

STRENGTHS AND SORPTIVITY OF LIGHTWEIGHT FOAMED CONCRETE WITH CRUSHED STEEL SLAG

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ABSTRACT

Rapid construction development demands numerous raw materials namely river sand from the nature and yield a great amount of wastes namely steel slag. These result in depletion of natural sand and also result in environmental issues for steel slag disposal. As needed, the researchers are attempting to incorporate steel slag in construction materials to reduce the environmental impact. Meanwhile, as construction speed, cost, and handling capacity are concerned, lightweight construction materials namely lightweight foamed concrete are demanded at load-bearing and non-load bearing components during construction. Based on these demands, this study is aim to evaluate the effects of crushed steel slag on strength properties and water absorption of lightweight foamed concrete with hardened density of $1650 \pm 75 \text{ kg/m}^3$. In this study, sand and steel slag were underwent gradation control to have a specific gradation, cement to sand ratio of 1:1 and steel slag replacement levels of 0%, 25%, 50%, 75%, and 100% was adopted. The specimens were water cured at temperature of 26 to 29 °C. When the steel slag replacement level was increased, the results showed decreased compressive, split tensile and flexural strengths. On the other hand, the compressive strength achieved minimum structural strength of 17 MPa at steel slag replacement level of 25% and lesser. Besides, the specimens with 75% to 100% steel slag replacement levels achieved better long term strength development after 28 days compared to those with 25% to 50% replacement levels. In addition, water absorption and sorptivity were increased with the higher steel slag replacement level. For all the replacement levels, water absorption and sorptivity of the specimens were in the range of 9.8% to 21.4% and $0.179 \text{ mm/min}^{0.5}$ to $0.427 \text{ mm/min}^{0.5}$ respectively. Based on the strength and sorptivity results, it is feasible to replace sand with 2.36mm gradation steel slag at up to 25% in lightweight foamed concrete for structural application.

Keywords: Lightweight Foamed Concrete, Steel Slag, Strength Properties, Sorptivity, Specific Gradation.

1. INTRODUCTION

Lightweight foamed concrete (LFC) is obtained by introducing stable foam to cement mortar by selected method and suitable foaming agent to achieve wide range of densities from 400 kg/m^3 to 1840 kg/m^3 , and is applied widely in structural, partition, insulation, and filling grades (Neville & Brooks, 2004; Ramamurthy *et al.*, 2009).

LFC is able to fulfill various construction demands. For instance, its low density shorten construction period by reduce demand in transport and workmanship, and by allow larger pre-cast segment. Besides, its low density can reduce foundation design requirement.

As reviewed by Amran *et al.* (2015), annual market size of foamed concrete is estimated 250,000 – 300,000 m^3 in the UK, 50,000 m^3 in Western Canada, and 250,000 m^3 just in floor heating system in Korea (Jones & McCarthy, 2005; Rößler & Odler, 1985; Yang *et al.*, 2014).

It was observed and concluded that foamed concrete has potential to utilize industrial wastes such as incinerator bottom ash, recycle glass, rubber tyre (crumbs), foundry sand, and china clay as raw materials. These industrial wastes will cause environmental issues if not disposed or reused properly (Jones *et al.*, 2005; as cited in Falade *et al.*, 2015).

Steel slag (SS) is by-product of steel manufacturing. From the researches carried out in the Asian country, approximately 10% of SS was produced from the production of steel (Oluwasola *et al.*, 2014). According to statistic done by The World Steel Association, 1620 million tons of crude steel was produced world wise, in which, 3.8 million tons was produced in Malaysia at 2015 ("Steel Statistical Yearbook", 2017). So, it can be estimated approximately 0.38 million tons of SS was produced at 2015 in Malaysia.

Steel slag utilization rate is relatively high at developed country. A survey conducted by EUROSLAG at 2012 among its members (European steelworks and processing companies) shows that 21.4 million tons of SS was produced but 24.7 million tons was used, which make up 115.4% of utilization rate ("2012: Euroslag", 2017). In additional, in Japan, 74.6% of SS production was sold externally and 24% was used internally, which make up 96.6% of utilization rate at 2016 ("Iron and Steel Slag Statistics: NIPPON SLAG ASSOCIATION", 2017).

However, SS utilization rate is relatively low at developing and undeveloped country. The utilization rate of SS is only 22% in China (Yi *et al.*, 2012). And the utilization rate of SS in Malaysia is also very low compared to advanced country. Albeit, SS is still being used in some applications such as asphalt aggregate for road construction, sub-base, cement stabilization, ground improvement, and some other miscellaneous usages (Oluwasola *et al.*, 2014).

When utilization rate of SS is low, SS is disposed and result in problems such as land usage issue, social issue, environmental issue, health issue, etc. In order to increase SS utilization rate, by intended to mitigate impacts caused by SS disposal and meanwhile reduce construction cost, the researchers were attempting to introduce SS to various construction materials such as normal weight concrete as well as foamed concrete.

Maslehuddin *et al.* (2003) replace coarse aggregate (SG=2.51) with steel slag (SG=3.51) in normal concrete and obtain 5% improvement in compressive strength, reduction in absorption and permeability, but no significant improvement in the flexural and split tensile strengths, in which, density of concrete increased by 17% after replacement.

Olonade *et al.* (2015) replace sand with SS in normal concrete with strength of around 21MPa and found 9.8% to 11.5% increment for compressive strength at 25% to 50% SS replacement levels and no significant effect on flexural strength, in which, sand and SS have similar gradation but SS has slightly higher amount of particle passing through 0.6mm sieve size, and the density of concrete increased with SS replacement level.

Kothai and Malathy (2014) partially replace sand (SG=2.65) with steel slag (SG=2.95) in normal concrete with compressive strength of around 24MPa and found increment of compressive strength at 5% to 10% when SS replacement level is between 20% and 40%, but increment on tensile strength is negligible; the gradation shows that SS used has larger portion of particle with smaller sieving size than that of sand.

Falade *et al.* (2015) replace river dredged sand (SG=2.66) with pulverized steel slag (SG=3.47) in LFC and found that the compressive strength is gradually increased up to 20% from 0% to 30% SS replacement level, further increment of SS replacement level had reduced the strength, in which, the densities and 28 days strengths of LFCs is 1211 kg/m³ to 1422 kg/m³ and 2.519 MPa to 4.370 MPa respectively depend on curing method, but the gradation of sand and SS are not specified. Besides, the study also reported a higher compressive strength for air-cured specimens compared to water cured specimens.

Based on the above literature review, it was found that the feasibility of SS to be incorporated in medium and high strength LFC for both structural and non-structural purposes is worth to be investigated.

This paper is aimed to study the effects of crushed steel slag on strength properties of LFC with density of 1650 ± 75 kg/m³ in terms of compressive, split tensile, and flexural strengths at ages of 7, 28, 56, and 90, days, where the gradation of SS is same as that of sand, SS is replacing the sand at replacement levels of 0%, 25%, 50%, 75% and 100%, water to cement ratio and dosage of super-plasticizer are vary in each SS replacement level to obtain specific base mix mortar density and specific volume of foam. Besides, effect on other properties namely water absorption and sorptivity are also included in this study.

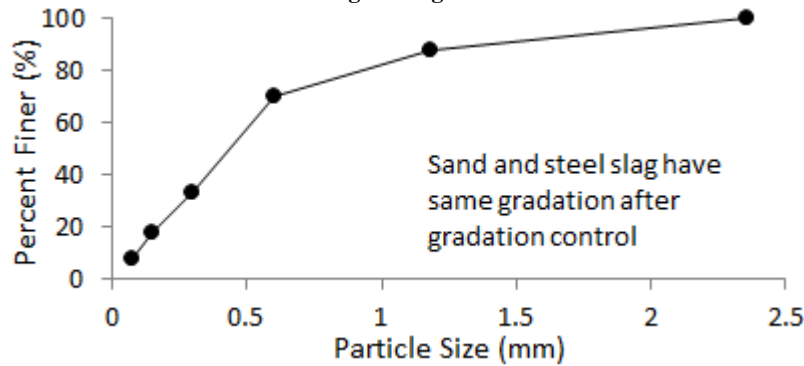
2. EXPERIMENTAL PROCEDURES

2.1 MATERIALS

Cement, sand, steel slag, water, foam agent and super-plasticizer (SP) were used to prepare testing specimens.

The ordinary Portland cement (OPC) complying with Type I Portland Cement in accordance with ASTM C 150 (2005) was selected. It was sieved through 300 μ m to remove all lumps, and stored in moisture-proof container indoor before mixing (Tiong *et al.*, 2017). The natural river sand was oven-dried; the SS obtained from local hot-roll steel manufacturer, was washed, oven-dried, and crushed. Both sand and SS were subjected to gradation control to have equivalent gradation as shown in **Figure 1** (Tiong *et al.*, 2017).

Figure 1: Gradation of Sieved Sand and Crushed and Sieved Steel Slag With 100% Passing Through 2.36mm Sieve Size



The water used was tap water from the municipal water supply in accordance with ASTM C 1602 (2006). The foaming agent used was type of petroleum base synthetic detergent. Besides, the carboxylic ether type super-plasticizer was used in this study (Tiong *et al.*, 2017).

Foam was produced by using foam generator. Foaming agent was mixed with water at ratio of 1:30 in foam generator. Thereafter, high pressure was used to push the mixture through a series of wire mesh to produce the foam with density of approximately $40 \pm 5 \text{ kg/m}^3$.

2.2 MIX PROPORTIONS

In this study, LFCs was prepared by using pre-foaming method, where base mix mortar and pre-formed foam were produced separately, then, weighted foam was added to mortar part by part, and mix thoroughly thereafter (Ramamurthy *et al.*, 2009; Byun *et al.*, 1998).

Base mix mortar and foamed concrete were hand mixed in mixing bowl. Mix proportion for reference mix (0% steel slag replacement) was adopted; with refer to Tiong *et al.* (2017). Cement to sand ratio of 1:1 was adopted. Water to cement ratio (w/c) of 0.38 in reference mix was adopted in which, further increment of w/c will subjected to strength decrement, and further decrement of w/c will adversely prolong mixing time. Due to higher specific gravity of SS than sand, w/c and dosage of super-plasticizer (SP) were adjusted at LFC mixtures with SS to obtain specific density and flowability consistency of base mix mortar as per reference mix. The LFC mix proportions, theoretical base mix densities, and theoretical foam amount required for different SS replacement levels are presented in **Table 1**.

Table 1: Mix Proportions and Details of Various Foamed Concrete with Different Replacement Levels of Steel Slag

| Replacement level | | 0% | 25% | 50% | 75% | 100% |
|--|---------------------------------------|-------|--------|-------|--------|-------|
| w/c | | 0.38 | 0.4325 | 0.485 | 0.5375 | 0.59 |
| SP (%) | | 1 | 0.75 | 0.5 | 0.25 | 0 |
| material per m ³ foamed concrete | cement (kg) | 693 | 678 | 664 | 650 | 637 |
| | sand (kg) | 693 | 509 | 332 | 163 | 0 |
| | steel slag (kg) | 0 | 170 | 332 | 488 | 637 |
| | water (kg) | 261 | 291 | 320 | 349 | 376 |
| | SP (L) | 2.63 | 2.20 | 1.61 | 0.87 | 0.00 |
| base mix density (kg/m ³) ¹ | | 2214 | 2214 | 2213 | 2213 | 2213 |
| foam required | volume (m ³) ² | 0.255 | 0.255 | 0.255 | 0.254 | 0.254 |
| | mass (kg) | 11.47 | 11.46 | 11.45 | 11.45 | 11.44 |

Note:

¹Base mix mortar density fixed at around 2214 kg/m³

²Foam volume fixed at around 0.255m³/m³

³Final LFCs density fixed at $1650 \pm 75 \text{ kg/m}^3$

2.3 TESTING METHODS

Testing methods included inverted slump test, compression, split tensile, and flexural tests, water absorption test, and sorptivity test.

Before casting, inverted slump test was performed as per ASTM C 1611 (2005) to determine the spread diameter of LFC. The slump cone, as per ASTM C 143 (2008), was inverted and placed on a flat base plate, and then filled with LFC. The slump cone was then lifted up vertically with a distance of 225 ± 75 mm in 3 ± 1 seconds. The average spread diameter was measured after the LFC stop flowing (Tiong *et al.*, 2017).

The hardened specimens were water cured at temperature of 26 to 29 °C until 1 day before testing day. Then, the specimens were oven-dried for 1 day before testing. Three specimens were tested for each testing method and each testing day.

Compressive test was conducted as per BS EN 12390-3 (2002). The cubical specimens with dimension of 100 mm were tested by using a universal compression machine with loading rate of 3 kN/s (Tiong *et al.*, 2017).

Split tensile test was conducted as per BS EN 12390-6 (2000). The cylindrical specimens with 100 mm diameter and 200 mm length were place horizontally with packing strip and tested by universal compression test machine with loading rate of 1.76 kN/s (Tiong *et al.*, 2017).

Flexural test was conducted using centre-point loading method as per BS EN 12390-5 (2000). The specimens with width and depth of 40mm and total length of 160mm were tested by using testing machine named INSTRON 5582 with effective length of 120mm and loading rate of 0.008 mm/min (Tiong *et al.*, 2017).

Water absorption (WA) was conducted as per BS 1881-122 (1983). The saturated surface dry weight and oven-dried weight of cubical test specimens with dimension of 100 mm were measured to calculate WA.

Sorptivity test was conducted as per ASTM C 1585 (2004). The cylindrical specimens with 100 mm diameter were oven-dried and cut to 50 mm height. Then the specimens were weighted and immersed in water at depth of 1-2 mm by resting on steel rods to allow free water movement. The weight of the specimens was measured at 5, 10, 15, 30, 60, 90, 120, and 150 minutes.

3. RESULTS AND DISCUSSION

The properties of LFCs investigated included fresh property namely spread diameter and hardened properties namely compressive, split tensile, and flexural strengths, water absorption, and sorptivity. The 7 days and 28 days compressive, split tensile, and flexural strengths results of LFC reference mix are referred to Tiong *et al.* (2017).

3.1 WORKABILITY

Inverted slump test results were shown in **Table 2**. It was noticed that spread diameter increased gradually when SS replacement level increased to 25% and 50%, and then reduced dramatically when SS replacement level increased to 75% and 100%.

**Table 2: Spread Diameter of Various Foamed Concrete
with Different Replacement Levels of Steel Slag**

| Replacement Level | 0% | 25% | 50% | 75% | 100% |
|----------------------|-----|-----|-----|-----|------|
| Spread Diameter (mm) | 655 | 780 | 840 | 590 | 560 |

The initial increment might due to increment of water content, and final decrement might due to decrement of SP dosage. It was observed that spread diameter reduced when volume of foam exceed certain level due to high air content and adhesiveness of foam while addition of SP increased the flow rate (Amran *et al.*, 2015). When SS replacement level is 50% and below, in which SP dosage is 0.5% of cement weight and above, the SP is able to encounter this sort of adhesiveness and spread diameter is continue to increase with water content. When SS replacement level is 75% and above, in which SP dosage is below 0.25%, the SP dosage is insufficient to encounter the adhesiveness of foam, hence the spread diameter reduced.

3.2 COMPRESSIVE STRENGTH

The results of compressive strength with hardened density, performance index (PI), and percentage of compressive strength at various ages corresponding to 28 days compressive strength were tested and evaluated in **Table 3**. PI is proportion of strength to the unit density of 1000 kg/m³, calculated by strength divided by density (Tan *et al.*, 2015). Compressive strength results were also shown in **Figure 2**.

The results show that compressive strength was reduced when SS replacement level was increased. It was caused by larger amount of water content at higher SS replacement level to maintain specific base mix density and volume of foam required. It was found that certain amount of fine SS is able to improve the strength of concrete (Kothai & Malathy, 2014; Falade *et al.*, 2015), but effect from high water content was dominant the effect of SS. The previous researches which indicate increment of strength might because SS used have smaller specific gravity and LFC used have larger amount of foam and lower strength, so the adverse effect from added water is overcome by favourable effect from SS (Falade *et al.*, 2015); or because SS used have larger amount of particle with smaller particle size (Kothai & Malathy, 2014; Olonade *et al.*, 2015). Besides, when SS replaces sand in normal weight concrete, the density of concrete is increased and not required to reduce the density to as per reference mix.

Table 3: Compressive Strength Result for Various Foamed Concrete with Different Replacement Levels of Steel Slag

| Replacement level | | 0% | 25% | 50% | 75% | 100% |
|-------------------|---------------------------------------|------|------|------|------|------|
| 7 days | Hardened Density (kg/m ³) | 1647 | 1650 | 1635 | 1608 | 1627 |
| | Compressive Strength (MPa) | 17.0 | 12.8 | 11.3 | 8.1 | 7 |
| | PI (MPa/1000kg/m ³) | 10.3 | 7.8 | 6.9 | 5.0 | 4.3 |
| | 7 days / 28 days Strength | 69% | 70% | 72% | 70% | 71% |
| 28 days | Hardened Density (kg/m ³) | 1677 | 1652 | 1638 | 1617 | 1639 |
| | Compressive Strength (MPa) | 24.8 | 18.3 | 15.6 | 11.5 | 9.8 |
| | PI (MPa/1000kg/m ³) | 14.8 | 11.1 | 9.5 | 7.1 | 6.0 |
| 56 days | Hardened Density (kg/m ³) | 1625 | 1643 | 1642 | 1609 | 1620 |
| | Compressive Strength (MPa) | 22.3 | 17.7 | 15 | 12.4 | 10.9 |
| | PI (MPa/1000kg/m ³) | 13.7 | 10.8 | 9.1 | 7.7 | 6.7 |
| | 56 days / 28 days Strength | 90% | 97% | 96% | 108% | 111% |
| 90 days | Hardened Density (kg/m ³) | 1630 | 1604 | 1642 | 1580 | 1620 |
| | Compressive Strength (MPa) | 21.7 | 16.1 | 14.2 | 10.1 | 9.5 |
| | PI (MPa/1000kg/m ³) | 13.3 | 10.0 | 8.6 | 6.4 | 5.9 |
| | 90 days / 28 days Strength | 88% | 88% | 91% | 88% | 97% |

In aspect of aging effect, the compressive strength was decreased at later age; the decrement might due to smaller density achieved for the specimens tested at later age as shown in **Table 3**. Compressive strength of LFCs with SS replacement levels of 0%, 25%, and 50% started to decrease at 56 days, and compressive strength of LFCs with SS replacement levels of 75%, and 100% started to decrease at 90 days. For specimens with 75% and 100% SS replacement levels, the density achieved at 56 days was lower than that of 28 days, but the strength was still increased at from 28 days to 56 days. The strength was dropped at 90 days when the density achieved for 90 days specimens was further lower than that of 56 days. It was hence can be observed that SS might have favourable effect on long term strength. The aging effect can also be observed at **Table 3**, in which, the percentages of strength at 56 days and 90 days to 28 days were generally higher for specimens with 75% and 100% SS replacement levels compared to that of 25% and 50% SS replacement levels.

Figure 2: Compressive Strength of Lightweight Foamed Concrete with Various Steel Slag Replacement Levels at Different Ages

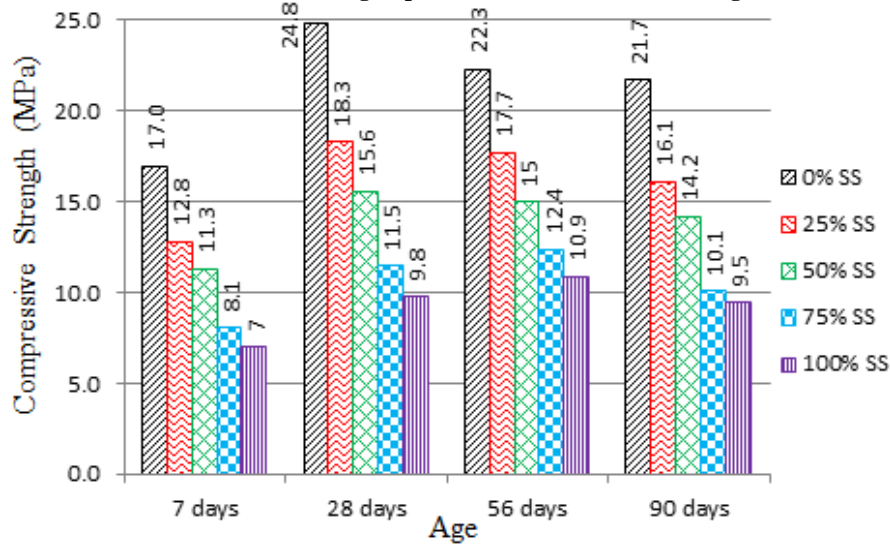


Table 4: Split Tensile Strength Result for Various Foamed Concrete and Different Replacement Levels of Steel Slag

| Replacement level | | 0% | 25% | 50% | 75% | 100% |
|-------------------|---------------------------------------|------|------|------|------|------|
| 7 days | Hardened Density (kg/m ³) | 1626 | 1641 | 1649 | 1622 | 1638 |
| | Split Tensile Strength (MPa) | 1.60 | 1.10 | 0.90 | 0.80 | 0.40 |
| | PI (MPa/1000kg/m ³) | 1.0 | 0.7 | 0.5 | 0.5 | 0.2 |
| | 7 days / 28 days Strength | 80% | 73% | 69% | 89% | 44% |
| 28 days | Hardened Density (kg/m ³) | 1659 | 1656 | 1650 | 1640 | 1642 |
| | Split Tensile Strength (MPa) | 2.00 | 1.50 | 1.30 | 0.90 | 0.90 |
| | PI (MPa/1000kg/m ³) | 1.2 | 0.9 | 0.8 | 0.5 | 0.5 |
| 56 days | Hardened Density (kg/m ³) | 1632 | 1647 | 1629 | 1613 | 1610 |
| | Split Tensile Strength (MPa) | 1.80 | 1.60 | 1.30 | 1.10 | 0.90 |
| | PI (MPa/1000kg/m ³) | 1.1 | 1.0 | 0.8 | 0.7 | 0.6 |
| | 56 days / 28 days Strength | 90% | 107% | 100% | 122% | 100% |
| 90 days | Hardened Density (kg/m ³) | 1654 | 1620 | 1641 | 1606 | 1637 |
| | Split Tensile Strength (MPa) | 2.10 | 1.40 | 1.20 | 1.20 | 0.90 |
| | PI (MPa/1000kg/m ³) | 1.3 | 0.9 | 0.7 | 0.7 | 0.5 |
| | 90 days / 28 days Strength | 105% | 93% | 92% | 133% | 100% |

3.3 SPLIT TENSILE STRENGTH

The results of split tensile strength with hardened density, performance index, and percentage of split tensile strength at various ages corresponding to 28 days split tensile strength were tested and evaluated in **Table 4**. Split tensile strength results were also shown in **Figure 3**. The relationship between split tensile strength and compressive strength for the LFCs is also shown at **Figure 4**.

Figure 3: Split Tensile Strength of Lightweight Foamed Concrete with Various Steel Slag Replacement Levels at Different Ages

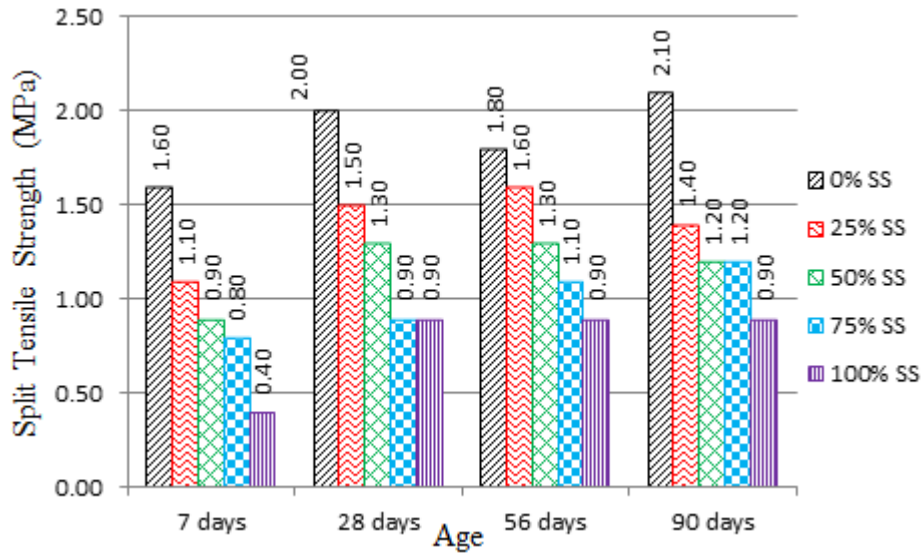
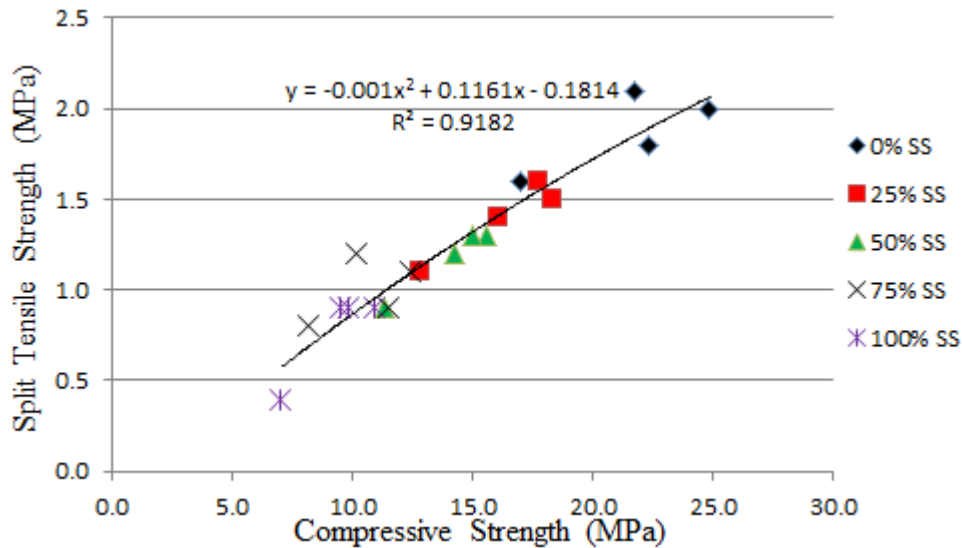


Figure 4: Relationship between Split Tensile Strength and Compressive Strength of Lightweight Foamed Concrete with Various Steel Slag Replacement Levels



Similar to compressive strength, the results show that the split tensile strength was reduced when SS replacement level was increased due to high w/c. The split tensile strength, as general trend, is increased with testing age for up to 56 days and then slightly dropped at 90 days. The aging effect of split tensile strength can be observed at **Table 4**, in which, the percentages of strength at 56 days and 90 days to 28 days were generally higher for specimens with 75% and 100% SS replacement levels compared to that of 25% and 50% SS replacement levels.

The split tensile strength is in the range of 7.8% to 11.9% corresponding to that of the compressive strength. As shown in **Figure 4**, the relationship between split tensile strength and compressive strength is non-linear, whereas, split tensile strength increases at decreasing rate when compressive strength increased.

3.4 FLEXURAL STRENGTH

The results of flexural strength with hardened density, performance index, and percentage of flexural strength at various ages corresponding to 28 days flexural strength were tested and evaluated in **Table 5**. Flexural strength results were also shown in **Figure 5**. The relationship between flexural strength and compressive strength of the LFCs was also shown at **Figure 6**.

Similar to compressive strength, the results show that flexural strength was reduced when SS replacement level was increased due to high w/c. The flexural strength was very high in early age and maintained for up to 90 days; as majority trend, flexural strength was increased slightly with testing age for up to 28 days and then slightly dropped at 56 and 90 days. The strength decrement might also cause by lower density of specimens in later testing age compared to that of 28 days.

The flexural strength is in the range of 31% to 47% corresponding to that of the compressive strength. As shown in **Figure 6**, the relationship between the flexural strength and the compressive strength is non-linear, whereas, the flexural strength increases at decreasing rate when the compressive strength increased.

Table 5: Flexural Strength Result for Various Foamed Concrete with Different Replacement Levels of Steel Slag

| Replacement level | | 0% | 25% | 50% | 75% | 100% |
|-------------------|---------------------------------------|------|------|------|------|------|
| 7 days | Hardened Density (kg/m ³) | 1625 | 1652 | 1634 | 1581 | 1655 |
| | Flexural Strength (MPa) | 7.60 | 5.80 | 4.90 | 3.80 | 3.30 |
| | PI (MPa/1000kg/m ³) | 4.7 | 3.5 | 3.0 | 2.4 | 2.0 |
| | 7 days / 28 days Strength | 97% | 91% | 92% | 86% | 89% |
| 28 days | Hardened Density (kg/m ³) | 1632 | 1628 | 1618 | 1606 | 1577 |
| | Flexural Strength (MPa) | 7.80 | 6.40 | 5.30 | 4.40 | 3.70 |
| | PI (MPa/1000kg/m ³) | 4.8 | 3.9 | 3.3 | 2.7 | 2.3 |
| 56 days | Hardened Density (kg/m ³) | 1616 | 1621 | 1604 | 1575 | 1563 |
| | Flexural Strength (MPa) | 7.50 | 6.00 | 5.60 | 4.10 | 3.90 |
| | PI (MPa/1000kg/m ³) | 4.6 | 3.7 | 3.5 | 2.6 | 2.5 |
| | 56 days / 28 days Strength | 96% | 94% | 106% | 93% | 105% |
| 90 days | Hardened Density (kg/m ³) | 1596 | 1581 | 1635 | 1583 | 1606 |
| | Flexural Strength (MPa) | 7.20 | 5.60 | 5.50 | 3.80 | 3.70 |
| | PI (MPa/1000kg/m ³) | 4.5 | 3.5 | 3.4 | 2.4 | 2.3 |
| | 90 days / 28 days Strength | 92% | 88% | 104% | 86% | 100% |

Figure 5: Flexural Strength of Lightweight Foamed Concrete with Various Steel Slag Replacement Levels at Different Ages

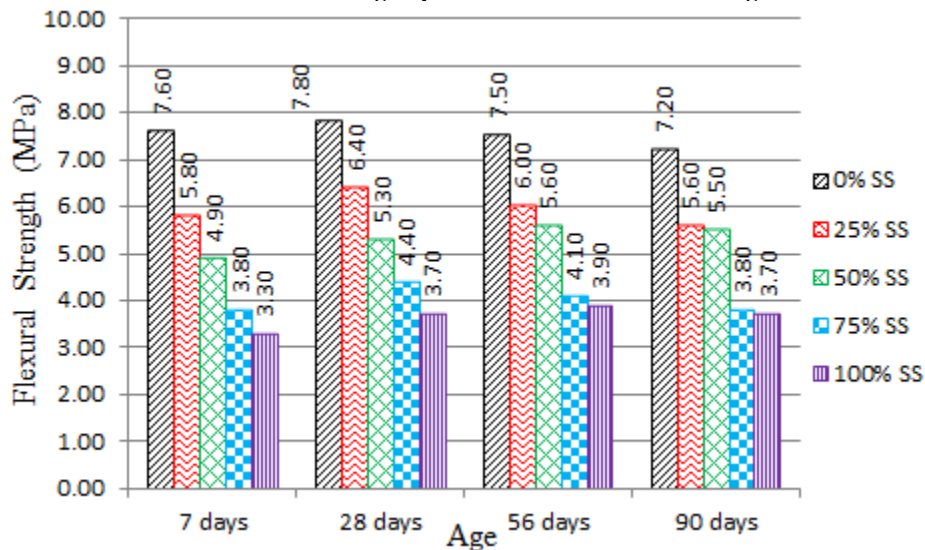
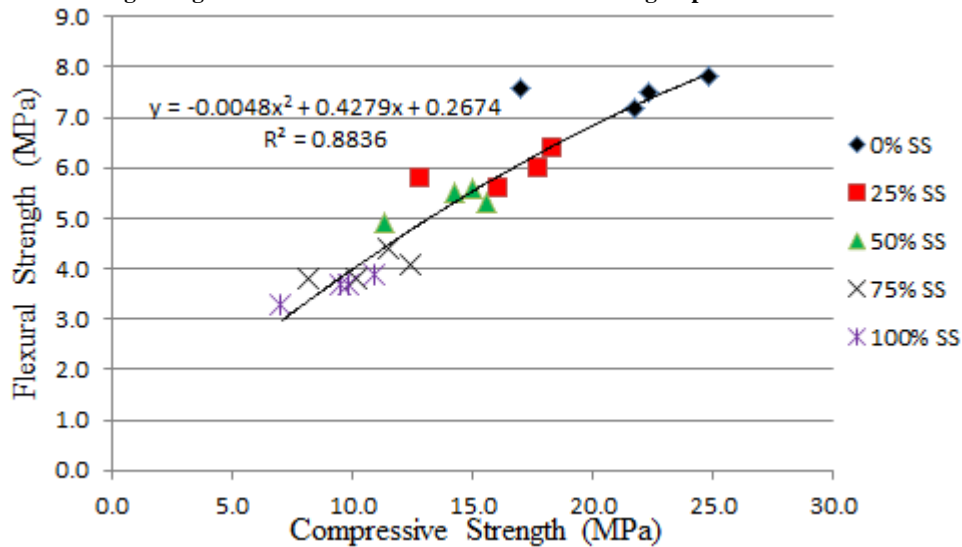


Figure 6: Relationship between Flexural Strength and Compressive Strength of Lightweight Foamed Concrete with Various Steel Slag Replacement Levels



3.5 WATER ABSORPTION

Water Absorption was shown at **Figure 7**. Water absorption was fall between 9.8% and 21.4% for 7 days to 90 days specimens. The result is fluctuated but it shows a trend of increasing with increased SS replacement level as more water was introduced to achieve targeted base mix mortar density and the excessive water formed more void in the LFC.

There is no observable trend of changes when testing age increased. The longer the testing age, the more cement grain reacts with water. When the cement reacts with water to form C-S-H gel, there is a volumetric reduction, and empty capillary pores formed in C-S-H gel (Neville & Brooks, 2004). As such, water absorption shall increase with testing age. The relationship between water absorption and compressive strength for the LFCs is shown in **Figure 8**. The results show that the relationship between water absorption and compressive strength is non-linear, whereas, water absorption is decreased at decreasing rate when the compressive strength increased.

Figure 7: Water Absorption of Lightweight Foamed Concrete with Various Steel Slag Replacement Levels at Different Ages

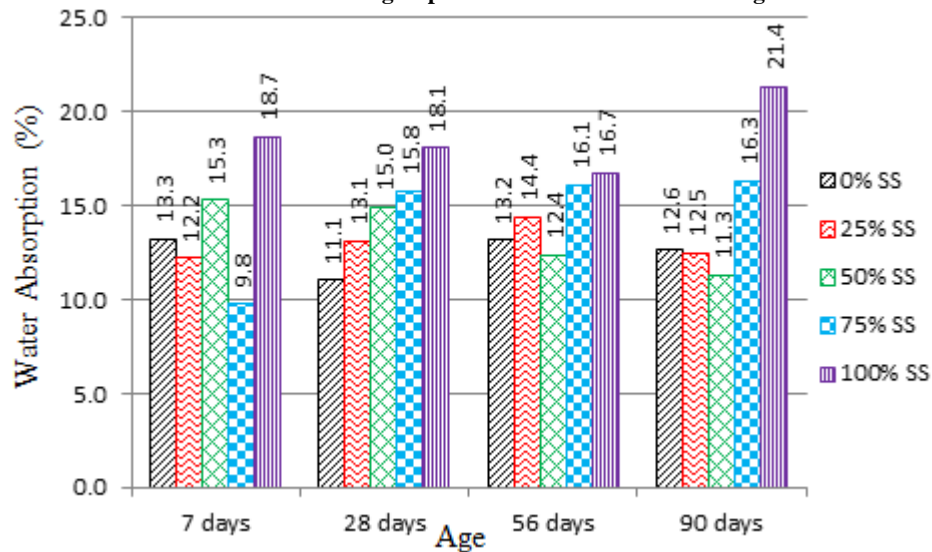
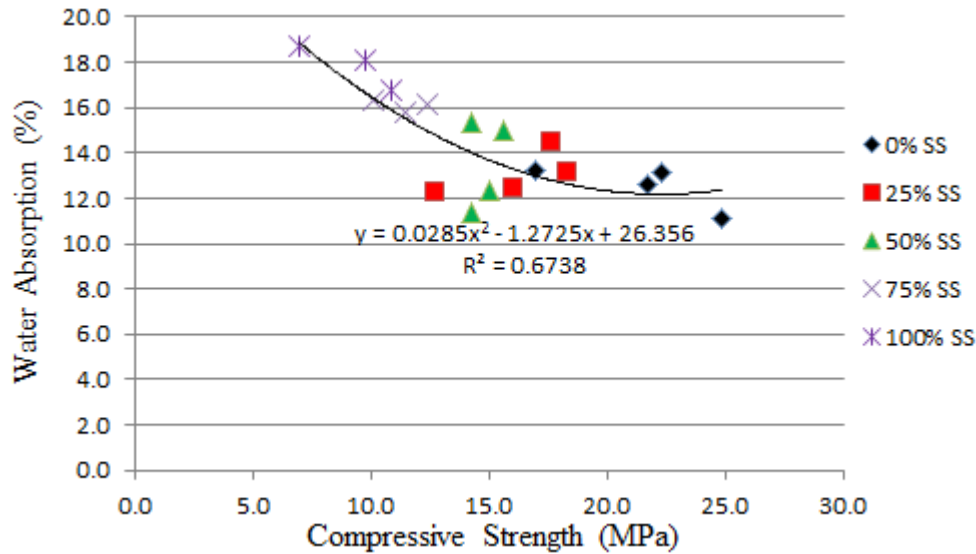


Figure 8: Relationship between Water Absorption and Compressive Strength Of Lightweight Foamed Concrete with Various Steel Slag Replacement Levels



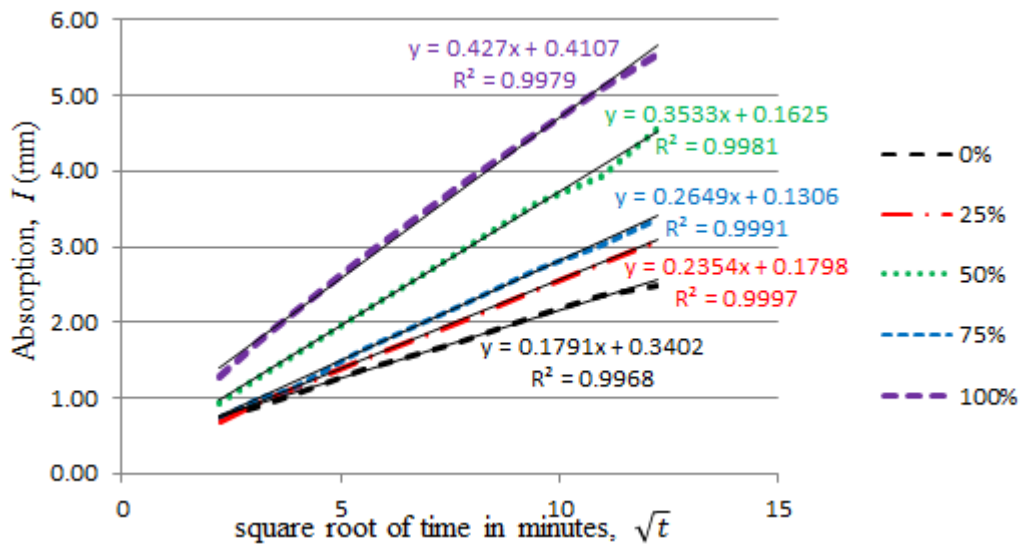
3.6 SORPTIVITY

Absorption was shown at **Figure 9**. **Figure 9** shows that the absorption is increased with increased SS replacement level at 28 days, which is similar to result shown in water absorption.

Pitroda & Umrigar (2013) reported that sorptivity shall be less than $6 \text{ mm/hr}^{0.5}$, which is equivalent to $0.774 \text{ mm/min}^{0.5}$, for laboratory concrete in order to fulfil the acceptable limits for durability index.

The sorptivity (rate of water absorption) is the slope of plotted absorption line against square root of time. By extract the slope of the trend line, 28-day sorptivity of LFCs with 0%, 25%, 50%, 75%, and 100% of SS replacement levels are $0.179 \text{ mm/min}^{0.5}$, $0.235 \text{ mm/min}^{0.5}$, $0.353 \text{ mm/min}^{0.5}$, $0.265 \text{ mm/min}^{0.5}$, and $0.427 \text{ mm/min}^{0.5}$ respectively, which are lower than $0.774 \text{ mm/min}^{0.5}$.

Figure 9: Sorptivity of Lightweight Foamed Concrete with Various Steel Slag Replacement Levels at Age of 28 Days



4. CONCLUSIONS

Several conclusions can be drawn as the following:

- A. The reference mix and the 25% steel slag mix achieved compressive strength of 17MPa and above.
- B. Excessive foam amount reduced flowability of lightweight foamed concrete due to high air content and adhesiveness of foam.
- C. The compressive, split tensile, and flexural strengths of the lightweight foamed concrete decreased when steel slag replacement level increased at the specific density.
- D. The strengths of the lightweight foamed concrete decreased when water to cement ratio increased.
- E. The development of compressive and split tensile strengths at 56 days and 90 days corresponding to 28 days are generally higher for specimens with 75% and 100% steel slag replacement levels compared to that of 25% and 50% steel slag replacement levels.
- F. The steel slag based lightweight foamed concrete has high early flexural strength and maintain the strength up to age of 90 days.
- G. The split tensile strength and flexural strength of the lightweight foamed concrete are in the range of 7.8% to 11.9% and 31% to 47% respectively corresponding to that of the compressive strength.
- H. Both split tensile and flexural strengths of the lightweight foamed concrete have non-linear relationship with compressive strength, whereas, the both strengths increased with compressive strength at decreasing rate.
- I. Water absorption and sorptivity of the lightweight foamed concrete are increased with increment of steel slag replacement level.
- J. Sorptivity of the lightweight foamed concrete is within the acceptance limits of durability indexes.
- K. Based on the strengths and sorptivity results, it is feasible to replace sand with crushed steel slag at up to 25% in lightweight foamed concrete for structural application.
- L. However, assessment in other perspectives such as carbonation and fire resistance shall be done to assure suitable application of steel slag foamed concrete.

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