement rate of GGBFS can increase the probability of cracking [22].

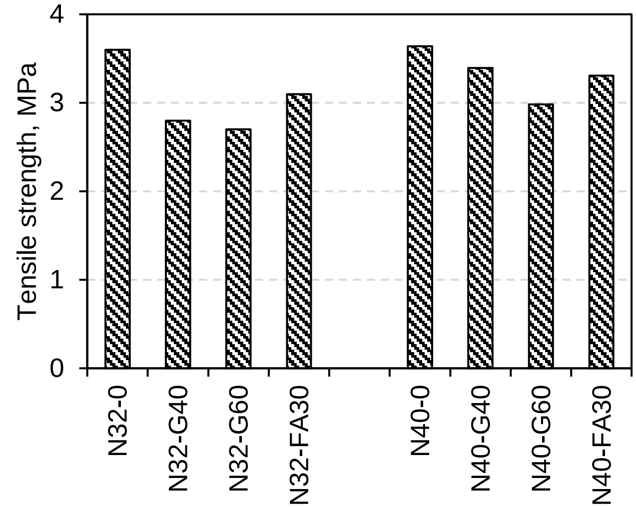



**Figure 4. Tensile strength of different mixes at 7 days**

### *3.2.2 Modulus of elasticity*

The moduli of elasticity of different mixes at 7 days are presented in Figure 5. Similar to the tensile strength (Figure 4), increasing the amount of SCMs reduced the modulus of elasticity of concrete at early ages. The stiffer the concrete is, the more susceptible it is to crack [23]. However, it should be noted that the replacement of cement content with SCMs decreased both the tensile strength and modulus of elasticity and these two mechanical parameters have an opposing effect on time to cracking. Therefore, their relative values may be used to determine the potential of cracking. It will be discussed in the next section.

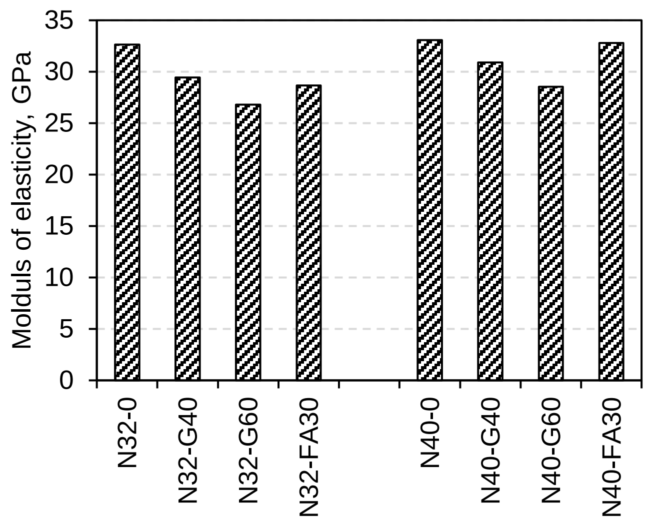



**Figure 5. Modulus of elasticity of different mixes at 7 days**

### *3.2.3 Tensile strength vs modulus of elasticity*

The ratio modulus of elasticity (Ec) to tensile strength (ft) at day 7 is presented in Figure 6 for all mixes. It is expected that concretes with the lower ratio may have the highest cracking resistance (longer time to cracking). Slag concrete mixes i.e., N32-G40, N32-G60, N40-G40, N40-G60 show higher Ec/ft ratio compared to control concretes (Figure 6). Therefore, GGBFS inclusion produced stiffer concrete with lower tensile strength at 7 days reducing the time to cracking (Figure 2). However, fly ash concretes was similar or superior to that of reference concrete but time to cracking was greater (Figure 2). Increased ductility of fly ash blended concrete was reported previously [9]. This proves that other mechanisms such as shrinkage rate and tensile creep must be contributing to the delay in cracking for fly ash blended concrete [20, 24]. The stress caused by restraint shrinkage can be reduced by creep relaxation and can lead to a delay in cracking [17, 25, 26]. Fly ash blended concrete tends to have higher tensile creep as reported in the literature [25, 27, 28]. Therefore, further investigation is required to include all contributing parameters while assessing the susceptibility of cracking of SCM blended concrete.

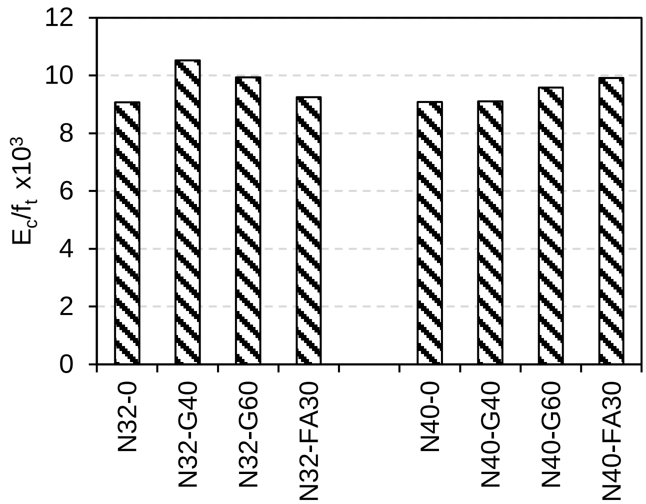



**Figure 6. Ratio of modulus of elasticity to tensile strength of different mixes at 7 days**

## 4. Conclusion

This study provided knowledge about the comparative performances of SCM blended concrete under restrained shrinkage. The following conclusions can be drawn from the observed behaviour:

- Increasing concrete compressive strength is reducing time to cracking
- Overall GGBFS reduces and fly ash increases time to cracking
- Time to cracking is not well correlated with the free shrinkage measured when cracking was observed
- Strength grade, tensile strength, and modulus of elasticity of concrete alone cannot be used to estimate the time to cracking of concrete

Further investigation is recommended to determine the effect of other parameters such as tensile creep on cracking potential.

## 5. Acknowledgement

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