Mechanical properties of concrete using ferronickel slag as fine aggregate and supplementary cementitious material

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MECHANICAL PROPERTIES OF CONCRETE USING FERRONICKEL SLAG AS FINE AGGREGATE AND SUPPLEMENTARY CEMENTITIOUS MATERIAL

ASHISH KUMER SAHA[1*] AND PRABIR KUMAR SARKER[2]
[1]PHD STUDENT, SCHOOL OF CIVIL AND MECHANICAL ENGINEERING, CURTIN UNIVERSITY, AUSTRALIA.
[2]ASSOCIATE PROFESSOR, SCHOOL OF CIVIL AND MECHANICAL ENGINEERING, CURTIN UNIVERSITY, AUSTRALIA.
[*]CORRESPONDING AUTHOR EMAIL: A.SAHA@POSTGRAD.CURTIN.EDU.AU

This study evaluates the combined use of granulated ferronickel slag (FNS) as fine aggregate and ground granulated ferronickel slag (GFNS) as a supplementary cementitious material (SCM) in concrete. Test results show that 30% cement replacement by GFNS reduced the 28-day compressive strength. However, gradual strength development continued to 180 days by the pozzolanic reaction of GFNS. Strength of concrete also improved with the increment of FNS fine aggregate up to 50% due to the improved grading of aggregate. The correlations of tensile strength, flexural strength and elastic modulus with compressive strength were not affected by the use of GFNS and FNS aggregate. Overall, the mechanical properties of concrete using 30% GFNS as SCM together with 50% FNS as fine aggregate were similar to those of control concrete after 56 days of age. Thus, use of GFNS and FNS aggregate can be considered as a viable option for producing green concrete.

1.0 INTRODUCTION

Concrete is the most highly used construction material in the world due to its ease of manufacturing process, availability of raw materials, ease of casting into any shape and high resistance against weathering actions. The demand of concrete is increasing at an exponential rate due to the massive infrastructure developments in countries like China and India (Avgerou[1]). It has been estimated that concrete has an annual growth rate of 6% around the globe (Ghods[2]). Concrete manufacturing requires huge amounts of natural resources such as sand, stone and water. Fine aggregate occupies about 25% to 35% of the total volume of concrete and it is primarily used as a filler for economic purposes. The properties of fine aggregate such as density and gradation influence the strength and durability properties of concrete (Saha[3], [4], Sakoi[5], Dimitrioglou[6]).

In order to find good quality sand for construction purposes, uncontrolled sand mining has been observed in different parts of the world, including Australia and Italy (Davis[7], Preciso[8]). Excessive and unplanned sand dredging has adverse environmental impacts and this can damage waterfront structures (Padmalal[9], Liu[10]). Therefore, use of different alternatives to natural sand such as manufactured sands and various industrial slags in concrete production has been extensively investigated in the recent years (Masterbuilder[11]).

On the other hand, industrial by-products usually require careful handling and proper disposal techniques to prevent the risk of groundwater contamination (Kumar[12], Santucci[13]). Thus, reuse of industrial by-products in concrete can improve the sustainability aspects of concrete and reduce the costs of concrete production and waste management (Pellegrino[14], Sahu[15]). Different types of industrial slags such as ferronickel slag, ferrochromium slag, steel slag and copper slag have been studied in recent years in order to understand their effects as aggregate in concrete (Saha[16], Rahman[17], Biskri[18], Dos Anjos[19]).

Industrial slags can be broadly categorised as either electric arc furnace (EAF) slag or blast furnace slag (BFS) depending on the production process. Blast furnace requires larger area and generates more carbon dioxide than electric arc furnace (Proctor[20]). Thus, considerable difference can be observed between the properties EAF slag and BFS due to the difference in the production process. EAF slag usually shows higher density and hardness as compared to BFS (Faleschini[21], Özbay[22]).

Industrial slags are also classified by cooling method of the molten slag. There are two different cooling methods such as rapid water-cooling to granulated slag and slow cooling by natural air in slag pits. The cooling method can have a significant effect on the microstructure of hardened slag. Rapid cooling of molten slag may result in crystalline defects and a large quantity of amorphous phase that exhibits pozzolanic property. Thus, GFNS may have a prospective use as supplementary cementitious material (SCM) (Chiang[23]). On the other hand, air-cooled slags consist of more crystalline phases and are shown to be more suitable for use as aggregate (Sahu[15]).

In this study, electric arc furnace FNS was used as fine aggregate and GFNS was used as a supplementary binder in concrete. The FNS was sourced from Société Le Nickel (SLN), New Caledonia, where water-cooling is used to granulate the molten FNS. The slag has been used for decades in land filling and as aggregate for concrete in New Caledonia (Saha[24], [25]). Previous experimental results showed pozzolanic property of GFNS, which makes it comparable to other pozzolans such as fly ash and GGBFS (Rahman[17]). Therefore, GFNS was used as a SCM and FNS fine aggregate was used as an alternative of natural sand. Workability and mechanical properties such as compressive strength, flexural strength, splitting tensile strength and elastic modulus of concrete using GFNS and FNS fine aggregate were investigated.

2.0 MATERIALS & METHODS

2.1 MATERIALS

Ordinary Portland Cement (OPC) was used as the primary binder. Locally available natural sand and granite aggregate were used as fine and coarse aggregates, respectively. The physical appearance of FNS and sand are shown in Figure 1. It is noticeable that FNS particles are angular in shape and consist of different particle sizes, while sand particles are more spherical and finer than FNS. The physical properties of cement and GFNS are given in Table 1. GFNS has a similar specific gravity to that of OPC with a higher

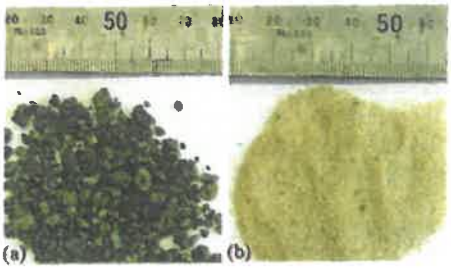


FIGURE 1: **Physical appearance of fine aggregates.**

Blaine's fineness. The chemical compositions of OPC and FNS are given in Table 2. FNS has significantly higher silicon and magnesium contents with very low calcium as compared to OPC. It was found previously that the magnesium of FNS is present in the form of crystalline forsterite ferroan that did not go into reaction to produce expansive $Mg(OH)_2$ (Rahman[17]).

Properties	OPC	GFNS
Specific gravity	3.16	2.95
Specific surface area (m²/kg)	337	430

TABLE 1. **Physical properties of binder.**

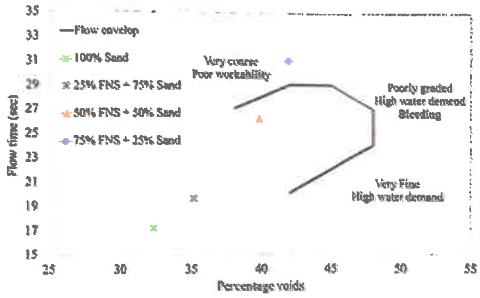


FIGURE 2: **Sand flow test envelope.**

Properties	Sand	FNS
Bulk density (SSD) (gm/cm³)	2.16	2.78
Apparent particle Density (gm/cm³)	2.32	2.85
Water absorption (%)	0.35	0.42
Fineness modulus (FM)	1.95	4.07
Flow cone test (flow time, sec)	17	Did not flow
Uncompacted void content (%)	32	44

TABLE 2. **Chemical compositions of binder (mass percentage).**

Materials	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	CaO	Na_2O	K_2O	Cr_2O_3	LOI*
OPC	20.29	5.48	2.85	1.24	2.49	63.11	0.29	0.45	0.02	3.39
GFNS	53.29	2.67	11.9	31.6	-	0.42	0.11	-	1.08	-

*LOI: Loss on ignition

TABLE 3 **Physical properties of fine aggregates.**

Physical properties of the aggregates are given in Table 3. It can be seen that FNS aggregate has similar absorption and higher density and fineness modulus as compared to sand. The flow cone test results for different combinations of FNS with sand are shown in Figure 2, where the flow times are plotted against voids content along with the sand flow envelop. FNS aggregate did not flow in the flow cone test while sand had a flow time of 17 sec. It can be seen that flow time and voids content increased with the increase of FNS content in the fine aggregate. Figure 2 shows that the combination of 75% FNS with 25% sand is plotted in the zone of poor workability. However, the combinations of 25% FNS and 50% FNS with sand are plotted within the flow envelop.

The grain size distributions of fine aggregate and recommended limits of AS 2758.126 are presented in Figure 3. It can be seen that 100% FNS aggregate exceed the allowable limit; however, all other aggregate combinations remained within the recommended limits. The figure also points out that sand consists of mostly uniformly graded particles, while the combination of 50% sand with 50% FNS is seen to be a well graded fine aggregate.

2.2 METHODS

The concrete mix proportions are shown in Table 4. The control mix with 100% OPC as the binder and 100% sand as fine aggregate is designated by PC-FNS0. GFNS in the mix designation indicates 30% cement replacement by GFNS and the number after FNS indicates the volume percentage of FNS aggregate in concrete. The water to binder ratio (W/B) was kept constant at 0.33 and a naphthalene based superplasticiser was used to improve workability of the fresh concrete.

TABLE 4 **Concrete mix proportions and slump.**

Mix ID	Binder (kg/m³)		Fine aggregate (kg/m³)		Coarse aggregate (kg/m³)	W/B	Superplasticiser (kg/m³)	Slump (mm)
	OPC	GFNS	Sand	FNS				
PC-FNS0	390	0	710	0	1194	0.33	4	130
GFNS-FNS0	273	110	710	0	1194	0.33	4	135
GFNS-FNS25	273	110	532	217	1194	0.33	4	140
GFNS-FNS50	273	110	355	435	1194	0.33	4	150
GFNS-FNS75	273	110	177	652	1194	0.33	4	125
GFNS-FNS100	273	110	0	870	1194	0.33	4	115

The concrete was mixed in a 70 L concrete mixer with saturated surface dry (SSD) aggregates. Workability of concrete was determined by measuring the slump in accordance with AS 1012.3.1[27]. The specimens cured by immersion in water up to 28 days. The reported results are mean values obtained from three identical specimens. Compressive strength of concrete was determined using 100 mm × 200 mm cylinders at 7, 28, 56 and 180 days of age, according to AS 1012.9[28]. Flexural strength was determined at 28 days using 400 mm × 100 mm × 100 mm beams as per AS 1012.11[29]. Splitting tensile strength was determined at 28 days using 150 mm × 300 mm cylindrical specimens in accordance with AS 1012.10[30]. Modulus of elasticity was tested at 28 days according to AS 1012.17[31].

3.0 RESULTS AND DISCUSSION

3.1 WORKABILITY

Slump values of the concrete mixtures are given in Table 4. It can be seen that slump varied from 110 mm to 145 mm. There was no noticeable change of slump by the use of GFNS as 30% replacement of cement. However, slump increased from 135 mm to 150 mm for using 50% FNS aggregate as replacement of sand. Thus, there was about 4% and 10% increase of slump by the use of 25% and 50% FNS aggregate, respectively. This increment of slump is attributed to the higher density and lower water demand of FNS aggregate than sand. On the other hand, there was a notable reduction of slump for FNS contents beyond 50%. The reductions of slump were 8% and 19% by the use of 75% and 100% FNS aggregate, respectively.

This reduction of workability by the high percentages of FNS aggregate is attributed to the higher angularity and larger sizes of FNS particles. The decrease of workability for using high percentages of FNS aggregate is consistent with the sand flow test results shown in Figure 2. It can be seen from Figure 3 that the fine aggregate containing 75% FNS was plotted in the zone of poor workability. However, the mean slump values of concrete using up to 100% FNS fine aggregate were above 100 mm. All the concrete mixtures were compacted on a vibrating table without any segregation and excessive bleeding.

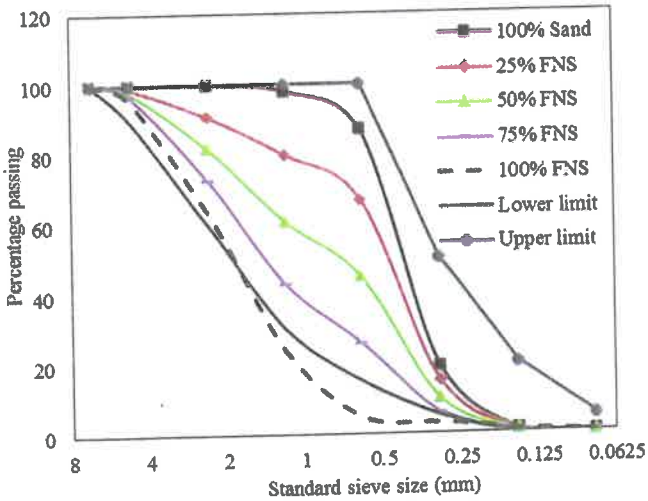
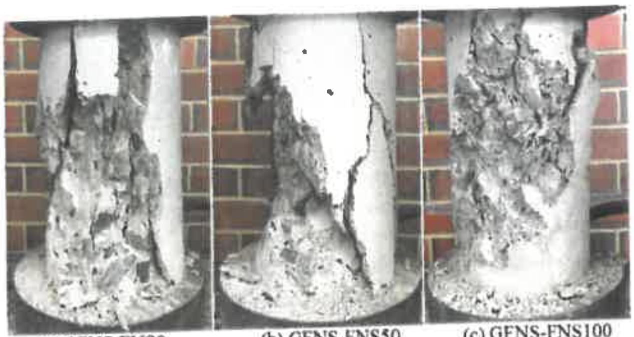


FIGURE 3: Particle distribution of sand, FNS and recommended limits of AS 2758.1[26].

3.2 COMPRESSIVE STRENGTH

Figures 4 (a), (b) and (c) show the typical failure patterns of cylinders with 0%, 50% and 100% FNS aggregates, respectively. No significant difference in the failure patterns could be observed due to the use of FNS aggregate. FNS fine aggregate was found uniformly distributed in the cylinders.



(a) GFNS-FNS0 (b) GFNS-FNS50 (c) GFNS-FNS100

FIGURE 4: Failure patterns of concrete with different percentages of FNS aggregate.

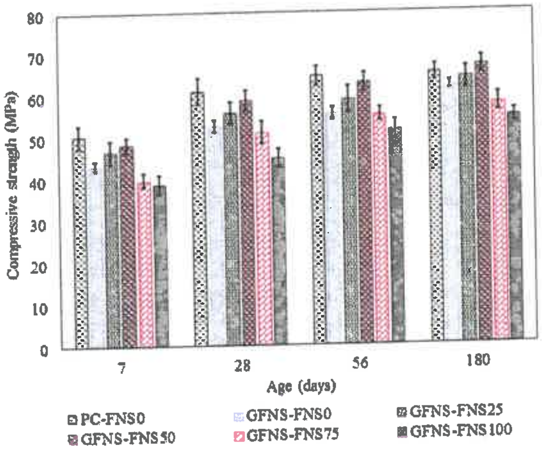


FIGURE 5: Mean compressive strengths of concrete mixtures.

The mean compressive strengths of concrete mixtures at different ages are shown in Figure 5, with error bars at one standard deviation. The results show a noticeable reduction of the early-age compressive strengths of mix GFNS-FNS0 as compared to PC-FNS0. For instance, the 7-day compressive strength decreased from 51 MPa to 44 MPa, which is a 14% reduction by the use of 30% GFNS. This reduction of compressive strength is attributed to the very low calcium content of GFNS. Compressive strength of mix PC-FNS0 then increased to 61 MPa and 65 MPa at 28 days and 56 days, respectively. The compressive strength then remained almost same up to the age of 180 days.

On the other hand, compressive strength of mix GFNS-FNS0 increased to 53 MPa, 56 MPa and 62 MPa at 28 days, 56 days and 180 days, respectively. This shows that compressive strength of the concrete using 30% GFNS continued to increase up to 180 days. Though strength of the GFNS mix was 13% less than that of the control mix at 28 days, the difference reduced to 5% at 180 days of age. Therefore, strength increased at a higher rate in the GFNS concrete than the control mix at ages after 28 days. The higher rate of strength development at later ages is attributed to the pozzolanic reaction of GFNS. Similar effect of GFNS was previously observed by Rahman[17]. Furthermore, inclusion of FNS by up to 50% of the fine aggregate showed considerable strength increase of concrete. However, there was noticeable strength decrease beyond 50% replacement of sand by FNS. At 28 days, compressive strength increased by 6% and 11% for using 25% and 50% FNS aggregate, respectively. However, the use of 75% and 100% FNS aggregate resulted in 3% and 15% reductions of 28-day compressive strength, respectively. Similar trends were observed at 7, 56 and 180 days of age. At 180 days, the compressive strength increments were 3% and 8% for 25% and 50% FNS aggregates, respectively. On the other hand, at the same age, 7% and 12% strength reductions were observed for 75% and 100% FNS aggregates, respectively. The strength increment by up to 50% FNS aggregate is attributed to the improved aggregate gradation and higher density of FNS aggregate. On the other hand, beyond 50% replacement level, the higher angularity and larger size of FNS particles increased voids content that resulted in the reduction of compressive strength.

3.3 FLEXURAL STRENGTH

Flexural strength of the concrete samples after 28 days of curing is shown in Figure 6. It can be seen that flexural strength decreased from 6.10 MPa to 5.09 MPa due to 30% cement replacement by GFNS when 100% natural sand was used as fine aggregate. This is 16% reduction of flexural strength by the use of 30% GFNS as a binder. It can be seen that flexural strength of the specimens using 30% GFNS as SCM gradually increased to 6.13 MPa for 50% FNS aggregate. The flexural strength improvements were 7% and 20% for 25% and 50% FNS aggregate, respectively. However, there were 2% and 7% flexural strength reductions in the specimens using 75% and 100% FNS aggregate, respectively. The trend of flexural strengths is seen to be similar to that of compressive strength. The ratio of flexural strength to compressive strength of the mixtures varied in the range of 0.10 to 0.12.

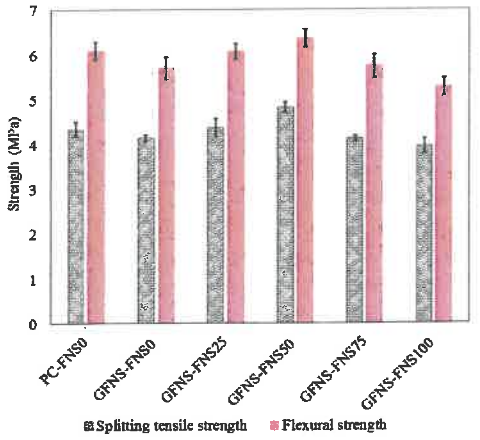


FIGURE 6: **Mean flexural & splitting tensile strength of concrete.**

3.4 SPLITTING TENSILE STRENGTH

Splitting tensile strengths at 28 days are shown in Figure 6. It can be seen that there was a marginal strength reduction by about 5% due to 30% cement replacement by GFNS. Splitting tensile strength increased by 5% and 16% due to the use of 25% and 50% FNS aggregate, respectively. Besides, the splitting tensile strength of concrete with 75% FNS aggregate was almost same as that of the concrete without FNS aggregates. There was a 5% decrease in splitting tensile strength due to 100% replacement of sand by FNS aggregate. The increase of splitting tensile strength up to 50% FNS is attributed to the improved interlocking of the angular FNS particles. However, splitting tensile strength then declined with further increase of FNS content due to the increased voids content. The ratio of splitting tensile strength to compressive strength varied in the range of 0.07 to 0.09. Overall, splitting tensile strength varied showing a similar trend of compressive strength.

3.5 MODULUS OF ELASTICITY

The modulus of elasticity results are shown in Figure 7. It can be seen that modulus of elasticity of the specimens varied within a range of 34 GPa to 42 GPa. Modulus of elasticity gradually increased with the increment of FNS aggregates up to 50%, whereas further replacement reduced the modulus of elasticity. It can be seen that modulus of elasticity decreased from 42 GPa to 37 GPa by the use of 30% GFNS as cement replacement. Modulus of elasticity then increased to 38 GPa and 42 GPa for 25% FNS and 50% FNS aggregate, respectively. Besides, further replacement of sand by FNS aggregate such as 75% and 100% reduced modulus of elasticity to 36 GPa and 34 GPa, respectively. Thus, the variations of modulus of elasticity also showed same trend as compressive strengths of the mixtures.

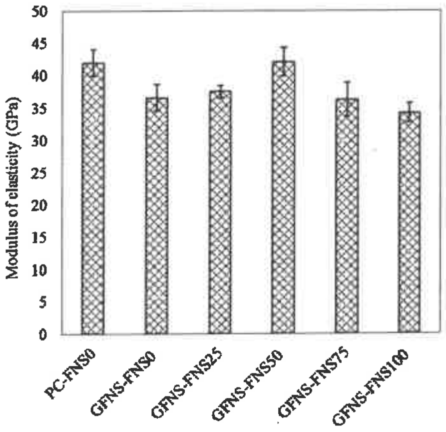


FIGURE 7: **Modulus of elasticity of concrete.**

4.0 CONCLUSIONS

Workability of concrete was not affected by the addition of 30% GFNS as a supplementary binder. Workability slightly increased with the use of FNS fine aggregate up to 50% and then decreased for 75% and 100% FNS. The decrease of workability by the large volumes of FNS aggregate is consistent with the increased voids contents and flow times shown by the sand flow cone tests.

It was found that 30% cement replacement by GFNS reduced the 7-day and 28-day compressive strengths of concrete by 16% and 13%, respectively. However, the strength reduction was only 5% at 180 days. The late-age strength development is attributed to the pozzolanic reaction of GFNS. The use of FNS aggregate showed increased compressive strength for up to 50% replacement of sand. Compressive strength then decreased for 75% and 100% FNS contents. The increment of strength is attributed to the effect of FNS on the grading improvement of fine aggregate. The decline of strength for FNS contents beyond 50% is attributed to the increased void content by the larger size FNS particles. The trends of flexural and splitting tensile strengths, and elastic modulus of concrete with inclusion of GFNS and FNS aggregate were similar to that of compressive strength.

Overall, the use of 30% GFNS as a cement replacement and 50% FNS fine aggregate can be considered as a viable option to produce green concrete without compromising the mechanical properties.

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