# PERFORMANCE EVALUATION OF SPECIAL CONCRETE WITH STEEL SLAG AND WASTE GLASS

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## ABSTRACT

In this work, tests on concrete built from waste glass and steel slag are presented. Both lightweight aggregate concrete and concrete with limestone aggregate underwent reference testing. Slump, density, elastic modulus, compressive strength, and flexural strength were used to analyse the material characteristics of various kinds of concrete. To examine the impact of aggregate type on the fire performance, fire tests on plain concrete columns with a diameter of 250 mm and a height of 800 mm were carried out. The study's findings show that it is possible to use steel slag and/or waste glass in place of all coarse aggregate or a portion of fine aggregate. Concrete made from steel slag may be made more workable and less dense by adding waste glass. The compressive strength, flexural strength, and elastic modulus of the steel slag concrete were equivalent to or even greater than those of the control limestone aggregate concrete. Only a slight effect on the mechanical qualities of concrete was noticed when coarse aggregate was substituted by up to 17.5% waste glass. Steel slag and waste glass have shown the capacity to increase the fire resistance of concrete due to their superior thermal and/or mechanical qualities.

***Keywords:*** Concrete; Steel slag; Waste glass; Lightweight aggregate; Mechanical properties; Fire performance.

## 1. Introduction

One of the most frequently utilised building materials worldwide is concrete. There has been an increase in interest recently in using waste goods and byproducts in concrete. In addition to lowering the cost of making cement and concrete, using these materials has a number of environmental advantages, such as lowering landfill costs, conserving energy, and preventing pollution. The microstructure, mechanical, and durability characteristics of mortar and concrete may also be improved by their use [1].

In the past, considerable studies have been reported on application of steel slag (a by-product of the steel-making process) as aggregate in concrete [2,3]. In general, concrete with steel slag has comparable or slightly higher compressive strength, flexural strength, splitting tensile strength and modulus of elasticity, as compared to concrete with normal aggregates. Meanwhile, it was reported that steel slag had a negative impact on the workability of concrete mixes with high substitution ratio since steel slag was more angular than the roundish normal aggregate [4]. Apart from that, a potential risk in using steel slag lies in the fact that it may contain a small amount of free lime (CaO) and/or free magnesium oxide (MgO) that can result in volumetric instability (expansion) of concrete. This risk, however, can be eliminated or greatly reduced by weathering the slag in outdoor conditions for a sufficient period of time before using [5].

Efforts have also been made to use crushed waste glass in concrete to replace coarse and/or fine aggregates [6,7]. It indicates that the replacement with waste glass aggregate generally causes a strength reduction in concrete depending on the replacement ratio. The compressive, tensile and flexural strengths of concrete decrease with the increase of waste glass content. Meanwhile, it is found that using waste glass as fine aggregate has less impact on the compressive and flexural strengths of concrete than using waste glass as coarse aggregate [8]. Furthermore, partial Numerous research have previously been published on the use of steel slag, a waste product of the steel-making process, as aggregate in concrete [2,3]. In comparison to concrete made with regular aggregates, concrete made with steel slag typically has equivalent or slightly better compressive strength, flexural strength, splitting tensile strength, and modulus of elasticity. Meanwhile, it was claimed that steel slag, which is more angular than the roundish typical aggregate, had a detrimental effect on the workability of concrete mixes with high replacement ratios [4]. In addition, there may be a tiny quantity of free lime (CaO) and/or free magnesium oxide (MgO) in steel slag, which might cause concrete to expand and become volumetrically unstable. However, by allowing the slag to weather in outside circumstances for a sufficient amount of time before to use, this danger can be completely removed or significantly decreased [5].

mechanical toughness and endurance [9,10]. The biggest issue with utilising discarded glass as aggregate in concrete, however, is the potential for an alkali-silica reaction (ASR) between the cement paste and the glass aggregate, which might cause excessive expansion and obvious breaking in the concrete. Previous studies suggest that the ASR impact can be diminished or completely eliminated by lowering the particle size of waste glass [11] and using low-alkali cement or cement containing pozzolanic elements [12]. The use of powdered glass powder as an additional cementitious material has been demonstrated to be one of the most successful strategies for reducing the risk of ASR in concrete [9,13]. Glass powder with an average particle size of 17 m was utilised by Afshinnia and Rangaraju [13], and they discovered that the most effective ASR.When the average size of glass powder was further reduced to 8.4 □m, the partial replacement of 20% (cement or sand) with fine glass powder was very effective in suppressing alkali-silica reactivity in (mortar or concrete) made with 80% natural sand replacement with fine glass aggregate [9]. Kamali and Ghahremaninezhad [9] believed that the ASR reactivity reduction was due to microstructure densification with lower alkalis mobility as well as a reduction in available alkalis in the pore, as a result of pozzolanic property of glass powder.

Additionally, according to recent studies, employing steel slag as coarse and fine particles in concrete might enhance its post-fire qualities [14,15]. Similar to this, research shows that replacing coarse and/or fine aggregate with waste glass in low proportions increases the post-fire strength of concrete [16,17]. This was explained by the impermeability and improved flow characteristics of concrete brought on by the internal filling of internal fissures with molten glass, which improved the pore structure and improved resistance in concrete [16,17]. In addition, waste glass is renowned for having better heat retention and lower thermal conductivity when compared to natural aggregates [1]. Lightweight aggregate concrete is anticipated to have increased fire resistance for a similar reason [18]. For instance, Peng et al. [19] discovered that lightweight aggregate concrete (sintered from reservoir sediments) had thermal conductivity that was only around 53% of that of standard concrete.

No study has been done to look at the combined use of steel slag and waste glass in concrete, despite the fact that utilising them as aggregates in concrete can result in reasonable concrete qualities with considerable economic and environmental benefits. For their combined usage, it is anticipated that the advantages of both waste glass and steel slag may be employed. Investigating the "hot" behaviour of concrete incorporating steel slag and waste glass is necessary in the interim [20]. In light of the foregoing, reference tests on concrete prepared with limestone and lightweight particles are compared to examine the viability of utilising both steel slag and waste glass to replace some or all of the coarse/fine aggregate in concrete. Additionally, the impact of aggregate type on concrete's fire performance is looked at.

## 2. Experimental investigation

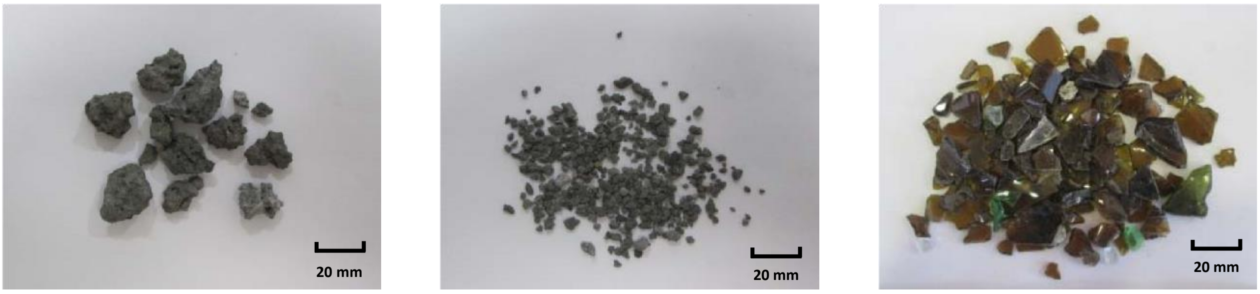
To compare the qualities of concrete built with various types of aggregate, two separate types of testing were conducted: room temperature tests and fire tests.

### ***2.1. Material tests at room temperature***

#### *2.1.1. Materials*

It was decided to employ a blend of cement that is often used in Australia and contains a significant amount of granulated blast furnace slag. In this test, natural river sand was used as the standard fine aggregate. The ready-to-use liquid additive Polyheed 850 superplasticizer, provided by BASF Australia Ltd., was chosen since it is designed to reduce water absorption. This admixture is a non-chloride and naphthalene-based water reducer that complies with ASTM C494/C [21]. It has a density of around 1.3 g/cm3 and a PH value of 6.

As a lightweight aggregate, volcanic scoria with nominal diameters of 14 mm and 20 mm was employed. A nearby steel mill provided the raw electric arc furnace steel slag. The air-cooled steel slag had been exposed to the elements for more than a year. This might significantly lower the amount of free CaO and MgO as well as the likelihood of volume expansion in concrete containing steel slag [4]. In lieu of coarse aggregate, coarse steel slag that passed through a 20 mm screen and was kept on a 4.9 mm sieve was used, and fine steel slag that passed through a 4.9 mm sieve was used in its stead. 4.9-10 mm and 4.9-16 mm waste glass of two distinct kinds were substituted for some of the coarse aggregate. They were supplied by a nearby business and made of shattered bottles. It should be mentioned that employing big size glass aggregate carries a risk of ASR. In this study, the coarse aggregate was only up to 17.5% replaced with waste glass in order to limit the possible ASR growth. Further study is still needed to examine the potential ASR growth and viable solutions for ASR reduction, even at this replacement ratio. Steel slag, discarded glass, and lightweight aggregate are only a few of the numerous forms of aggregates employed in this study as replacements. Table illustrates the grading of several types of aggregates.



(a) Coarse steel slag (b) Fine steel slag (c) Waste glass (4.9–16 mm)

(d) Waste glass (4.9–10 mm) (e) 14 mm lightweight aggregate (f) 20 mm lightweight aggregate

**Fig. 1.** Steel slag, waste glass and lightweight aggregate used in the test.

**Table 1** Sieve analysis of different types of aggregate.

| Sieve size (mm) | Percentage passing | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Limestone | Coarse steel slag | Fine steel slag | Waste glass | | Lightweight aggregate | | Natural sand |
| | | | | 4.9-16 mm | 4.9-10 mm | 14 mm | 20 mm | |
| 26.5 | 100 | 100 | – | 100 | 100 | 100 | 100 | – |
| 19 | 91.9 | 91.6 | – | 100 | 100 | 100 | 53.0 | – |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 13.2 | 32.2 | 72.3 | – | 87.4 | 100 | 84.0 | 2.0 | – |
| 9.5 | 3.8 | 46.4 | – | 61.8 | 96.4 | 8.0 | 2.0 | 100 |
| 4.75 | 0.9 | 8.9 | 94.4 | 3.1 | 6.3 | 4.0 | 2.0 | 100 |
| 2.35 | 0.9 | 0.2 | 44.6 | 0.07 | 0.05 | 1.0 | 1.0 | 96.0 |
| 1.18 | – | – | 16.8 | – | – | – | – | 92.0 |
| 0.6 | – | – | 6.2 | – | – | – | – | 74.0 |

The specific gravity, density, and water absorption of each type of aggregate were assessed in accordance with ASTM C127 [22] and C128 [23], respectively. Three measurements were made in each instance, and Table 2 shows the average of those results. In Table 3, which was examined using a JEOL 6510LV scanning electron microscope (SEM) and a Moran Scientific Microanalysis System, the chemical composition of each type of aggregate is shown. Calcium oxide (CaO) makes up the majority of waste glass and lightweight aggregate, whereas silicon dioxide (SiO2) makes up the majority of limestone. In contrast, steel slag has a more complex composition than other aggregates and mostly comprises the oxides of FeO, CaO, SiO2, and Al2O3.

**Table 2** Properties of different types of aggregate.

| Aggregate | Apparent specific saturated gravity dried basis | Density on an oven dried basis (kg/m$^3$) | Density on an and surface- (kg/m$^3$) | Absorption (%) |
|---|---|---|---|---|
| Limestone | 2.65 | 2621 | 2629 | 0.32 |
| Coarse steel slag | 3.51 | 3174 | 3268 | 2.95 |
| Fine steel slag | 3.57 | 3404 | 3447 | 1.31 |
| 4.9–16 mm waste glass | 2.67 | 2668 | 2672 | – |
| 4.9–10 mm waste glass | 2.48 | 2481 | 2483 | – |
| 14 mm lightweight aggregate | 1.75 | 1474 | 1630 | 10.62 |
| 20 mm lightweight aggregate | 1.58 | 1337 | 1490 | 11.42 |
| Natural sand | 2.61 | 2611 | – | 10.5 |

**Table 3** Chemical composition of different types of aggregate.

| Aggregate | Chemical composition (percent by mass) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | FeO | $TiO_2$ | CaO | $K_2O$ | $SiO_2$ | $Al_2O_3$ | MgO | $Na_2O$ | MnO |
| Limestone | – | – | 95.0 | – | 3.5 | 1.5 | – | – | – |
| Steel slag | 14.5 | 0.5 | 37.8 | 0.2 | 19.8 | 20 | 4.3 | 0.2 | 2.6 |
| Amber glass | 0.6 | 0.1 | 11.0 | 0.2 | 74.9 | 1.1 | 0.1 | 11.9 | – |
| Green glass | 0.3 | – | 9.5 | 0.2 | 74.2 | 1.5 | – | 13.7 | – |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Clear glass | – | 0.2 | 9.9 | 0.6 | 75.9 | 0.6 | 0.1 | 12.6 | – |
| Lightweight aggregate | 8.6 | 1.7 | 4.7 | 2.2 | 54.9 | 19.3 | 3.8 | 4.6 | – |

### *2.1.2. Compounding and mixing*

Table 4 summarises the mix proportions of concretes prepared with various types of aggregates. The mixes were created to examine the impact of adding various types of aggregate on the characteristics of concrete. At room temperature, two batches of concrete were made and examined. The first batch of concrete mixes had an effective water/cement ratio of 0.55 and a cement content of 400 kg/m3. In contrast to mix LWC-1, which substituted lightweight aggregate with nominal sizes of 14 mm and 20 mm for coarse aggregate, mix NC-1 employed crushed limestone with a maximum nominal size of 20 mm. All of the coarse material in mix CSSC-1 was replaced with coarse steel slag (4.920 mm). Glass waste (4.916) for mix SSGC-1.

For the second batch of concrete, the effective water/cement ratio was decreased to 0.40 and the cement amount in all mixes was slightly raised to 420 kg/m3. Limestone served as the coarse aggregate in the reference mix NC-2, just like it did in the first batch. In mix CSSC-2, coarse aggregate was entirely replaced with coarse steel slag (4.920 mm), whereas lightweight aggregate with a nominal size of 14 mm was utilised as coarse aggregate in mix LWC-2. For mix SSGC-2, waste glass (4.910 mm) was utilised to replace 17.5% by volume of coarse aggregate, and coarse steel slag (4.920 mm) was used to replace the remaining coarse aggregate. In this batch, a different mix called FSSC-2 was created, in which all of the fine aggregate was replaced with fine steel slag that had passed through a 4.9 mm screen. Each type of concrete received a different amount of water reducer throughout the mixing process. Due to this, the workability of most concrete mixtures was comparable. For each kind of concrete, the actual water reducer dose was shown in Table 4. Clarification of the impact of various water reducer doses on the performance of concrete may require more investigation.

### *2.1.3. Specimen preparation and test methods*

The Western Sydney University used a pan mixer to mix concrete. For material testing at room temperature, concrete cylinders with dimensions of 100 mm in diameter and 200 mm in height were produced. At 3, 7, and 28 days old, the density, compressive strength, and elastic modulus were assessed. Additionally, 100100400 mm beam specimens were made to assess the flexural strengths of various concrete types after 3, 7, and 28 days. Concrete's dry density was assessed in advance of the mechanical test in accordance with AS 1012.12.1 [24]. While the modulus of elasticity was determined using the methods outlined in AS 1012.9 [25], the compression strength and flexural strength tests were conducted in accordance with AS 1012.11 [26].

## ***2.2. Fire tests of plain concrete columns***

### *2.2.1. Specimen preparation*

The mix proportions of NC-F, LWC-F, CSSC-F, and SSGC-F for the concrete specimens tested in fire were comparable to those of NC-2, LWC-2, CSSC-2, and SSGC-2 in the second batch, with the exception that the effective water/cement ratio was slightly raised to 0.42 to achieve the desired concrete compressive strength of 32 MPa at 28 days. By changing the mix FSSC-2 in the second batch, fine steel slag was added to mix FSSC-F based on the results of tests of concrete at ambient temperature. Instead of replacing 100% of the sand in mix FSSC-2 with fine steel slag, 42% of the sand was used in mix FSSC-F. For concrete tested in fire, specifics of the mix design are provided in Table 4. For each concrete mix, the gradation curve and fineness modulus of the combined coarse and fine aggregates are presented in Fig. 2. The mixing proportions of each concrete mix and the associated sieve analysis findings of the employed coarse and fine aggregates were used to compute the fineness modulus. The other mix designs, with the exception of mix FSSC-2, have comparable gradation curves. The fineness modulus for LWC-2 and LWC-F was 2.25, whereas the fineness modulus for FSSC-2 was 4.12. The range of the fineness modulus for the remaining concrete mixtures was 2.96 to 3.82.

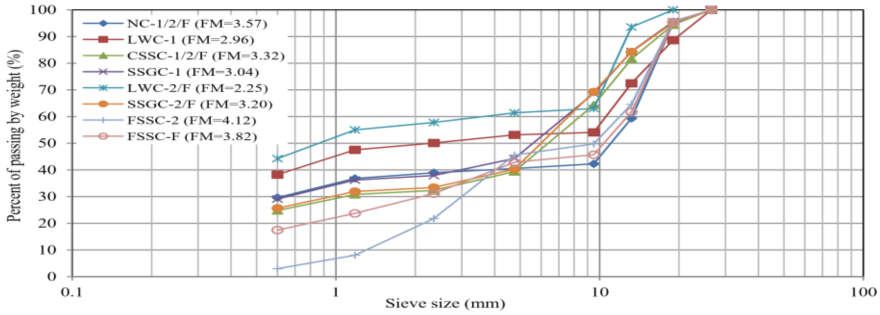


**Fig. 2.** Gradation curve and fineness modulus of combined coarse and fine aggregates.

Five identical round plain concrete columns, each measuring 250 millimetres in diameter and 800 millimetres in height, were created using the various concrete mixtures mentioned above. The concrete was poured using steel moulds. Each concrete specimen has three thermocouples installed to track the temperature rise. The positions of the thermocouples in the cross-section are depicted in Fig. 3(a). Two thermocouples were used to gauge the temperatures at the cross-section's centre (Point 3), and the concrete's outer surface (Point 1), respectively. A third thermocouple was used to gauge the temperature at the intersection of the other two measurement points (Point 2).

A concrete age of 42 to 53 days was used to heat the concrete columns. For each specimen, Table 5 lists the measured concrete cylinder compressive strengths (fc') and elastic moduli (Ec) at 28 days and the time of the fire test.

**Table 4** Concrete mixture proportions.

| Batch | Mix | Cement (kg) | Aggregates (kg) | | | | | | | | Water (kg) | Water reducer (L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Coarse | | | | | | Fine | | | |
| | | | Limestone | Lightweight aggregate | | Coarse slag | Waste glass | | Natural sand | Fine slag | | |
| | | | | 20 mm | 14 mm | | 4.9-16 mm | 4.9-10 mm | | | | |
| 1st | NC-1 | 400 | 1020 | – | – | – | – | – | 680 | – | 220 | 0.6 |
| | LWC-1 | 400 | – | 318 | 318 | – | – | – | 680 | – | 220 | – |
| | CSSC-1 | 400 | – | – | – | 1338 | – | – | 680 | – | 220 | – |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SSGC-1 | 400 | – | – | – | 912 | 136 | – | 680 | – | 220 | – |
| 2nd | NC-2 | 420 | 1083 | – | – | – | – | – | 722 | – | 168 | 1.4 |
| | LWC-2 | 420 | – | – | 490 | – | – | – | 722 | – | 168 | 2.2 |
| | CSSC-2 | 420 | – | – | – | 1432 | – | – | 722 | – | 168 | 1.0 |
| | SSGC-2 | 420 | – | – | – | 1193 | – | 179 | 722 | – | 168 | 2.0 |
| | FSSC-2 | 420 | 1083 | – | – | – | – | – | – | 989 | 168 | 1.2 |
| Fire test | NC-F | 420 420 | 1070 | – – | – | – – | – – | – – | 714 714 | – – | 176.4 | 1.4 |
| | LWC-F | | – | | 480 | | | | | | 176.4 | 2.2 |
| | CSSC-F | 420 | – | – | – | 1418 | – | – | 714 | – | 176.4 | 1.0 |
| | SSGC-F | 420 | – | – | – | 1170 | – | 175 | 714 | – | 176.4 | 2.0 |
| | FSSC-F | 420 | 1070 | – | – | – | – | – | 413 | 413 | 176.4 | 1.2 |

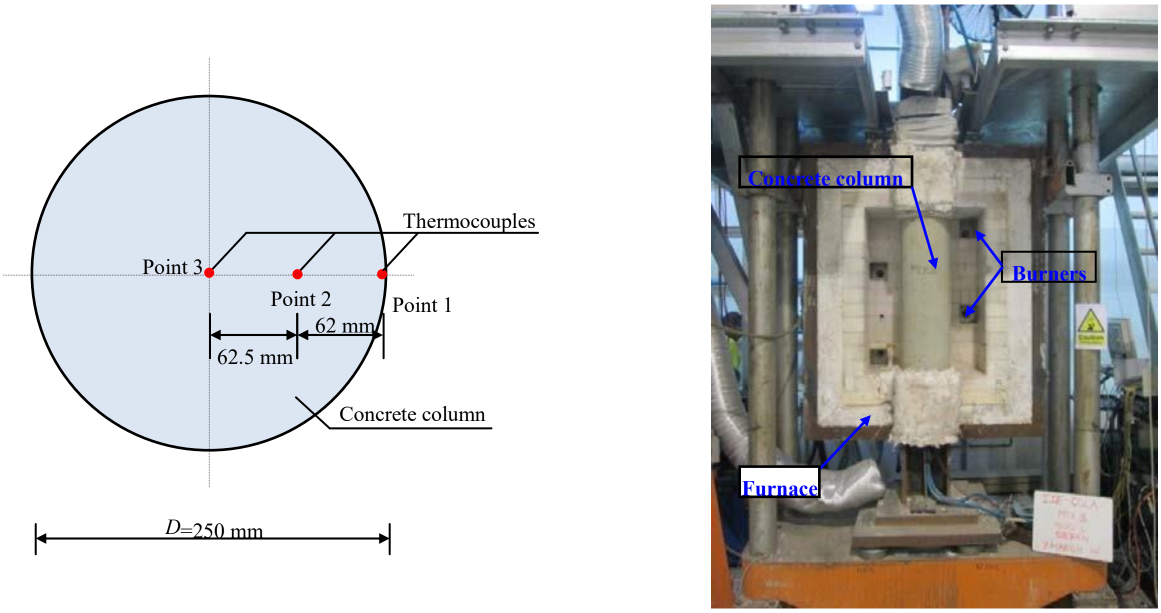
### 2.2.2. Test setup and procedure

The Western Sydney University in Australia's Structures Laboratory used a gas furnace to conduct the fire tests. The floor area of the furnace chamber is 640 mm wide by 630 mm deep, and its height is 880 mm. The concrete specimen was put in the furnace as illustrated in Fig. 3(b) before being exposed to fire. The specimen was then subjected to the predefined axial compressive load (No). Nu is the ultimate load-bearing capability of the concrete column at room temperature, and the load level (n) is defined as No/Nu. Nu is calculated as Acfc',test, where Ac denotes the column's cross-sectional area and fc',test denotes the concrete's determined compressive strength on the day of the fire test. All specimens' load level (n) was initially set at 0.45. However, the initial NC-F specimen with limestone aggregate only managed a brief 15-minute fire resistance period under this load level. If the specimens in the fire could sustain the load for a longer amount of time, it was envisioned that the impact of aggregate type on the fire performance could be examined more clearly. Thus, for the remaining four concrete columns, the load level was decreased to 0.3. For each specimen, the actual applied load No is listed in Table 5.

**Table 5** Details of concrete columns tested in fire.

| Specimen label | Load level $n$ | Applied load $N_o$ (kN) | essive strength $f_c'$ (MPa) | | Modulus of elasticity $E_c$ (GPa) | |
|---|---|---|---|---|---|---|
| | | | 28 days | Fire test | 28 days | Fire test |
| NC-F | 0.45 | 872 | 36.1 | 39.5 | 33.4 | 32.7 |
| LWC-F | 0.3 | 448 | 29.0 | 30.4 | 18.6 | 20.7 |
| CSSC-F | 0.3 | 587 | 37.4 | 39.9 | 36.1 | 36.7 |
| SSGC-F | 0.3 | 594 | 35.2 | 40.4 | 34.8 | 36.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| FSSC-F | 0.3 | 721 | 48.1 | 49.0 | 44.1 | 46.0 |



(a) (b)

**Fig. 3.** Positions of thermocouples in the cross-section and the test setup.

## 3. Material properties of concrete at room temperature

### *3.1. Workability*

The new mixtures were typically well-coordinated and usable. During the installation of the concrete, there was no separation of the coarse aggregate particles from the mortar matrix. After placement, however, no visible bleeding was discovered in the newly placed concrete. At the time of placement, common slump tests were used to gauge the concrete's workability. For various concrete mixtures, the measured initial slump values are displayed in. As anticipated, the concrete mixes with the first batch's higher water/cement ratio of 0.55 often had greater slump values than the mixes with the second batch's lower water/cement ratio of 0.40. Compared to the other mixes in the same batch, CSSC-1's concrete had reduced workability because steel slag was used to substitute coarse aggregate 100 percent of the time. Because coarse steel slag has more angular forms than other aggregates, it has a lower workability [3]. The slump values of various concrete mixes in the second batch were kept at a comparable level by adding an appropriate volume of water reducer. Additionally, it was discovered that waste glass might raise the slump value of concrete made with steel slag. This is because waste glass and cement paste do not adhere as well to one another [16].

### *3.2. Density*

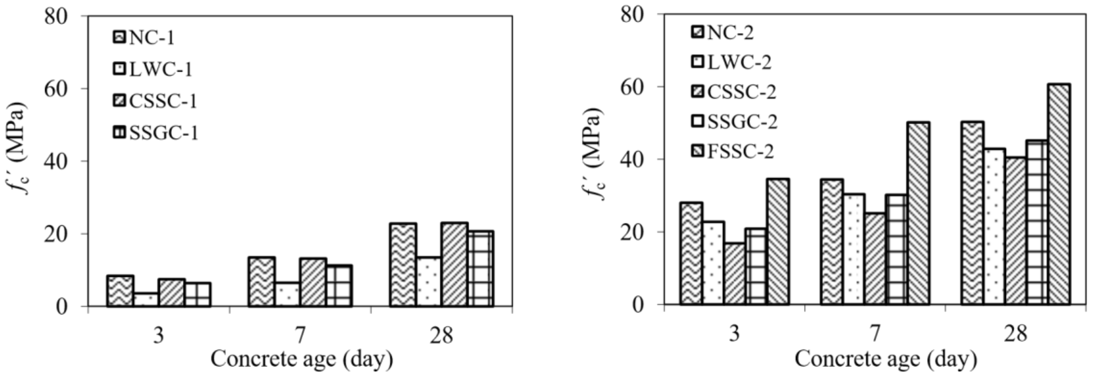
The table shows the measured density values for concrete at ages of 3, 7, and 28 days. From the age of 3 days to 28 days, the density of a particular concrete mix stayed mostly constant and only slightly varied, which might be explained by measurement mistakes. The proportionate increases or decreases in densities of various types of concrete are displayed in brackets in Table in comparison to the density of the typical concrete with limestone. As can be observed, the lightweight aggregate's comparatively low specific gravity caused the density of the lightweight concrete to decrease by over 20%. LWC-2's density, nevertheless, was a little bit greater than LWC-1's. This is because mix LWC-2 was made with less lightweight aggregate than usual.

Another finding is that the concrete density rose by around 10% when steel slag was used as the coarse material. On the other hand, the concrete density rose by around 13% if simply the sand was substituted with steel slag. Because waste glass has a lower specific gravity than steel slag, adding it to steel slag concrete may be able to reduce the density increase. The density increase in the concrete mixes SSGC-1 and SSGC-2 created with steel slag and waste glass was only around 5% when compared to the reference concrete.

### *3.3. Mechanical properties*

#### *3.3.1. Compressive strength*

The compressive strengths (fc') of several kinds of concrete at various ages are contrasted in Fig. 4. With increasing concrete age, the compressive strength rose. Meanwhile, it was discovered that all forms of concrete were significantly impacted by the water to cement ratio. When the water/cement ratio was decreased from 0.55 to 0.40, the compressive strength of a certain type of concrete nearly doubled.



(a) First batch (b) Second batch

**Fig. 4.** Compressive strength for different types of concrete.

Due to the poorer pore structure of lightweight aggregate, particularly for big size aggregate (20 mm), lightweight concrete (LWC-1) in the first batch of concrete had the lowest compressive strength. This strength was only about half that of conventional concrete. The second batch (LWC-2) of lightweight concrete only used 14 mm lightweight aggregate, and its strength was around 85% that of regular concrete. In order to get better concrete strength for lightweight concrete, smaller size lightweight aggregate may be employed. The fc'-value of LWC-2 at 28 days was 42.9 MPa, which is the equivalent of structural concrete.

The use of steel slag aggregate has been shown in several studies to boost the concrete's compressive strength by up to 20% or even more [3,28]. This is primarily explained by the increased angularity of steel slag aggregate, which, when compared to natural aggregate, might result in better mechanical interlock with cement paste [29]. But several studies also suggest that steel slag concrete's compressive strength is comparable to or even lower than that of the reference concrete [4,5,30,31]. For instance, Brand and Roesler [29] assessed how two different kinds of steel slag aggregate affected the characteristics of concrete. One form of steel slag concrete was found to have a compressive strength that was 5.1% greater than dolomite concrete, but the other type of steel slag concrete had a 12.7% lower compressive strength. It emphasises that many parameters, including cooling process, chemical composition, porosity, density, and ageing method, should be taken into consideration since the quality of steel slag aggregate has an impact on concrete strength as well.

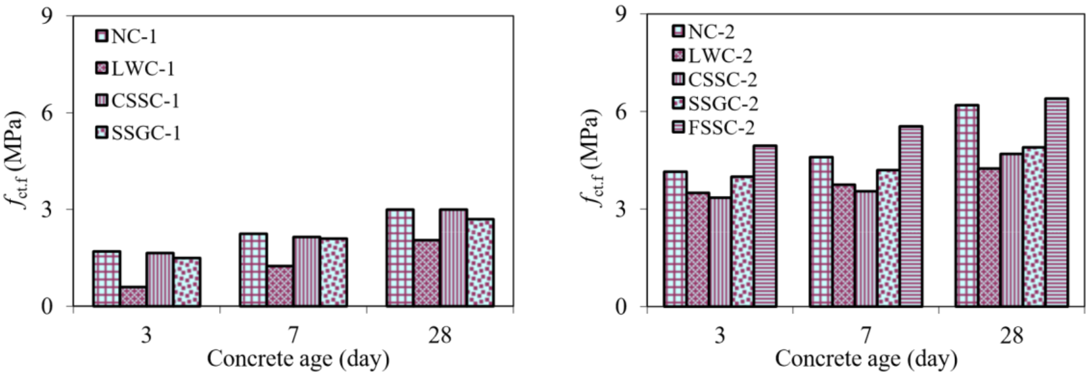
At 28 days, CSSC-1's compressive strength for the present concrete samples was 23.0 MPa, which was nearly as strong as the reference mix NC-1's 22.8 MPa. However, CSSC-2's observed fc'-value at 28 days was only 40.5 MPa, much lower than the control mix NC-2's recorded fc'-value of 50.3 MPa. Following examination of the crushed samples, it was discovered that the failure plane for CSSC-2 was through the steel slag aggregate itself, but for mixes CSSC-1, NC-1, and NC-2, fractures only happened in the cement paste and in the transition zone between the paste and aggregate. Therefore, the coarse steel slag's comparatively poor quality prevented the concrete from achieving a greater strength. This might be as a result of the steel slag's very lengthy weathering time. Steel slag aged from 0 to 3 months was studied by Kawamura et al. [32]. They discovered that when the slag weathered, its specific gravity fell and its propensity to absorb water rose. As the steel slag weathered, the compressive strength of concrete also significantly dropped. Of course, more investigation into steel slag is needed to determine the ideal weathering time.

It is anticipated that coarse waste glass will have a negative impact on the strength of concrete because it has bad form, poor surface qualities, and a high degree of friability [8]. The equivalent mix without waste glass (CSSC-1) had a similar strength of 23.0 MPa whereas mix SSGC-1 had a compressive strength of 20.7 MPa at 28 days. When compared to the control mix NC-2, the compressive strength for SSGC-2 in the second batch at 28 days dropped by 10.1%. In contrast to mix CSSC-2 with coarse steel slag, mix SSGC-2 showed a greater compressive strength. At 28 days, SSGC-2's fc'-value was 45.2 MPa whereas CSSC-2's was 40.5 MPa. This is because the SSGC-2 changed the maximum size of waste glass from 16 mm to 10 mm. The compressive strength of SSGC-2 was improved by substituting smaller-sized waste glass with larger-sized steel slag. According to Shao et al. [11], employing waste glass of a smaller size can lessen its negative impact on the compressive strength of concrete. Due to the relatively little impact on concrete strength, a replacement ratio for waste glass of up to 17.5% by volume may often be deemed appropriate.

The mix FSSC-2 produced a fc'-value of 60.7 MPa at 28 days, which was 20.7% stronger than the comparable compressive strength of the control mix NC-2. This mix had 100% of the sand replaced by fine steel slag. The use of fine steel slag resulted in an increase in strength because of the improved interlocking between porous steel slag and cement paste, which improved the transition zone between the paste and aggregate [29]. It appears that the quality of the fine steel slag was unaffected by the prolonged weathering.

### 3.3.2. Flexural strength

According to Fig. 5, flexural strength of a particular kind of concrete (fct.f) rose with increasing concrete age in a manner similar to compressive strength. For the same kind of concrete, the fct.f increased dramatically when the water/cement ratio was decreased from 0.55 to 0.40. The age of the concrete and the water to cement ratio had less of an impact on the flexural strength than on compressive strength, though. For the first batch of concrete, the fct.f/fc' ratio varied from 0.20 to 0.23 at 3 days, with the exception of the lightweight concrete. The ratio decreased to roughly 0.13 after 28 days. The ratio of fct.f/fc' for the first batch of lightweight concrete mix LWC-1 ranged from 0.15 to 0.19. The fct.f/fc' ratio for the second batch of concrete varied between 0.14 to 0.20 at 3 days and 0.10 to 0.12 at 28 days.



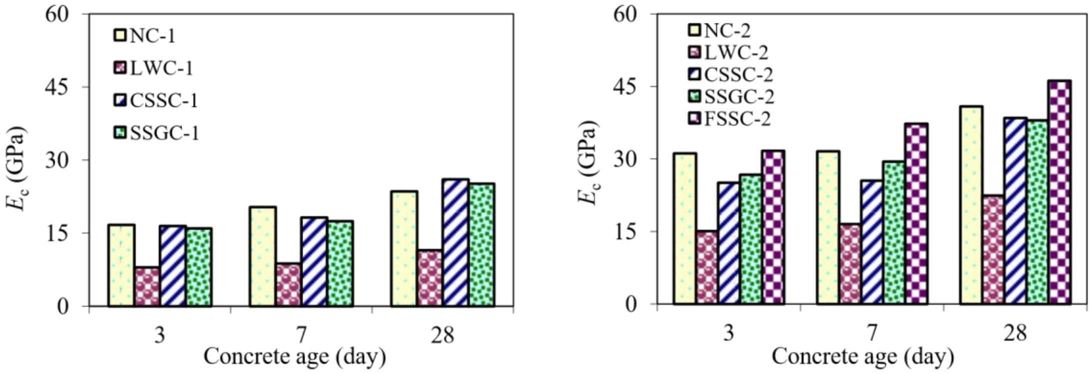
(a) First batch (b) Second batch

**Fig. 5.** Flexural strength for different types of concrete.

In general, aggregate type had a comparable impact on flexural strength as it did on compressive strength. Lightweight concrete often has the lowest flexural strength of all the different forms of concrete. The flexural strength of lightweight concrete was around 68% that of regular concrete at a concrete age of 28 days. Similar flexural strength was found for mix CSSC-1 created with coarse slag aggregate concrete when compared to the control mix NC-1, however mix CSSC-2's flexural strength was 19–24% lower than that of the control mix NC-2. When compared to concrete mix CSSC-1 in the first batch, adding waste glass to mix SSGC-1 reduced flexural strength by 2.3% to 10%. On the other hand, when smaller-sized waste glass was added in the second batch to replace larger-sized coarse steel slag, flexural strength for mix SSGC-2 increased by up to 16.3%. The early stage flexural strength was greatly boosted by around 20% by using fine steel slag substitution in mix FSSC-2. Only 3.2% more flexural strength was seen in mix FSSC-2 at day 28 compared to control mix NC-2.

### *3.3.3. Modulus of elasticity*

In Fig. 6, the elastic modulus (Ec) values for several kinds of concrete are contrasted. With increasing concrete age, the modulus of elasticity rose consistently. The value of Ec was dramatically raised by decreasing the water/cement ratio. The impact of aggregate type on Ec generally had a comparable effect to that on compressive strength. Among all varieties of concrete, lightweight concrete had the lowest Ec values; its elastic modulus was only approximately half that of the control concrete in the same batch. Others [18] observed a similar discovery, which can be attributed to the lightweight aggregate's large number of pores. Although steel slag also has internal pores, steel slag concrete had an elasticity modulus that was significantly closer to that of regular concrete. When compared to the control mix NC-1 with a water/cement ratio of 0.55, the modulus of elasticity for mix CSSC-1 created with coarse slag aggregate was similar to or even greater. When compared to the control mix NC-2, Ec of mix CSSC-2 with a water/cement ratio of 0.40 was around 19% lower at 3 and 7 days, but only about 6% lower after 28 days. When compared to mix CSSC-1 in the first batch, concrete mix SSGC-1 included larger-sized waste glass, which resulted in a 3.0–4.1% reduction in Ec. Similar modulus of elasticity was obtained for mix SSGC-2 at 28 days when compared to mix CSSC-2 when smaller-sized waste glass was used in the second batch to replace larger-sized coarse steel slag; the values of Ec for mix SSGC-2 at 3 and 7 days were, respectively, higher than those of mix CSSC-2. Fine steel slag replacement in mix FSSC-2 raised Ec by 13–18% at 7 or 28 days compared to control mix NC-2, but had no discernible effect at 3 days.



(a) First batch (b) Second batch

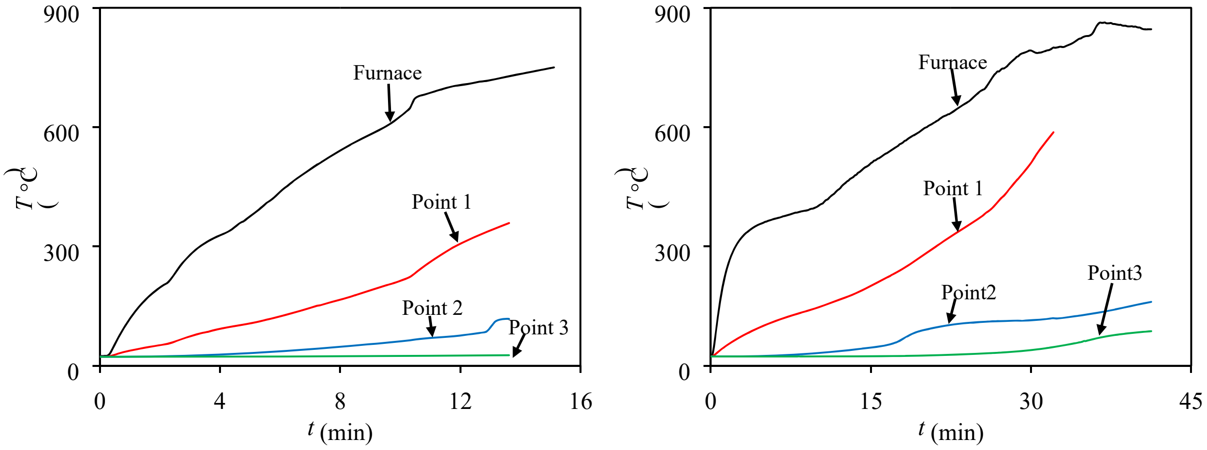
**Fig. 6.** Modulus of elasticity for different types of concrete.

## 4. Fire behaviour of concrete

### *4.1. Temperature distribution*

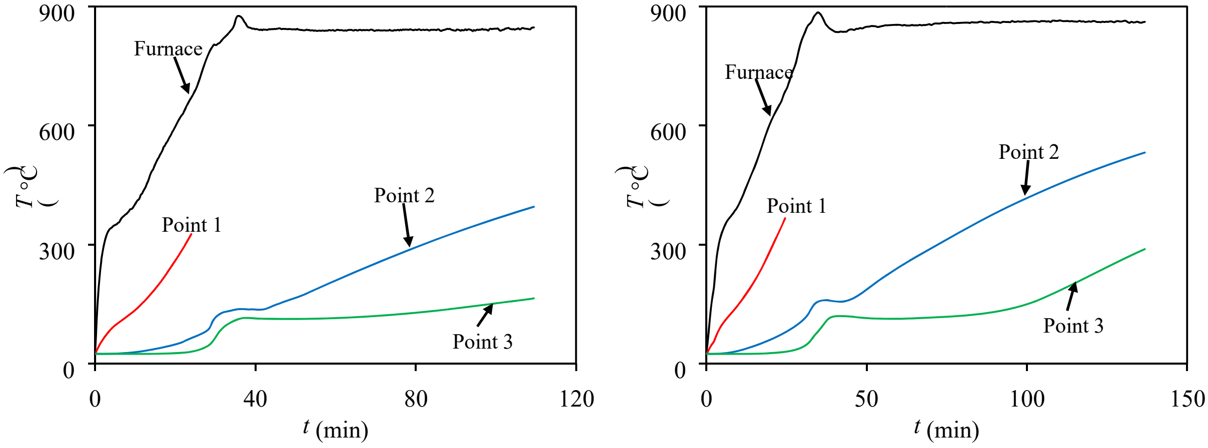
The observed temperature (T) vs time (t) curves for various concrete columns are shown in Fig. 7. The graphic also shows the average furnace temperatures as a function of time. It should be mentioned that several of the thermocouples used to detect the concrete's outside surface temperature malfunctioned during the fire test, hence the corresponding recorded temperatures were only accessible for a brief time during the fire exposure. As was previously noted, concrete column NC-F (normal concrete) collapsed after 15 minutes of fire exposure, therefore instead of reaching 800 °C in the furnace, this specimen only achieved 750 °C.

Because concrete has a relatively limited heat conductivity, the temperatures inside a concrete column were often lower than the temperature inside a furnace. Water evaporation caused the observed T-t curves at points 2 and 3 to plateau at about 100 °C. Part of the heat transfer rate in a column may be represented by the beginning of the plateau at point 2. For point 2 in NC-F (normal concrete), LWC-F (lightweight concrete), CSSC-F (coarse steel slag concrete), SSGC-F (concrete with coarse steel slag and glass), and FSSC-F (fine steel slag concrete), the corresponding moments reaching 100 °C were 13 min, 22 min, 29 min, 29 min, and 26 min, respectively. As can be observed, the porous structure of the lightweight aggregate and steel slag helped to reduce the heat transmission, which is why the temperature rise in lightweight concrete and steel slag concrete was slower than that in conventional concrete. The temperatures of points 2 and 3 at 100 minutes are compared to further assess the temperature development in various varieties of steel slag concrete. For the specimens CSSC-F, SSGC-F, and FSSC-F, the measured temperatures were 366 °C, 417 °C, and 414 °C at point 2 and 153 °C, 150 °C, and 182 °C at point 3, respectively. The heat transmission appears to have been the slowest in CSSC-F, followed by SSGC-F, and the quickest in FSSC-F.



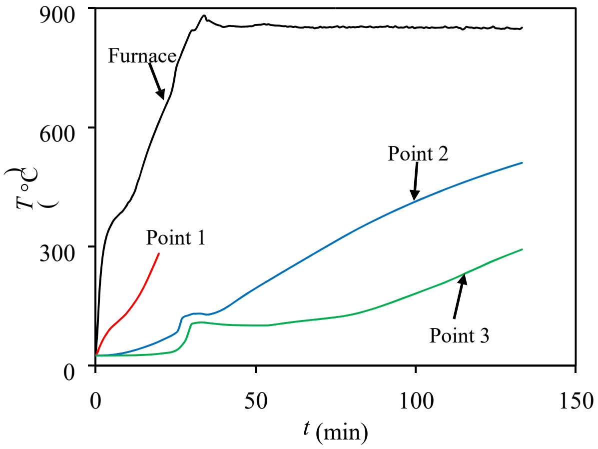
(a) NC-F (normal concrete)

(b) LWC-F (lightweight concrete)



(c) CSSC-F (coarse steel slag concrete)

(d) SSGC-F (concrete with steel slag & glass)

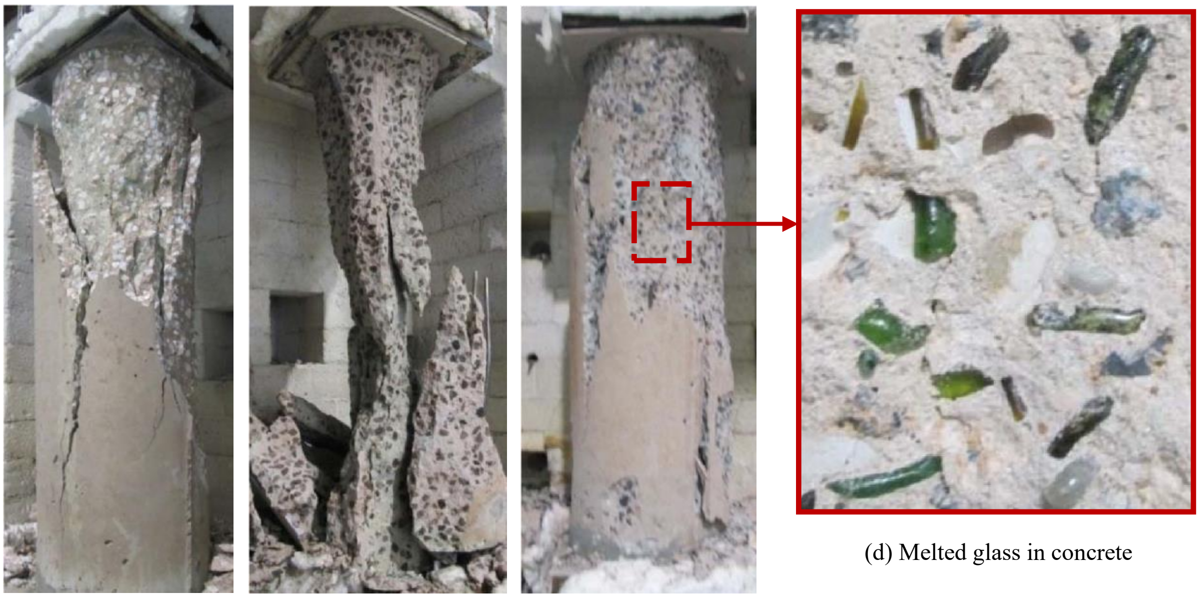


(e) FSSC-F (Fine steel slag concrete)

**Fig. 7.** Measured temperatures for different columns.

### *4.2. General observation*

During the test, two different failure scenarios were seen. One of them has considerable concrete spalling caused by the combined effects of warmth and axial stress. This failure mechanism was demonstrated by two concrete columns labelled NC-F (normal concrete) and LWC-F (lightweight concrete), as illustrated in Fig. 8(a) and (b). The other type of failure, as illustrated in Fig. 8(c), was brought on by a substantial axial distortion of the column with less concrete spalling. Concrete columns built with steel slag showed this form of collapse, indicating superior concrete integrity during the fire test. This might be explained by the steel slag's porous nature, which permits water vapour to easily escape at high temperatures and reduces internal pore pressure.



(d) Melted glass in concrete

(a) Normal concrete

(b) Lightweight concrete

(c) Concrete with steel slag & glass

**Fig. 8.** Failure mode for typical concrete columns after test.

### *4.3. Deformation development*

The concrete columns' axial deformation () against time (t) graphs are displayed in Figure 9. The expansion, contraction, and failure phases are the three common stages for the t curve. The concrete column began to expand during the expansion stage as a result of the thermal expansion of concrete until it reached the point of greatest axial expansion. Due to the loss of concrete's material qualities at high temperatures as the fire duration lengthened, the column progressively began to compress. Finally, the column's axial contraction deformation rose abruptly and the column failed when it was unable to withstand the imposed axial load.

With a fire resistance of 136 minutes, column SSGC-F outlasted the other four examples. All three columns containing steel slag had fire resistance that was greater than 100 minutes. In comparison to the steel slag concrete columns, the lightweight concrete specimen LWC-F broke after around 40 minutes, showing a much poorer fire resistance. The typical concrete column NC-F has a fire resistance of 15 minutes at a higher load level of 0.45. Even if the load level of specimen NC-F were lowered to 0.3, specimen NC-F would still have a lower fire resistance than specimen LWC-F since it is predicted that lightweight concrete columns will have stronger fire resistance than standard concrete columns [34]. This argument shows that steel slag concrete performed better in a fire.

First off, using porous steel slag prevented the concrete from becoming too hot. In addition, steel slag is a substance created at temperatures as high as 1650 °C [15]. Thus, using steel slag aggregate can significantly improve concrete's thermal stability.

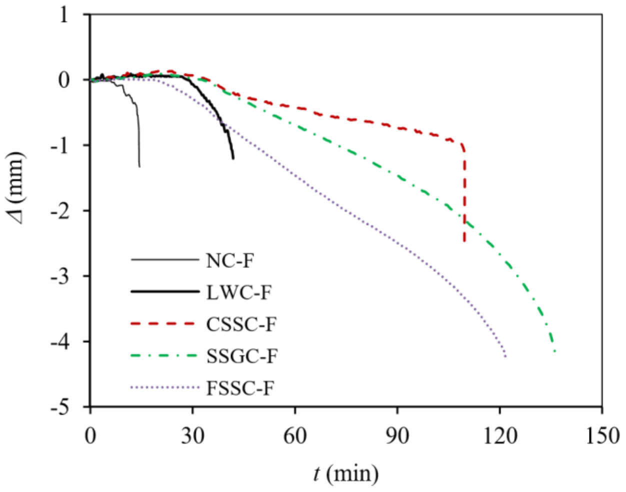


**Fig. 9.** Comparison of axial deformation (□) versus time (*t*) curves for the concrete columns.

The contraction rate of CSSC-F, which included coarse steel slag, was lower before failure than that of the other two columns, SSGC-F and FSSC-F, as can also be shown in Fig. 9. But CSSC-F showed an unexpected failure. It is possible to increase the deformation capacity and prevent unexpected concrete failure by utilising fine steel slag or adding waste glass. In particular, it may be beneficial to lessen the thermal stress brought on by the differential in thermal expansion and contraction at the concrete surface.

## 5. Conclusions

The following conclusions can be drawn based on this study:

(1) Waste glass may make steel slag concrete more workable. To keep the concrete workable, it is advised to only replace a portion of the natural fine aggregate with fine steel slag.

(2) Using waste glass as an additive to steel slag concrete can reduce the density increase caused by the use of steel slag as aggregate.

(3) Concrete's mechanical qualities can be improved by adding coarse steel slag aggregate, however utilising inferior coarse steel slag might backfire. Weathering has no overt impact on the quality of fine steel slag. The mechanical qualities of concrete are only slightly affected when waste glass is substituted for coarse steel slag at a replacement ratio of up to 17.5% by volume.

(4) Waste glass and steel slag have the ability to increase concrete's fire resistance.

It should be mentioned that the current study solely examines the effects of steel slag and waste glass on the mechanical characteristics and fire performance of concrete at macroscopic sizes. The microscopic textures and chemical changes of concrete with or without steel slag/waste glass before and after exposure to fire still need to be studied in more detail. Such information is necessary to direct future efforts to enhance the performance of concrete and to make it easier to apply concrete in practise.

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