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The Mechanical Properties of Concrete Incorporating Steel Slag as Supplementary Cementitious Material

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Abstract. Steel slag (SS) is a kind of industrial solid waste usually been dumped at landfills and causes environmental pollution. Previous studies have demonstrated that SS can be an alternative material to be used for making concrete and could achieve good mechanical properties, which not only reduce natural resources depletion but also improve environmental quality. This study aims to evaluate the effectiveness of SS as supplementary cementitious material (SCM) partially replacing cement on workability and mechanical properties of fresh and hardened concrete. X-ray fluorescence test, slump test, compressive strength test and ultra-pulse velocity test have been conducted. Mix designs are determined with replacement proportion of cement by SS of 0, 10%, 20%, 30%, 40% and 50%. Results show that replacement of cement by SS up to 50% increase the workability of concrete. The density of concrete ranges from 2083 to 2373 kg/m^3, with and without replacement of SS at curing age of 1-day, 3-day and 28-day. Compressive strength of concretes incorporating SS is lower than that of plain concrete. 1-day and 3-day compressive strength of concrete incorporating SS decrease with the increase in replacement of SS while 28-day compressive strength reach peak at 30% replacement and further replacement of SS reduce 28-day compressive strength. The ultra-pulse velocity (UPV) values of concrete have good relationship with compressive strength with the correlation coefficient of 0.92, 0.87 and 0.70 of 1-day, 3-day and 28-day experiment data, respectively. This study indicates the SS can be used for making concrete.

1 Introduction

Concrete plays an important role in construction development which used to construct building, bridges and highways. Therefore, more cement is needed to be manufactured to cater the concrete consumption of the market since cement is one of the components of concrete production. The cement manufacturing industry has contributed severe impacts to the environment such as depletion of non-renewable resources, emission of carbon dioxide and human health issue. In 2019, Malaysia was produced 16.1 million metric tons of cement which means same amount of carbon dioxide was emitted from the cement industry since one tons of cement generate approximately one tons of carbon dioxide to the atmosphere [1]. In order to reduce the cement consumption, some potential waste material such as fly ash (FA), silica fume (SF), metakaolin (MK) and steel slag (SS) are used as a supplementary cementitious material in concrete production. SS is the by-product of steel and iron industry which produced by quenching the molten iron slag from blast furnace in water. A granular and glassy product is formed and grinded into powder. Around 0.45 to 0.5 tonnes of SS will be generated when 1 tonne of steel is produced and dispose to landfill causing environmental issue [2]. Recycling and reuse the waste material as supplementary cementitious material in concrete production is one of the solutions to overcome improper waste disposal. Furthermore, replace cement with optimum amount of well-treated waste material produced an environmentally friendly concrete with higher compressive strength compared with conventional concrete [3]. Many researchers were focus on utilizing potential waste product in concrete production to overcome depletion of non-renewable resources and environmental issue. The present paper focuses on investigating concrete development of M60 grade concrete with partial replacement of cement with SS via 10%, 20%, 30%, 40% and 50%. The cubes are tested for compressive strength and ultrasonic pulse velocity (UPV).

2 Literature Review

Since SS could react with cement hydration products and generate more C-S-H gels to improve the strength of concrete, SS is regarded as an alternative material to replace cement. As solid waste from metallurgical industry, the chemical components of SS are influenced by the ore source and metallurgical methods. Therefore, the variable chemical component is a key feature of SS which also cause difficulty on the utilization of SS as the sustainable material in construction activities. As one of type of SS, basic oxygen furnace slag (BOFS) has CaO, SiO_2, Fe_2O_3, free CaO content ranging 30-50%, 10-15%, 10-30% and 2-10% [4]. It can be seen that BOFS has low SiO_2 content and high Fe_2O_3 content compared with other supplementary cementitious materials such as fly ash and silica fume. This feature could be a key feature to identify SS such as BOFS. Although SS has low hydration activity compared with cement, it could be a good alternative material to replacement cement for making concrete and make the strength of concrete incorporating SS meet the required strength in construction activity. Many researchers study the effect of the addition of SS on the strength of concrete. Kumar et al. [5] studied the effect of SS powder on the mechanical properties of self-compacting concrete with recycled coarse aggregate. In the study, cement was replaced with SS powder with the replacement ratio of 10%, 20%, 30%, 40% and 50% and the water cement ratio was 0.33. The results showed that the early compressive strength (3-day and 7-day) of concrete incorporating SS power were lower than control specimen without SS. With the increasing addition of SS powder, the compressive strength of concretes was decreasing. When the curing age reach 28 day, the compressive strength of concrete with 10% replacement of SS powder was higher than that of control specimen and further addition of SS powder cause the reduction on compressive strength. Therefore, 10% was the optimum mix design. In contrast, the study of Boukendakdji et al. [6] showed different results. The replacement ratio of SS in the experiment were 0, 10%, 20%, 30%, 35%, 36%, 37% and 40% with water cement ratio of 0.32. At early stage (7-day curing age), the compressive strength of concretes with the addition of SS were higher than that of concrete without SS. With the increase of addition of SS up to 36% replacement, the compressive strength of concrete was increasing and reach the top at 36% replacement ratio. Further addition causes the reduction on compressive strength of concrete. As for 28-day compressive strength of concrete, the 10% replacement of SS cause the reduction on compressive strength compared with that of control specimen, while the increasing addition of SS make the compressive strength of concrete increase and further addition cause the reduction on compressive strength of concrete. Many reasons have been presented for explaining the variable optimum mix design including but not limited to: a) the addition of SS produces more C-S-H gel which improves the properties of pores in concrete; b) the SS affects the hydration environment of combined binder; c) the variable content of chemical components of SS [7,8,9]. However, the consensus cannot be reached. Therefore, further study is necessary.

3 Materials and Methodology

3.1 Materials

3.1.1 Binders. The binders used in this study included ordinary Portland cement (OPC) and SS powder. The OPC with 28-day strength of 42.5 MPa was produced by YTL Sdn Bhd and has Blaine's surface area, initial setting time, soundness (mm) and BET Surface Area (m^2/g) of 3.2 m^2/kg, 130 mins, 1.0 mm and 1.29 m^2/g, respectively. The OPC used in this study was classified as Type I cement according to MS EN 197 Part 1 [10]. The SS used for this study was obtained as raw material from Eastern Steel Sdn Bhd. To reach the target particle size before using, the raw SS clinker was processed by ball mill machine, stone crusher and grinding machine successively. The SS powder passing 150 mesh was acquired for experiment. The chemical composition of binders has been shown in Table.1.

3.1.2 Aggregate. The sand used as fine aggregate in this study were from local river. The particle size of fine aggregate ranges from 0.15 to 5 mm with Fineness modulus of 2.9. The sand was air-dried before mixing. The coarse aggregates used were sieved passing through 10 mm sieve and retained on the 4.75mm sieve to control the nominal size of coarse aggregate in between 5mm to 10mm and the consistency of the concrete specimens. The particle sizes of fine and coarse aggregate are shown in Figure 1.

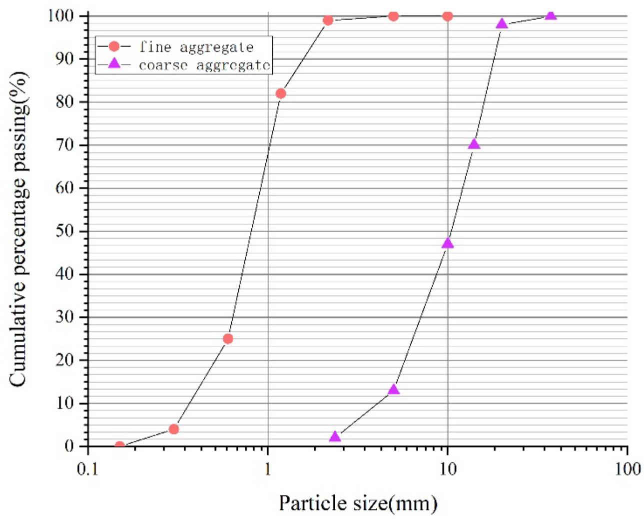

Fig.1 Particle size distribution of fine and coarse aggregate used in this study

3.1.3 Water. Tap water supplied in the concrete lab was used to produce all the concrete mixtures and for specimens curing.

3.1.4 Superplastizer. The superplasticizer used in this study was Sika ViscoCrete which can reduce the water consumption and improve the workability of the concrete mixes. Previous study showed a good compatibility between Sika ViscoCrete and all OPC types according to BS 5075 [11]. The superplasticizer content of 2% by mass of total binders was used for all the concrete mixtures.

3.3 Mix proportions

In this study, six mix designs were used to prepare concrete specimens. M0 without any addition of SS were designated as control concrete. In other mix designs, cement was replaced by SS powder from 10% to 50% with interval of 10% to make mixed binders and identified as M10, M20, M30, M40 and M50, respectively (Table 1). Water cement ratio of 0.36 was selected in this study.

3.4 Mixing and curing

To achieve continuity and uniformity of concrete specimens, ingredients were mixed by stage. The fine and coarse aggregates were added in drum mixer and stirred for 3 minutes followed by addition of the binder materials (OPC and SS) as per mix designs for another 3 minutes. Water was poured into along with the specified dosage of the superplasticizer and mixed for 3 more minutes. Pour the fresh concrete into moulds and placed for 24 h. Three specimens of every mix designs were cast for each test. After 24 h, specimens were demoulded and put into water immediately for water curing until testing. The temperature and humidity of the laboratory varied between 25-30 °C and 70-80%, respectively.

Table 1 Concrete mix design

Mix code	Content (kg/m^3)					
	OPC	SS	Water	Sand	Gravel	SP (%)
M0	575.0	0	207	435	1085	2.0
M10	517.5	57.5	207	435	1085	2.0
M20	460.0	115.0	207	435	1085	2.0
M30	402.5	172.5	207	435	1085	2.0
M40	345.0	230.0	207	435	1085	2.0
M50	287.5	287.5	207	435	1085	2.0

3.5 Testing

Testing were performed to investigate properties of fresh and hardened concrete, including slump test for fresh concrete, density, compressive strength and ultra-pulse velocity test for hardened concrete. Slump test was conducted to determine the workability of fresh concrete according to BS EN 12350-2 [12]. Compressive strength test was conducted on casting cubes at curing age of 1-day, 3-day and 28 day according to BS EN 12390-3 [13].

4 Result and Discussion

4.1 Chemical composition

The chemical composition of SS and cement are shown in Table 2. In comparison with cement used in this study, SS have lower SiO_2 and CaO content which are the main compositions for hydrate reaction to provide strength for concrete, while have higher Fe_2O_3 content influenced by metallurgical method. Characteristic of low SiO_2 and high Fe_2O_3 content with in the specific range could become a way to distinguish the type of steel slag [4].

Table 2 Chemical compositions of SS and cement used in this study

	Chemical composition (%)							
Binder	SiO_2	CaO	SO_3	Fe_2O_3	MgO	Al_2O_3	Na_2O	K_2O
SS	13.5	41.4	0.22	19.7	3.85	1.8	0.07	0.04
Cement	21.8	60.1	2.5	4.1	0.5	6.66	0	0.25

4.2 Workability

The workability of SS concretes increased by 98.46%, 106.15%, 138.46%, 146.15% and 161.54% respectively compared with plain concrete. As shown in Table 3, SS had improved the workability of fresh concrete due to its dispersive characteristics and physical properties such as smoothness and specular surface texture [14]. SS based concrete production had increased the workability and fluidity of the concrete which illustrated by BS EN 12390 [15]. A similar workability trend of SS concrete was presented by Pan et al. [16] due to the grading and smooth texture of the SS. SS particles absorbed lesser water than OPC while concrete mixing which increased the flow ability of the concrete due to lesser hydration reaction take place as the SS replacement increased [17]. The addition of SS in concrete reduces incidences of early thermal cracking on the concrete due to lower early heat generated during concrete mixing since SS required minimal water moisture for early hydration process and thereby increasing the workability of the concrete [14].

Table 3 The slump results of concrete

Mix Code	Slump result (mm)
M0	65
M10	129
M20	134
M30	155
M40	160
M50	170

4.3 Density

The effect of SS on the density of concrete at different curing age has been showed in Figure 2. Results showed that the density of concrete increase with the increasing replacement ratio of SS. This may due to the higher specific gravity of SS than that of cement [18]. It was notable that the density of concrete at 3-day curing age host highest value compared with at 1-day and 28-day curing age for each mix design. At the replacement level of 0 and 10%, the density of concrete at 28-day curing age was lower than at 1-day curing age. However, when the replacement ratio exceeds 10%, the density of concrete at 28-day curing age was higher than at 1-day curing age.

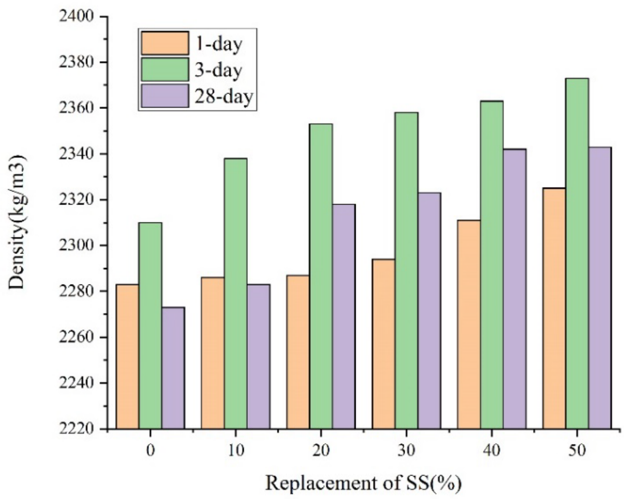

Fig. 2 The density of concrete with different replacement ratio of SS at the curing age of 1-day, 3-day and 28-day

4.4 Compressive strength

Figure 3 showed the effect of replacement ratio of SS on the compressive strength of concrete incorporating SS as SCM. It can be observed that the compressive strength of concrete with replacement by SS are lower than that of concrete without replacement by SS. With the increase in replacement ratio of SS, 1-day and 3-day compressive strength of concrete decrease. In comparison with the compressive strength of concrete of mix design M0, the decrease in compressive strength of concrete M10, M20, M30, M40, M50 are 29%, 30%, 43%, 59% and 75% for 1-day curing age, respectively, and are 7%, 20%, 30%, 37% and 53% for 3-day curing age, respectively. This result indicated the increasing addition of SS in concrete decrease the early strength (1-day and 3-day) of concrete [19]. However, there is a different trend for compressive strength of concrete after replacing cement with SS at the curing age of 28-day. In comparison with M10 concrete, when the replacement ratio of SS increase from 10% up to 30%, the compressive strength of M20 and M30 concrete increase 1% and 10%, respectively. Further increase in replacement of SS cause reduction on compressive strength of concrete of M40 and M50 of which compressive strength are lower than M10 concrete. The difference of development on compressive strength between at early stage and at 28-day curing age may influenced by the hydration reaction of SS. Due to the low hydration rate of SS, the addition of SS slows down the early stage hydration rate of cement-SS combined binder [20]. Therefore, the early compressive strength of concrete with the addition of SS is decreasing with the increasing SS replacement ratio. However, with the development of curing age, the combined binder with the addition of SS fully hydrate and make the difference between compressive strength of concrete with and without the addition of SS reduce. In this study, the optimum compressive strength of concrete is with the 30% replacement of cement by SS, which is 8% lower than that of M0 mix design. The correlation analysis of early strength and 28-day compressive strength were also investigated in this study. Result showed that the 28-day compressive strength of concrete has better correlations with that of 1-day curing age than 3-day curing age, of which the correlation coefficient are 0.8 and 0.67, respectively. The correlation between early strength and 28-day compressive strength is shown in Figure 4.

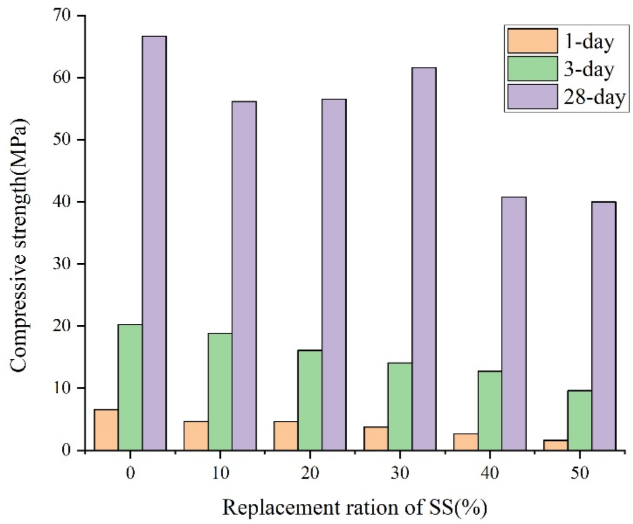

Fig. 3 The compressive strength of concrete with different replacement ratio of SS at the curing age of 1-day, 3-day and 28-day

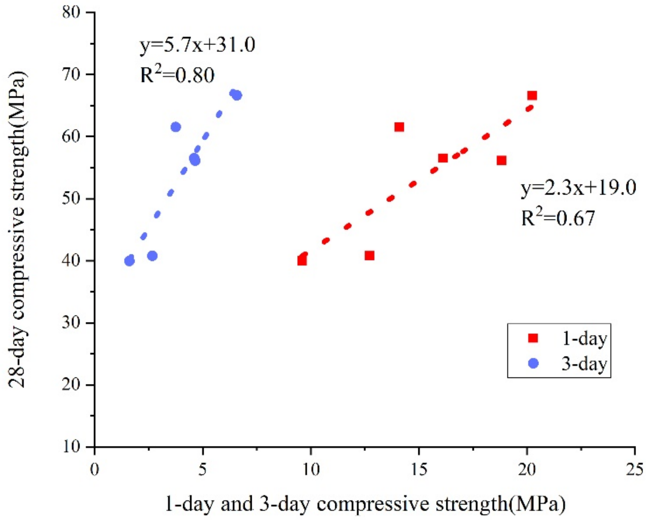

Fig. 4 The correlation between early strength and 28-day compressive strength

4.5 UPV

As shown in Figure 5, the UPV results increased as the concrete curing age increased. The concrete quality can be determined according to Ahmmad et al. [22]. The control specimen at 1-day curing age has the highest UPV value where the concrete quality was classified as good concrete [21]. A decreasing UPV was obtained as the SS replacement ratio increased at every 10%. For the concrete with 10% to 20% of SS replacement were categorised as medium concrete quality due to the decrease in capillary voids in the concrete specimens by the formation of C-S-H gel from the hydration process and pozzolanic reaction [23]. The UPV drops significantly when the SS replacement up to 30% and above because the capillary void increased leads to decrease concrete quality. A similar trend can be observed for the concrete at 3-day curing age which the control specimen has the highest UPV value followed by the concrete with the addition of SS where the concrete quality was in the ranged of medium to good. However, 50% SS concrete was classified as doubtful concrete due to the excessive SS replacement reduced the total available cement for the hydration process eventually influenced the concrete quality. The concrete quality at 28-day curing age was in between medium to excellent concrete due to the formation of secondary C-S-H gel. The UPV values of the concrete with the addition of SS decreased significantly when the SS replacement over the optimum amount which results in adverse effect to the UPV of the concrete specimens. The UPV of blended concrete were low at the early stage of the concrete since the pozzolanic reaction took place at the later stage of the concrete [24].

A positive linear relationship between compressive strength and UPV of blended high performance concretes was identified in [25]. Figure 6 illustrated the different positive linear relationship at each concrete curing age. The R^2 value for correlation between compressive strength and UPV of the concretes with different SS replacement at the curing age of 1-day, 3-day and 28-day were 0.92, 0.87 and 0.70. The factors which affect the strength of the concrete may affect the UPV of the concretes where the concrete is controlled by the strength of the cement paste and the UPV is controlled by the properties of the aggregates used [26].

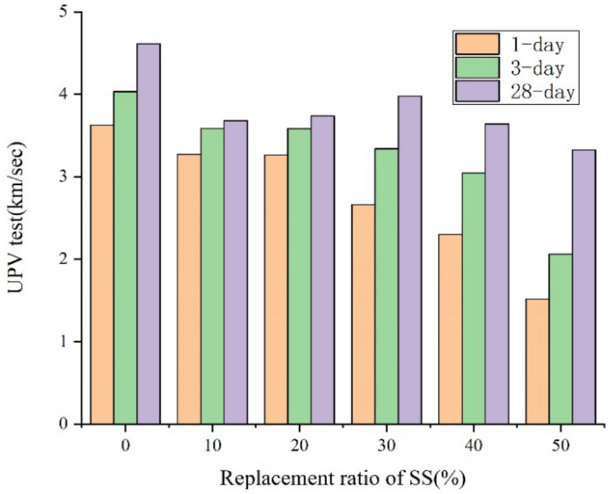

Fig. 5 The UPV values of concrete with and without the addition of SS at the curing age of 1-day, 3-day and 28-day

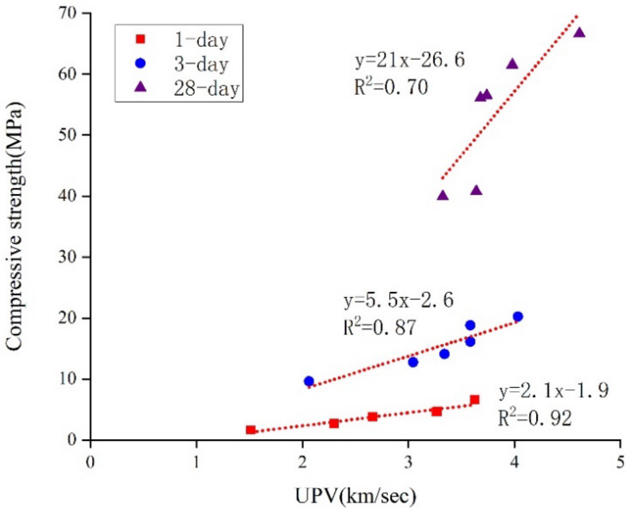

Fig. 6 The correlation between compressive strength and UPV of concrete with and without the addition of SS

5 Conclusion

SS could be an alternative material used to replace cement for making concrete which not only reduce the depletion of natural resources but also improve environmental conditions. The conclusions based on this study can be drawn as follow:

a) The SS used in this study is BOFS with content of SiO_2, CaO and Fe_2O_3 accounting for 13.5%, 41.4% and 19.7% of total mass, respectively. The lower SiO2, CaO and higher Fe_2O_3 compared with cement were the key feature of this type of SS.
b) The addition of SS improves the workability of concrete with the slump value ranging from 65 to 170 mm. The increasing replacement ratio of SS increases the slump value of fresh concrete.
c) It is observed that the density of specimen increases with the increase in the addition of SS which may due to the higher specific gravity of SS than cement.
d) The compressive strength of concrete with the addition of SS is lower than that of concrete without the addition of SS. The replacement of SS makes the early strength (1-day and 3-day) of concrete decrease, while the 28-day compressive strength of concrete goes up with the

replacement ratio up to 30% and then goes down with further replacement. The optimum replacement ratio of SS is 30%.

e) UPV value shows a similar trend with compressive strength value. The correlation coefficients between UPV and compressive strength at 1-day and 3-day curing age are 0.98 and 0.93, respectively, while at 28-day is 0.64.

Acknowledgements

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