



Carbon steel slag as cementitious material for self-consolidating concrete*

Yu-Chu PENG^{†1,2}, Chao-Lung HWANG³

⁽¹⁾Graduate Institute of Construction Engineering, National Taiwan University of Science and Technology, Taipei)

⁽²⁾Department of Leisure Management, Taiwan Hospitality and Tourism College, Taipei)

⁽³⁾Graduate Institute of Construction Engineering, National Taiwan University of Science and Technology, Taipei)

[†]E-mail: thtc001@gmail.com

Received Oct. 21, 2009; Revision accepted Feb. 23, 2010; Crosschecked June 3, 2010

Abstract: This study deals with the recycling of carbon steel slag (CSS) to produce self-consolidating concrete (SCC). Since the chemical composition of CSS is similar to that of Portland cement or blast furnace slag (BFS), it is expected to behave similarly. In the current study, the pozzolanic activity index of CSS is examined. Furthermore, the use of CSS as a pozzolanic material to partially replace Portland cement in the production of SCC is tested. We designed concrete mixtures with different water-to-cementitious material ratios (w/cm) keeping water and superplasticizer (SP) contents constant. Results showed that the design and performance of all the concrete mixtures used in this investigation were comparable to those of SCC and high performance concrete (HPC). However, compared to ordinary plain concrete (OPC), the additional CSS content increases the setting time. In the CSS mixtures set for 90 d, compressive strengths of 86%, 134% and 121% were attained as compared to the control concrete; the corresponding w/cm ratios were 0.28, 0.32 and 0.40, respectively. Verifying the soundness of the SCC for meeting the criteria for HPC, the ultrasonic pulse velocity (UPV) of CSS was found to be comparable to that of ordinary concrete. In conclusion, the recycling of CSS can be advantageously employed in the production of SCC.

Key words: Carbon steel slag (CSS), Self-consolidating concrete (SCC), Pozzolanic, Recycling

doi:10.1631/jzus.A0900635

Document code: A

CLC number: TU528

1 Introduction

In Taiwan, self-consolidating concrete (SCC) exhibiting high-flow behaviour is a widely used concrete material to solve conventional concrete problems such as honeycomb structures that occur as a result of poor practice. SCC is also used as the material of choice for heavily reinforced concrete structures located in seismic zones (Paczkowski and Kaszynska, 2007). Pozzolanic materials are important ingredients for making SCC (Mihashi and Yan, 1995). For many years, pozzolanic admixtures, such as blast furnace slag (BFS), pulverized coal ash (fly ash),

silica fumes, and copper slag, have been recycled to partially replace Portland cement in concrete mixtures. The main advantages of using pozzolanic materials are improvements in performance and significant reduction in the life-cycle costs of concrete structures; the latter, in particular, continues as a significant problem for engineers (Zhang *et al.*, 1999; Al-Jabri *et al.*, 2002; Li and Zhao, 2003). Materials such as steel slag, normally considered as waste, have promising applications as partial Portland cement replacements in concrete mixtures. Considerable research and development has been conducted to develop new concrete technologies such as SCC. Furthermore, the construction of durable concrete has also been pursued. Initially, pozzolanic admixtures were solid waste and it was extremely costly to treat and dump them into a final storage area. Today, however, in the

* Project supported by the Taiwan National Science Council (No. NSC-98-0410)

© Zhejiang University and Springer-Verlag Berlin Heidelberg 2010

concrete industries in Taiwan and elsewhere, these admixtures are important materials for the production of low-cost durable concrete, and an example of environmental protection and resource conservation.

In Taiwan, carbon steel slag (CSS) is a by-product of the reduction during the production of refining carbon steel in an arc furnace, and is seldom recycled. On average, the production of 1 t of carbon steel yields 10 kg of CSS waste, and hence, in Taiwan, more than 5.6×10^4 t of CSS is produced each year. Due to the relatively small amounts of CSS relative to BFS, Environmental Protection Agency (EPA) regulations had previously permitted the dumping of CSS. Today, the dumping of such waste is not permitted, and the proper disposal of CSS has become a huge problem. Since lime, coke and silicon iron are added to promote the reducing process during high-temperature-refinery scrap steel procedures, the CSS contains large amounts of CaO, SiO₂ and Al₂O₃. This waste composition, however, is similar to BFS or Portland cement (Chiang *et al.*, 2004; Peng, 2009). Hence, CSS can be considered for use as a pozzolanic admixture to partially replace Portland cement in a concrete mixture.

Rather than use CSS for backfill soil or as material to be retained in the plant, steel slag can be regarded as a low-quality clinker and can be used to partially substitute the clinker of composite Portland cement (Sakuraya, 1999; Wu *et al.*, 1999). In Japan and other industrialized countries, steel slag has already been applied for use in civil engineering applications, such as road base construction and soil stabilization (Roy and Idorn, 1982; Geiser, 1999). In Germany, about 17.1% of steel slag is used for highway construction, 5.4% is recycled, and 40.5% is used in agricultural fertilizer production (Hogan and Meusel, 1981; ACI Committee 211, 1993; Mihashi *et al.*, 1995; Monshi and Asgarani, 1999; Luxán *et al.*, 2000). The mineralogical composition of steel slag is as follows: anhydrous calcium silicates and silicoaluminates; gehlenite, larnite and bredigite; magnetite and magnesioferrite and manganese oxides (Esfahani and Kianoush, 2005; Hwang and Khayat, 2008; Koehler and Fowler, 2008). Thus, some researchers have tested the effects of mixed iron slag (36%–45%), steel slag (6%–22%) and limestone (40%–64%) on the setting time of cement paste and the compressive strength at 3, 7 and 28 d (Schindler *et*

al., 2007; Whitcomb and Kiousis, 2009). Nevertheless, other than documenting the chemical composition of CSS, there are few studies on the pozzolanic reactions after the addition of CSS.

2 Experimental

2.1 Material

The aggregate was quarried from I-Lan River, Northern Taiwan, and consisted of large amounts of elongate slate and fragile particles. The cement and superplasticizer (SP) used corresponded to ASTM C150 type I Portland cement and ASTM C494 type F high range water reducing agent (HWRA), respectively. A naphthalene lingo-sulfonate base was used for promoting the flow ability of SCC; the specific gravity was 1.18; pH 6.93 and chloride ion content, less than 50×10^{-6} . As a by-product of the carbon steel manufacturing process, while the carbon steel settles in the smelter (since its density is high), impurities remain on top. The carbon steel is then transported to a water basin maintained at a low temperature for solidification. The end product (CSS) is a hard solid material that is then sent to a crusher for further processing. The CSS is powdered to pass through sieve No. 4 (pore diameter 4.76 mm). Subsequently, it is re-ground for 3 h at a speed of 60 r/min to pass through sieve No. 200 (pore diameter 75 μm). In this study, type I Portland cement has been used. Class F fly ash and BFS were obtained from the Taiwan Power Company, China and China Steel Corporation, respectively. The SP was Glenium 51 obtained from the Taiwan Formosa Chemicals & Fibre Company, China. In Table 1, the specific gravities of Portland cement and CSS are listed as 3.14 and 2.67, respectively; further, CSS powder and Portland cement (type I) have specific surface areas of 2504 and 3622 cm²/g, respectively. Hence, CSS has the least fineness, which is characteristic of materials with low surface areas. As shown in Table 2, CSS is highly alkaline, with a pH of 11.50, an absorption capacity (saturated surface dry) of 7.60%, fineness modulus (FM) of 1.76 according to ASTM C136, and dry loose density of 1266 kg/m³ according to ASTM C29. Fig. 1 shows the relationships of CSS with BFS and Portland cement; the percentage of the main compositions (SiO₂ and CaO) of CSS lies between those of BFS and Portland cement.

Table 1 Physical properties and chemical compositions of OPC and CSS

Item		OPC	CSS
Physical property	Specific gravity	3.14	2.67
	Specific surface area (cm ² /g)	3622	2504
	pH	—	11.50
	Absorption capacity (%)	—	7.60
	Fineness modulus (FM)	—	1.76
	Dry loose density (kg/m ³)	—	1266
Chemical composition	SiO ₂ (%)	21.46	26.52
	Al ₂ O ₃ (%)	4.84	5.95
	Fe ₂ O ₃ (%)	3.12	3.78
	CaO (%)	62.34	46.45
	MgO (%)	2.87	13.27
	SO ₃ (%)	2.06	0.65
	f-CaO (%)	0.88	2.11
	Na ₂ O (%)	0.22	0.26
	K ₂ O (%)	0.70	0.11
	CaO/SiO ₂ (%)	2.91	1.75

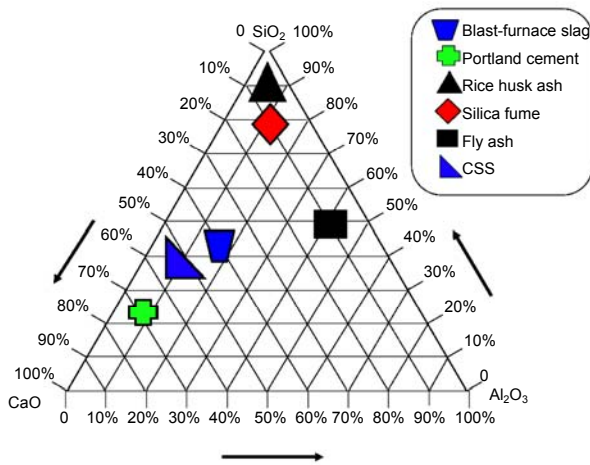


Fig. 1 Comparison of compositions of CSS, BFS and Portland cement

2.2 Mixture design

To obtain high-strength SCC with lower water content (160 kg/m³), in this study, w/cm ratios (water/(cement+CSS)) of 0.28, 0.32 and 0.40 were selected. Furthermore, large amounts of SP were added to achieve better flow behavior. CSS powder was used to replace 5.0%, 7.5% and 10% weights of Portland cement. Mixtures with three different w/cm ratios were prepared for ordinary plain concrete (OPC) and carbon steel slag concrete (CSC) (Table 2), designated as OPC28, OPC32 and OPC40 and CSC28, CSC32 and CSC40 (Kwan and Ng, 2008; Whitcomb and Kiousis, 2009).

3 Results and discussion

3.1 Workability of SCC

Fig. 2 illustrates slump vs. different w/cm ratios for both OPC and CSC. The figure indicates that all slump values are greater than 230 mm, the specification for SCC with high flow. Concrete with a lower w/cm ratio than 0.28—implying significantly high

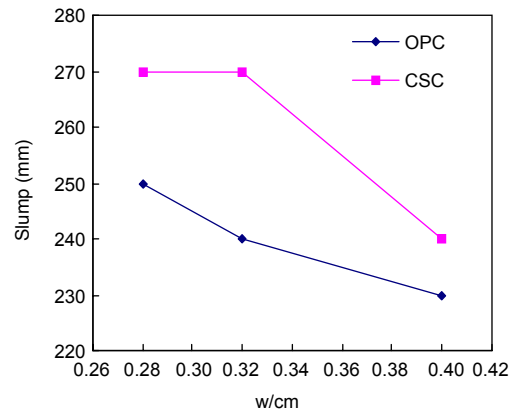


Fig. 2 Slump vs. various w/cm ratios of concrete

Table 2 Mixture proportion of self-consolidating concrete

Designation of concrete	w/c ratio ^a	w/cm ratio ^b	Mix proportion (kg/m ³)						
			Cement	CSS/Cement (%)	Fine aggregate	Coarse aggregate	Water	SP ^c	Water+SP
OPC28	0.28	0.28	572	—	757	901	145	15	160
OPC32	0.32	0.32	500	—	783	932	148	12	160
OPC40	0.40	0.40	400	—	820	976	152	8	160
CSC28	0.28	0.28	545	5.0	832	820	146	14	160
CSC32	0.34	0.32	465	7.7	861	849	149	11	160
CSC40	0.44	0.40	364	10.0	901	888	153	7	160

^a w/c ratio is water/cement; ^b w/cm ratio is water/(cement+CSS); ^c SP is superplasticizer

binder content—may lead to higher slump and satisfactory flow ability. For an identical dosage of SP mixtures, CSC has higher slump than OPC mixtures. Hence, it is clear that the use of CSS might improve the workability of SCC; and this is similar to the test results of the research papers referenced. Hence, the use of CSS in SCC can lead to high flow properties.

3.2 Setting time of SCC

Fig. 3 shows the effects of CSS on the penetration resistance of concrete, indicating that as the w/cm ratio of OPC or CSC increases, the penetration resistance decreases and the setting time increases. Further, the setting time of CSC is longer than that of OPC irrespective of the w/cm ratio. This is due to the low polymers admixture interface (PAI) values of CSS. Thus, the setting time increases with the decrease of CSS. This result is similar to the results in (Mihashi and Yan, 1995) which showed that the addition of BFS decreased the setting time of SCC.

3.3 Compressive strength of SCC

The compressive strength and percentage of concrete mixtures with different w/cm ratios at the specified age are shown in Table 3. The compressive strength of each mixture is greater than 41 MPa at 56 d. This satisfies the requirement that SCC must have high strength (Hogan and Meusel, 1981). The compressive strength of OPC and CSC with a w/cm ratio of 0.28 is either equal to or higher than 83 MPa at 90 d; however, compressive strength of CSC28 at any age is lower than that of OPC28. In contrast, the percentage of compressive strength is higher than 90% at 28 d, and it is reduced to 76% at 90 d. This corresponds to a 15% reduction in the PAI at 28 d. The compressive strength of CSC with a w/cm ratio of 0.32 or 0.40 at any age, however, is higher than that of OPC, and the percentages of compressive strength are from 106% to 134% and from 108% to 121%,

with respect to the w/cm ratio. This clearly indicates that the addition of CSS improves the strength development of cement paste as long as the w/c ratio is greater than 0.32 or w/cm is higher than 0.28. This means that the reactions of strength development of cement with CSS will be enhanced with sufficient water contents. However, it is suggested that the total water content of concrete, including the moisture in liquid admixture be maintained as low as possible to avoid large shrinkage and sedimentation (Peng and Huang, 2009; 2010). Fig. 4 shows the influence of CSS content on compressive strength: higher CSS content mixtures will cause lower compressive strength.

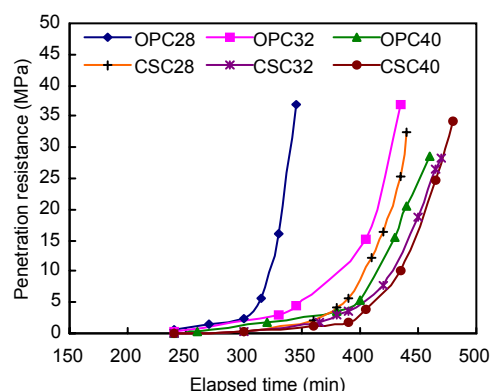


Fig. 3 Comparison between the OPC and CSC with respect to penetration resistance of concrete

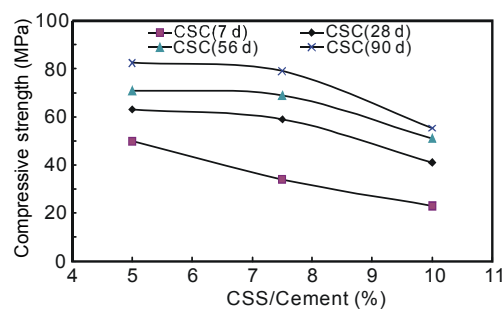


Fig. 4 Effect of CSS content at different ages on the compressive strength of SCC

Table 3 Compressive strength and percentage of compressive strength of concrete

Designation of concrete	w/c ratio ^a	w/cm ratio ^b	Compressive strength (MPa) (percentage of compressive strength (%)) ^c				
			3 d	7 d	28 d	56 d	90 d
OPC28	0.28	0.28	46.5 (100)	53.9 (100)	69.6 (100)	93.7 (100)	95.6 (100)
CSC28	0.29	0.28	42.9 (92)	50.0 (93)	63.2 (91)	71.0 (76)	82.5 (86)
OPC32	0.32	0.32	25.0 (100)	32.0 (100)	49.6 (100)	57.3 (100)	59.1 (100)
CSC32	0.34	0.32	26.5 (106)	34.1 (107)	58.5 (118)	69.4 (121)	78.9 (134)
OPC40	0.40	0.40	16.3 (100)	22.2 (100)	37.1 (100)	45.1 (100)	45.8 (100)
CSC40	0.44	0.40	17.6 (108)	24.1 (109)	40.7 (110)	50.6 (112)	55.3 (121)

^a w/c ratio is water/cement; ^b w/cm ratio is water/(cement+CSS); ^c Percentage of design strength

3.4 Ultrasonic pulse velocity of SCC

Theoretically, the ultrasonic pulse velocity (UPV) of a solid object is higher than that of air, and a high-density solid will have high UPV. Therefore, the UPV is a good measure of the soundness of hardened concrete. It is generally acknowledged that the UPV increases with concrete density. In our study, the UPV of all mixtures was greater than 4200 m/s. Table 4 shows the UPV and the difference in UPV between CSC and OPC (as a percentage) at each w/cm ratio, from 3 to 90 d. The UPV of CSC28 at all ages is lower by 1% to 2% than that of OPC28; however, the UPV of CSC32 and CSC40 is higher by 3% than that of OPC32 and OPC40, respectively. This result is similar to trend in compressive strength—the addition of CSS enhances the pozzolanic reaction with high w/c ratio or w/cm ratio, i.e., sufficient water. Fig. 5 shows a good linear relationship between the compressive strength and UPV of concrete for both OPC and CSC. In other words, UPV is a good method for evaluating the performance and homogeneity of SCC.

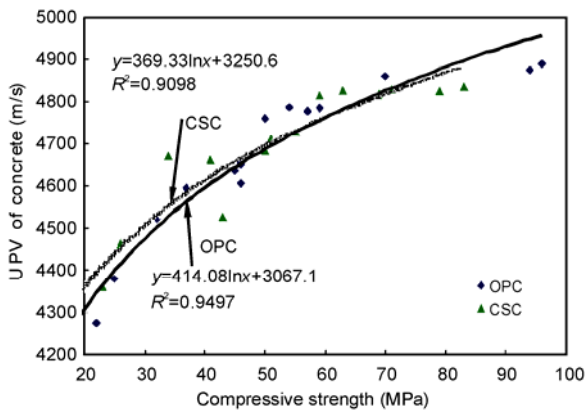


Fig. 5 Relationship between UPV and compressive strengths of OPC and CSC

3.5 Microstructure observation

Scanning electron microscopy (SEM) observations are conducted with specimens at the ages of 3 and 28 d. The image characteristics of concrete at 3 d are shown in Figs. 6a–8a. As shown in Fig. 6a, at the early age of 3 d, considerable amounts of hexagonal-shaped calcium hydroxide ($\text{Ca}(\text{OH})_2$), spherical-shaped C-S-H gel in CSC 28 (w/cm=0.28) and certain amounts of fine pores (dark zone) exist. Fig. 7a shows the presence of numerous rosette-shaped mono-sulfoaluminate (AFm) and small amounts of needle-shaped ettringite (AFt) in CSC32 (w/cm=0.32). Fig. 8a also shows that there are rosette-shaped AFm in CSC40 (w/cm=0.40). Here, the w/cm ratio is greater than or equal to 0.32 as a result of increase in CSS amounts and the existence of high Al_2O_3 and Fe_2O_3 contents. The primary hydration products are hexagonal-shaped $\text{Ca}(\text{OH})_2$, spherical-shaped C-S-H gel and a certain amount of rosette-shaped AFm. This observation confirms the conclusions made for both strength and UPV that the reaction of CSS with cement paste requires sufficient water to aid hydration. At a later age, as shown in Fig. 6b, the microstructure of CSC28 is extremely dense. Fig. 7b also shows the presence of numerous rosette-shaped AFm, but no needle-shaped AFt, while Fig. 8b shows large pores in CSC40 with a large amount of hexagonal-shaped $\text{Ca}(\text{OH})_2$ in the reaction process. This is advantageous for the hydration reaction of CSS, and it also indicates that more pores are observed with higher w/cm ratios.

4 Conclusions

In this study, we conducted investigations on the recycling of carbon steel slag CSS to produce SCC. Our conclusions are given as follows:

Table 4 Ultrasonic pulse velocity and percentage ultrasonic pulse velocity of self-consolidating concrete

Designation of concrete	w/c ratio ^a	w/cm ratio ^b	UPV of concrete (m/s) (percentage of UPV (%)) ^c				
			3 d	7 d	28 d	56 d	90 d
OPC28	0.28	0.28	4606 (100)	4787 (100)	4859 (100)	4876 (100)	4890 (100)
CSC28	0.29	0.28	4525 (98)	4683 (98)	4828 (99)	4830 (99)	4835 (99)
OPC32	0.32	0.32	4381 (100)	4523 (100)	4760 (100)	4777 (100)	4785 (100)
CSC32	0.34	0.32	4466 (102)	4669 (103)	4814 (101)	4821 (101)	4825 (101)
OPC40	0.40	0.40	4211 (100)	4274 (100)	4595 (100)	4635 (100)	4651 (100)
CSC40	0.44	0.40	4295 (102)	4361 (102)	4659 (101)	4709 (102)	4728 (102)

^a w/c ratio is water/cement; ^b w/cm ratio is water/(cement+CSS); ^c Percentage of UPV=(CSC/OPC)×100 at fixed w/cm ratios

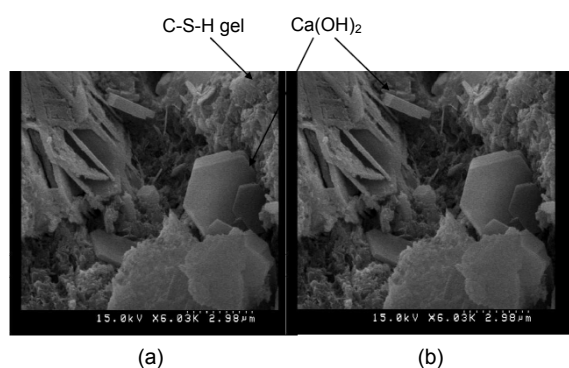


Fig. 6 SEM micrograph of CSC28 at (a) 3 d and (b) 28 d

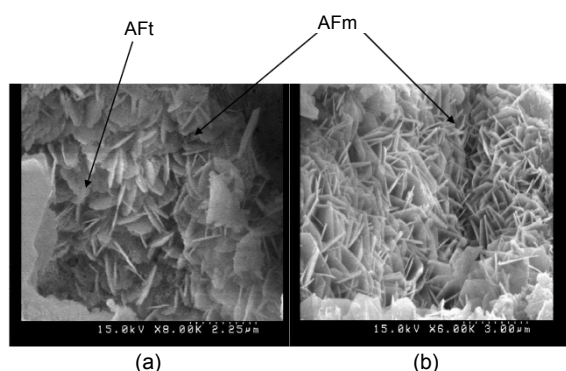


Fig. 7 SEM micrograph of CSC32 at (a) 3 d and (b) at 28 d

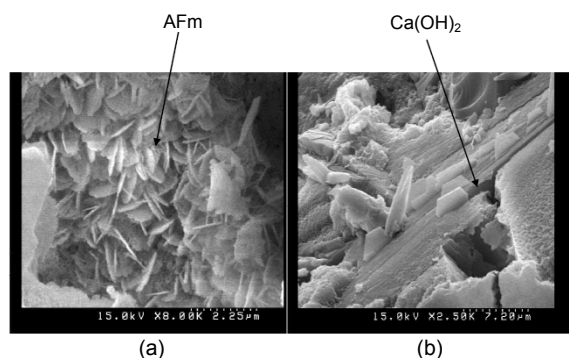


Fig. 8 SEM micrograph of CSC40 at (a) 3 d and (b) 28 d

1. The major chemical compositions of CSS are CaO , Al_2O_3 and SiO_2 , a composition similar to that of Portland cement and BFS. The PAI of CSS is 85% at 28 d. Hence, CSS can be expected to have good cementitious properties and effects.

2. CSS can be designed as easily as SCC. In comparison with OPC, increasing the CSS content will increase the setting time.

3. Concrete using CSS has a higher compressive strength than that using OPC. If w/cm ratios of 0.32 or 0.40 are used, the percentage of compressive strength

increases by more than 21% at 90 d.

4. As the amount of CSS in concrete increases, the compressive strength decreases. The strength is similar to other concrete, however, when CSS of 5.0%–7.5% is used, except at 7 d.

5. The SEM images show that the hydration rate of CSS is lower than that of OPC. Further, large amounts of Ca(OH)_2 and AFm are present in CSS as a cementitious material.

In this manner, we showed that CSS can potentially be used as a cementitious material in SCC.

References

- ACI Committee 211, 1993. Guide for selecting proportions for high-strength concrete. *ACI Materials Journal*, **90**:272-283.
- Al-Jabri, K., Al-Ghassani, M., Taha, R., 2002. Use of copper slag and cement by-pass dust as cementitious materials. *Cement Concrete and Aggregates*, **24**(1):2-7. [doi:10.1520/CCA10485J]
- Chiang, C.C., Chenn, Y.Y., Lin, T.Y., Hwang, C.L., 2004. The application of electric arc furnace reduction slags to high performance concrete. *Journal of the Chinese Institute of Civil and Hydraulic Engineering*, **16**:167-178.
- Esfahani, M.R., Kianoush, M.R., 2005. Bond strength of glass fibre reinforced polymer reinforcing bars in normal and self-consolidating concrete. *Canadian Journal of Civil Engineering*, **32**(3):553-560. [doi:10.1139/05-005]
- Geiser, J., 1999. Metallurgical Slag—Create a Future Construction Material. The International Associate of Metallurgical Slag Recycle and Utilization, Beijing, p.1-8.
- Hogan, F.J., Meusel, J.W., 1981. Evaluation for durability and strength development of a ground granulated blast furnace slag. *Cement Concrete and Aggregates*, **3**(1):40-52. [doi:10.1520/CCA10201J]
- Hwang, S.D., Khayat, K.H., 2008. Effect of mixture composition on restrained shrinkage cracking of self-consolidating concrete used in repair. *ACI Materials Journal*, **105**(5): 499-509.
- Koehler, E.P., Fowler, D.W., 2008. Dust-of-fracture aggregate microfines in self-consolidating concrete. *ACI Materials Journal*, **105**(2):165-173.
- Kwan, A.K.H., Ng, I.Y.T., 2008. Performance criteria for self-consolidating concrete. *Transactions Hong Kong Institution of Engineers*, **15**(2):35-41.
- Li, G., Zhao, X., 2003. Properties of concrete incorporating fly ash and ground granulated blast-furnace slag. *Cement and Concrete Composites*, **25**(3):293-299. [doi:10.1016/S0958-9465(02)00058-6]
- Luxán, M.P., Sotolongo, R., Dorrego, F., Herrero, E., 2000. Characteristics of the slags produced in the fusion of scrap steel by electric arc furnace. *Cement and Concrete Research*, **30**(4):517-519.
- Mihashi, H., Yan, X., Arikawa, S., 1995. Strength Properties

- and Frost Damage Resistance of High Performance Concrete Using Blast Furnace Slag and Silica Fume. Proceedings of the Fourth Weimar Workshop on High Performance Concrete, Germany, p.195-204.
- Monshi, A., Asgarani, M.K., 1999. Producing Portland cement from iron and steel slag and limestone. *Cement and Concrete Research*, **29**(9):1373-1377. [doi:10.1016/S0008-8846(99)00028-9]
- Paczkowski, P., Kaszynska, M., 2007. Self-consolidating Concrete for On-site Bridge Applications. International Conference Organised by the Institution of Civil Engineers, p.312-320.
- Peng, Y.C., Huang, C.L., 2009. Engineering properties of sintered waste sludge as lightweight aggregate in a densified Concrete mixture. *Journal of Chongqing University (English Edition)*, **8**(4):231-238.
- Peng, Y.C., Hwang, C.L., 2010. The concrete dense packing model and engineering properties of aggregate concrete with different densities. *Journal of University of Science and Technology Beijing*, **32**(3):366-369.
- Roy, D.M., Idorn, G.M., 1982. Hydration, structures, and properties of blast furnace slag cements, mortars, and concrete. *ACI Journal Proceedings*, **82**:444-457.
- Sakuraya, T., 1999. The Utilizing Condition of Metallurgical Slag and Steel Slag for Japanese Refinery Steel Industry. The International Associate of Metallurgical Slag Recycle and Utilization, Beijing, p.15-20.
- Schindler, A.K., Barnes, R.W., Roberts, J.B., Rodriguez, S., 2007. Properties of self-consolidating concrete for prestressed members. *ACI Materials Journal*, **104**(1): 53-61.
- Whitcomb, B.L., Kiouisis, P.D., 2009. Development of self-consolidating concrete for thin wall applications including validation. *Journal of Materials in Civil Engineering*, **21**(10):587-593. [doi:10.1061/(ASCE)0899-1561(2009)21:10(587)]
- Wu, X.Q., Zhu, H., Hou, X.K., Li, H.S., 1999. Study on steel slag and fly ash composite Portland cement. *Cement and Concrete Research*, **29**(7):1103-1106. [doi:10.1016/S0008-8846(98)00244-0]
- Zhang, M.H., Bilodeau, A., Malhotra, V.M., Kim, K.S., Kim, J.C., 1999. Concrete incorporating supplementary cementing materials: effect on compressive strength and resistance to chloride-ion penetration. *ACI Materials Journal*, **96**:181-189.

New Information on JZUS(A/B/C)

(<http://www.zju.edu.cn/jzus>)

In 2010, we have updated the website and opened a few active topics:

- The top 10 cited papers in parts A, B, C;
 - The newest cited papers in parts A, B, C;
 - The top 10 DOIs monthly;
 - The 10 most recently commented papers in parts A, B, C.
- (Welcome your comment and opinion!)

We also list the International Reviewers to express our deep appreciation and Crosscheck information etc.

If you would like to allot a little time to opening <http://www.zju.edu.cn/jzus>, you will find more interesting information. Many thanks for your interest in our journals' publishing change and development in the past, present and future!

Welcome you to comment on what you would like to discuss. And also welcome your interesting/high quality paper to JZUS(A/B/C) soon.

Top 10 cited A B	
Optimal choice of parameter...	
How to realize a negative r...	
Three-dimensional analysis ...	
THE POLYMERIZATION OF METHY...	
Hybrid discrete particle sw...	
	more
Newest cited A B C	
AN ULTRAHIGH VACUUM CHEMICA...	
RESEARCH ON THE METHODS OF ...	
STUDY OF THE EFFECTIVENESS ...	
Sliding mode identifier for...	
Buckling of un-stiffened cy...	
	more
Top 10 DOIs Monthly	
Continuum damage mechanics ...	
A numerical analysis to the...	
Model-based testing with UM...	
Nonlinear identification of...	
Global nutrient profiling b...	
	more
Newest 10 comments	
Robust design of static syn...	
Acute phase reactants, chal...	
Optimized simulated anneali...	
Advanced aerostatic analysi...	
Global nutrient profiling b...	
	more